

Start-up and Shut-down times of power CCUS facilities

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1. Executive Summary

The Department for Business, Energy and Industrial Strategy (BEIS) has commissioned AECOM to investigate potential improvements to the start-up and shut-down times of gas-fired power Carbon Capture, Utilisation and Storage (power CCUS) facilities. This report summarises the outputs of the study, including process modelling to demonstrate the performance of a range of configuration variants and inputs to the BEIS Dynamic Dispatch Model. A reference or 'standard' configuration case was identified to achieve 95% capture of normal carbon dioxide emissions from a modern H-Class Combined Cycle Gas Turbine power plant. The standard configuration was developed from open literature, project history and AECOM experience of carbon capture processes and is recorded in the Basis of Design, which is appended to this report. Results of the literature review are also provided in an appendix to this report.

A concept design was developed for the power CCUS facility, using Thermoflow 29 for the power cycle and ProMax 5.0 for the carbon capture process. Results of the simulation work are presented in the report, including concept material balances and estimated electrical and heat consumption of a 95% post-combustion capture plant. 35% MEA (no other solvent) was the solvent chosen for this study as an open-art, technology-neutral solvent.

The performance of the standard configuration plant at start-up and shut-down was evaluated, considering issues such as:

- Full system start-up and shut-down times
 - Minimum up time and minimum down time between runs
 - Ramp rates
 - CO₂ capture rates and residual emissions during start-up and shut-down
 - Minimum environmentally-compliant stable generation
 - Fuel burn during start-up and shut-down
 - Gross and net thermal efficiencies and penalty for operating 95% capture plant compared to unabated
- Further, three separate configurations plus one additional noteworthy option have been investigated for their potential to improve the full system performance based on the above metrics. Particular attention was paid to:
- Improvements to the start time, which will inform the likely merit order positioning for power CCUS plant competing against other fossil fuel facilities in a market with significant quantities of renewable generation.
 - Residual emissions during transient events, which govern an increasing share of plant operating life at lower capacity factors.

The un-optimised scenario (referred to as 'standard configuration') was modelled as a benchmark plant configured only for baseload operation i.e. with no measures taken to maintain high capture rates through plant starts or stops. The standard configuration was found to produce incremental emissions during start-up and shut-down and would not be expected to meet a 95% capture target in operation during start-up and shut-down. Four configuration options considered for their potential to improve the flexible performance of the standard configuration plant were:

1. Segregating solvent inventory during start-up between separate absorber and regenerator loops (without adding any extra solvent storage);
2. Added solvent storage and solvent buffer volume to maintain capture rate until regenerated lean amine is available;
3. Dedicated storage of heat for pre-heating the regenerator;
4. Fast-starting steam cycle technologies such as Benson boiler and/or HP bypass extraction to reduce the delay before steam extraction to the PCC plant.

Segregated inventory alone was found to give overall start-up capture rate of approximately 87% and therefore would not provide 95% capture throughout start-ups. However, segregated solvent inventory was found to readily combine with the three other options, reducing the impact of deploying any of the storage options to deliver an effective design.

2. Nomenclature

The following nomenclature have been used within this document.

Abbreviation	Description
BAT	Best Available Techniques
BEIS	Department for Business, Energy and Industrial Strategy
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine (Gas Turbine + Steam Turbine)
CCS	Carbon Capture and Storage
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CWS	Cooling Water Supply
CWR	Cooling Water Return
DCC	Direct Contact Condenser
FEED	Front End Engineering Design
GJ	Giga Joules
GT	Gas Turbine
GW	Giga Watts
HHV	Higher Heating Value
HMB	Heat and Material Balance
HRSG	Heat Recovery Steam Generator
ISO	International Standards Organisation
ITT	Invitation to Tender
LHV	Lower Heating Value
mbar	Millibar
MEA	Monoethanolamine
MW	Megawatt
MW.e	Megawatt electricity (distinguish from thermal)
MWh	Megawatt hours
MW.th	Megawatt thermal (distinguish from electrical)
NOx	Nitrogen Oxides

Abbreviation	Description
NTS	Notice to Synchronise
OPEX	Operating Expenditure
PCC	Post-combustion Carbon Capture
PFD	Process Flow Diagram
ppmv	Parts per million by volume
RH	Relative Humidity
SCR	Selective Catalytic Reduction
ST	Steam Turbine
TTES	Tank Thermal Energy Store
WN	Wobbe Number

3. Introduction

3.1 Project Overview

The Department for Business, Energy and Industrial Strategy (BEIS) is currently exploring the role that gas-fired power with Carbon Capture, Utilisation and Storage (power CCUS) can play in the UK electricity system. This was a commitment in the Government's 2018 'UK CCUS Deployment Pathway: An Action Plan'. Development of UK-based CCUS technology has been recognised by the Climate Change Committee as a key component of the most cost-effective pathway to meeting the UK's climate change emissions reduction targets¹.

Power CCUS can provide an important part of the electricity grid decarbonisation process, giving firm dispatchable low carbon generation. However, power CCUS may need to operate at lower load factors, such as mid-merit, as greater amounts of intermittent renewable energy systems are added to the electricity system between now and 2050².

Previous work on power CCUS can be broadly categorised as either:

- Various engineering studies from Concept through to Front End Engineering Design (FEED)-level definition based on defining a process for base-load generation. Limited detail of start-up behaviour, as the process design basis for these studies was to capture from a plant operating at baseload (and therefore typically no more than 20 starts per year total), with start/stop effects taken as negligible.
- Various academic studies considering optimisations including non-linear programming techniques to maximise revenue in a particular operating scenario or investigate the dynamic performance of a particular configuration in a specific scenario, rather than collecting plant characteristics at start-up and shut-down.

Relatively few papers have considered start-up, shut-down and ramping performance in detail³ and fewer still for modern H-Class CCGT plants with fast starting performance. BEIS has therefore commissioned AECOM to carry out a study to determine the performance of power CCUS plant during transient events, given future abated plant may run in a mid-merit role to support renewables, rather than supply baseload power.

This study has also been based on a 95% capture rate of carbon dioxide emissions, as opposed to most of the other literature which was in the 80%-90% range, to reflect the anticipated future requirements for power CCUS plant that will contribute to a net zero energy system. 95% capture was chosen for this study following guidance from BEIS to provide an early indication whether higher capture rates than 80-90% would be achievable, or whether fundamental equilibrium issues would be encountered at 95%.

3.2 Purpose

This report presents a concise summary of the study work to date, incorporating work done in the Basis of Design and literature review. The purpose of this report is to present the modelling assumptions, modelling results and provide a summary of overall study findings.

3.3 Study Objectives

The first objective of this study was to determine a technology-neutral PCC process to deliver 95% that could be considered a 'standard' PCC configuration for further investigation. Areas of study included:

- Determine an appropriate technology-neutral process (solvent choice, concentration and circulation rate)
- Dynamic response within the amine absorber from transient effects on CO₂ rate
- Dynamic response on the amine regeneration process (and reclaiming process if continuously operating) from available steam extraction rate and quality

An investigation of the potential options to improve the standard configuration power CCUS plant was then carried out, with three top configurations identified for further investigation according to a high-level checklist:

- Is the potential option compliant with current Best Available Techniques (BAT) for Large Combustion Plant?

¹ CCC welcomes Government's commitment to Carbon Capture and Storage technology; CCC; 2018;

<https://www.theccc.org.uk/2018/11/28/ccc-welcomes-governments-recommitment-to-carbon-capture-and-storage-technology/>

² Net Zero: The UK's contribution to stopping global warming; CCC; 2019; <https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/>

³ Flexibility of low-CO₂ gas power plants: integration of the CO₂ capture unit with CCGT operation; Ceccarelli, N. et al.; 2014; Energy Procedia; pp. 1703-1726

- What is the reduction in carbon capture plant response time due to dynamic changes in the power plant?
- Does the reduction in carbon capture response time eliminate the time spent generating unabated while starting the PCC plant?
- Can the plant running at part-load qualify for the higher emissions limits currently available below a certain MW generation threshold?
- What residual emissions are expected, if any?
- What are the associated engineering, commercial and technology risks for new-build plants?
- What are the associated challenges for retrofit of standard configuration CCGT+PCC plants with the selected options?

The three options with the top checklist scores were investigated further.

Finally, the study objectives included providing the results of the option investigation and data for flexible power CCUS plant to update the assumptions of the BEIS Dynamic Dispatch Model.

4. Reference Documents

Reference	Document Title
1	Literature Review
2	Basis of Design

5. Methodology

An initial literature review was carried out to gather evidence of power with Carbon Capture, Utilisation and Storage (power CCUS) processes and determine a typical or 'standard' configuration for investigation. The literature review aimed to answer questions posed by the Department for Business, Energy and Industrial Strategy (BEIS) in the Invitation to Tender (ITT):

1. How do unabated Combined Cycle Gas Turbine (CCGT) and standard configuration post-combustion Carbon Capture Utilisation and Storage (CCUS) power plants perform?
2. What is the best available evidence on the start-up and shut-down times associated with alternative configurations and/or operating strategies for CCUS power plants?
3. Based on a qualitative assessment, what three alternative configurations are best suited for further analysis, based on:
 - a. Their ability to improve the start-up times of 'standard configuration' power CCUS facilities without significantly impacting the power generation and CO₂ capture rate
 - b. The engineering and cost challenges associated involved in either newly building such facilities or retro-fitting 'standard configuration' power + CCUS stations to incorporate the alternative configurations and operating strategies
4. Based on metrics such as time, CO₂ vented, total cost etc., how would the selected alternative configurations perform in relation to the parameters identified in the first question?

The full literature review is provided in Ref. 1. Following the Literature Review, the next stage of the study was to set the design basis for the simulation work based on a wide variety of background information including gathered data from the literature review and AECOM's own project experience and judgement.

A representative conservative model of the power plant was then developed in Thermoflow, with outputs to a ProMax flowsheet containing the Post-Combustion Capture (PCC) model. The Thermoflow model was used to gather performance data on the reference power plant performance and inputs such as fuel gas composition, ambient conditions and site cooling strategy.

In order to simulate how the plant performs during the transient periods of start-up and shut-down, a number of key snapshots were identified during both transients of the power plant's operation. These snapshots represent the key characteristic points in the start-up and shut-down process. For example, defining the time at which steam extraction is available to start heating the reboiler, followed by the time at which the reboiler has received enough heat to begin regenerating amine in the stripper.

Based on the findings of the literature review, the chosen configuration options selected to improve flexibility were modelled using ProMax in addition to the base configuration PCC flowsheet. This software is a more developed resource for modelling carbon capture compared to Thermoflow, having rigorous reaction kinetic models to predict real column behaviour with no reliance upon simplified approaches to equilibrium. For each of the configuration options, as well as the standard PCC power plant, a summarised heat and material balance (HMB) sheet with the corresponding process flow diagram (PFD) was completed to record all the key data of the overall process. By comparing each of the HMB sheets and using them in further calculations, the different configurations were compared based on areas identified in the evaluation checklist discussed earlier in the Study Objectives.

6. Literature Review

The content within the Literature Review (Ref. 1) has been structured based on the key questions posed in the ITT. This document is provided in Appendix A of this report for reference and is summarised in the following paragraphs.

The first section related to the performance of unabated CCGT plants and assessed CCGT plants with PCC to characterise a hypothetical 'standard' configuration. The different performance indicators considered within the review include: the time and associated costs with start-up and shut-down, minimum up-time and down-time between operating cycles, ramping rates and minimum turndown of current CCGT plant, CO₂ capture rates and residual emissions, and thermal efficiency of the whole plant. By analysing each of these indicators for the unabated CCGT plant based on existing technical research and data from current plants in operation, an in-depth understanding of the plant's operation has been determined and used as the base of the further study.

Since the process of PCC for both coal and gas-fired power plants are comparable, with the use of PCC more established with coal-fired power plants, knowledge and performance characteristics from these plants can be applied to this study with minor adjustments.

The second section of the review focussed on the flexible operation of amine-based PCC and the different methods studied within academic papers. A large portion of the research within the area of power plant flexibility relates to the economic factors associated with the operation, as opposed to start-up and shut-down times. This means that only a limited number of sources were found that specifically investigate flexibility in terms of operating timings. From these select papers, several different strategies were investigated and compared with the main findings of each of the papers summarised in the Literature Review. This supported the final choice of the three configuration options to be further analysed in this study and gave an approximate idea of the likely impact each would have on the plant's operation.

7. Plant Configuration

7.1 Basis of Design for standard configuration

Having outlined each of the design conditions for the plant, the configuration of the standard CCGT plant for the study was defined. The selection of the equipment and layout of the plant was based on the current BAT for a large combustion plant, as requested in the ITT.

The chosen configuration of the standard unabated CCGT plant has the following characteristics:

- Gas inlet to the two Combined Cycle Gas Turbine (CCGT) trains of Siemens SGT5-9000HL for an unabated export capacity of approximately 1,740MW at International Standards Organisation (ISO) conditions (15°C, 60% relative humidity and sea level). Siemens SGT5-9000HL units have been used for the prime mover calculations carried out in this study as a typical example of modern H-Class CCGT. The power island was simulated in Thermoflow 29, using 2019 performance data. However, suitable design margins were added in the concept design work for the carbon capture plant to ensure a technology-neutral basis for the prime mover;
- Two (1 x 1) CCGT H-Class trains – Estimated capacity of approximately 1,740 MW (at the generator terminals) at site conditions (9°C, 80% relative humidity and 1013mbara per Ref. 2), each consisting of:
 - 1 Gas Turbines (GT) - Nominal capacity approximately 588 MW at ISO conditions;
 - 1 Heat Recovery Steam Generators (HSRG), configured as 3-pressure cycle with reheat and flue gas ducting connection to enable Post-Combustion Capture (PCC), horizontal layout to enable ducting connection;
 - 1 Steam Turbine (ST) - Nominal capacity approximately 277 MW at ISO conditions, condensing;
- Flue gas pre-treatment with Selective Catalytic Reduction (SCR), for NO_x removal.



Figure 1. Typical impression of two 1x1 H-Class CCGTs with post-combustion carbon capture

Addition of 95% PCC to each train of CCGT plant reduces the export capacity to approximately 1.47GW total. Additional equipment comprises:

- Axial fan blowers to overcome pressure losses through the gas treatment path (approximately 90mbar);
- Direct Contact Cooler (DCC) circulating water for capturing residual contaminants (mainly NO_x and residual SO₂) and cooling the flue gas for absorption;
- 35wt% MEA-based CO₂ capture system to reduce plant total CO₂ emissions during steady-state operation by 95%, comprising:
 - Absorber with water wash section for entrained amine removal;
 - Regenerator operating at approximately 2.2bara and 125°C to regenerate amine from 0.45mol/mol loading to 0.25mol/mol as a semi-optimised loading profile for energy efficiency;
 - Amine rich/lean cross-exchanger of plate-and-frame type;
 - Circulating amine and water pumps;
 - Heat exchangers for heat rejection to site cooling water circuit;
 - Site cooling water circuit along with heat rejection method (mechanical draft cooling towers, shared with the power plant);
 - Lean amine storage tank for draining during shut-down;
 - CO₂ compression and dehydration train for export at 150bara;

1 x 1 configuration was selected for the CCGT over 2 x 1 mainly due to alignment with the European market and previous work in the Energy Technologies Institute (ETI) Generic Business Case study⁴. Reference information was more readily available in the Literature Review to compare performance for 1 x 1 over 2 x 1, particularly with open-art MEA-based PCC. In addition, some small benefits have been noted for:

- Improved efficiency of 0.05-0.1% for 1x1;
- Higher overall output capacity by approximately 0.08% at base load;
- Lower auxiliary power consumption

Another reason for preferring a 1x1 arrangement for combining with PCC is fewer bespoke modifications to the steam cycle over 2x1. A 1x1 arrangement need only consider modifications to allow steam extraction in direct proportion to the overall plant load, whereas a 2x1 arrangement should also consider times with only one GT on demand. The 2x1 arrangement will likely have to support steam extraction at much lower relative HRSG turndown than 1x1 given that 100% loading of a single GT gives only 50% loading of the HRSG and ST.

SCR was included in all designs to reduce NO_x by 90% as this technology is now common on modern H-Class CCGT to meet emissions performance guarantees in normal operation.

The basis of other configuration selections is outlined in the Basis of Design report (Ref. 2).

⁴ Thermal Power with CCS; ETI; 2017; <https://www.eti.co.uk/programmes/carbon-capture-storage/thermal-power-with-ccs>

8. Process Modelling Scenarios

8.1 Design Conditions

In order to model the plant power, input conditions for the simulation models in both Thermoflow and ProMax were detailed in full. These have been described in depth within the Basis of Design (Ref. 2) with the following design conditions defined:

- Plant characteristics – Location, site, operation and CO₂ capture rate
- Feedstock and utility specification – Natural gas, plant make-up water, waste water treatment and chemicals supply specifications
- Environmental emissions basis – NO_x and CO production
- CCS plant design – Flue gas and blower, solvent, absorber, stripper, heat exchangers, pumps, compressor and reclaimer

8.2 Start-up / Operating Scenarios

In assessing the start-up process, the timings of the various key stages through the start-up procedure depend on the type of start, based on temperature of the plant, i.e. hot, warm or cold starts. The temperature of the plant is dependent on how long the plant has been offline before receiving notice to start back up. For a hot start, the defined shut-down period of the power plant is less than 8 hours, whereas for a cold start, the shut-down period is greater than 64 hours (see detailed definition of start type in Table 1). An operational start between these two periods is considered a warm start. Hot and cold starts are clearly defined. However, the exact threshold between the longer end of a warm start and the shorter end of a cold start varies. The downtime following a weekend shut-down approaches the threshold to be considered a cold start. Therefore, for annual emissions calculations, this study has conservatively categorised all starts as either hot or cold.

Table 1. Definition of plant start in power plant, for reference

Shut-down duration	Type of start	Typical scenario
<8 hours	Hot	Weekday starts
8 – 64 hours	Warm	Restart after weekend shut-down
>64 hours	Cold	Start from ambient after overhaul

During the operation of a power plant, the number of starts will depend on the loading scenario employed by the operator. Three different load scenarios are presented in Table 2 with an estimated number of starts and operating hours calculated based on the reliability and availability of typical single shaft CCGT plants.

Table 2. Estimated number of starts and operating hours for different load scenarios, for reference

Load scenario	Overall number of starts (hot + cold)	Number of operating hours
Baseload	30 (24 + 6)	8094
Two-shift	276 (221 + 55)	3854
Mid-merit	395 (355 + 40)	1802

8.3 Modelling Methodology

The modelling approach used to assess the start-up process in this study was to consider forward-looking steady-state snapshots, as a conservative approach, and apply the maximum GT flue gas emissions (and therefore capture demand on the PCC plant) at the end of each snapshot period across the whole time period between snapshots. No credit was taken for the lower emissions during ramping from the previous snapshot. Therefore, the estimates of emissions both from the HRSG and the residual emissions into the stack are conservative throughout. The start-up sequence described in Section 8.4.1 allows snapshots to be selected at appropriate times to characterise the flue gas behaviour at start-up. This approach was reversed for modelling of the shut-down process.

The start-up sequence described also takes no credit for steam extraction until the IP/LP cross-over pressure is expected to have stabilised to allow extraction, and therefore no credit is taken for intermediate extraction flows. The availability of some steam is worth noting qualitatively from the perspective that real plant performance would be somewhat better than the scenarios considered in this study. However, the exact timings and ramp rates would be project-specific rather than generally applicable. Thus, availability of partial steam extraction was ignored in this study to draw generic conclusions that would be applicable across modern plant.

8.4 CCS Plant Snapshots

The processes of both start-up and shut-down of the CCS plant have been broken down into the key events with the timings and flowrate data defined. This helps to separate the overall transient profile into smaller periods to focus on during further analysis. A full description of each process can be found in the Basis of Design (Ref. 2) which describes the overall start-up process of the power plant and the CCS plant.

The following subsections present a summary of the snapshots identified for both the start-up and shut-down process used throughout the modelling of the CCS plant. These snapshots were chosen as they capture the distinct key events during the transient period and would be clearly defined when modelled.

8.4.1 CCS Plant Start-up Snapshots

The general start-up process for the 'standard' CCGT configuration with post-combustion CCS has been separated into five key stages with the below activities:

- Snapshot 0: Receiving notice to synchronise (NTS) from the grid to start generation
- Snapshot 1: Ignition within the GT occurs after the rotational speed setpoint is reached and the GT then accelerates to 3000rpm and picks up approximately 15% load (plus design margin). The PCC plant simulation ignores the changes in CO₂ emissions during the period from ignition to 15% and takes emissions during the entirety of the time from ignition to Snapshot 1 as those at 15% GT load (plus design margin).
- Snapshot 2: GT is ramped up to 50% load. CCS plant simulation takes taking emissions during the ramping from 15% to 50% as the 50% level (plus design margin) for the entire Snapshot duration.
- Snapshot 3: GT is ramped to 75% for a hot start (emissions taken as 75% load immediately) or held at 50% for a cold start (emissions stay at 50% load). Snapshot 3 is the first point where credit for steam extraction is taken and the simulation takes steam into the PCC plant for the heating of the stripper column.
- Snapshot 4: Plant operating at full capacity and CCGT start-up process is complete, GT is ramped to 100% load for a hot start or held at 50% for a cold start. PCC plant start-up continues until the regenerator start-up is complete.

A summary of the start-up process is presented in Table 3 with the relevant timings of both the hot co-start and cold start as well as the approximate flowrates of flue gas for each snapshot. This represents the performance of the power plant at its design baseload conditions with the entire start-up process taking 30 and 200 minutes for hot starts and cold starts, respectively.

Table 3. Snapshots of flue gas flowrate to CCS plant during start-up, starting at time = 0

Description	Snapshot No.	Time for hot co-start, mins	Time for cold start, mins	Flue gas flowrate, kg/s
Notice to synch, start-up sweep	0 (initial)	0	0	Nil
First firing	1	5	15	511 (Note 1)
Ramping up, 50% full load	2	20	25	681 (Note 1)
Steam export	3	25	60	823 (Note 1)
Full load	4	30	200	1,021 (Note 1)

Note 1 – start-up flue gas flows given are those direct from the Thermoflow material balance with no design margin, rather than based on fractions of the design flow for the PCC plant itself (1,100kg/s). The concept design

of the CCS plant was carried out at the design flow of the PCC plant and then performance estimated off-design at the Table 3 part-load values.

8.4.2 CCS Plant Shut-down Snapshots

The final snapshot for start-up when the plant is operating at full capacity can be used as the initial snapshot of the shut-down process with the continuation of the numbering system. As with the start-up process, the shut-down sequence can be separated into five key stages with steady-state snapshots identified as follows:

- Snapshot 4: Order from control centre to initiate shut-down process when operating at full capacity
- Snapshot 5: Load of both GT and ST held briefly having ramped down to 30% of the GT's full load
- Snapshot 6: ST completes its shut-down sequence while the GT load is held. Available steam for extraction assumed to be negligible. Regenerator stripping from Snapshot 6 is on residual heat in PCC plant only.
- Snapshot 7: GT load reduced to 5% and held to allow the power generator to split from the system
- Snapshot 8: Final load from the plant is removed and GT shaft is decoupled

As with the start-up process, a summary of the process, with the timings of each snapshot and the approximate flue gas flowrate, can be presented as shown in Table 4.

Table 4. Snapshots of flue gas flowrate to CCS plant during shut-down, starting at time = 0

Description	Snapshot No.	Time for shut-down, mins	Fuel Gas Flowrate, kg/s
Initiate unit shut-down at full load	4 (initial)	0	1020
Ramping down, 30% full load	5	5	547
ST complete shut-down	6	15	547
GT load hold, 5% full load	7	30	499
No plant load	8	45	Nil

9. Modelling Results

9.1 Introduction

Thermoflow material balance data was input to the ProMax flowsheet and a 35wt% MEA-based process was developed to achieve 95% capture from the flue gas of the Siemens 9000HL 1x1 CCGT. Margins were applied on the flue gas flow rates, rounding up to 1,100kg/s flue gas as outlined in the Basis of Design Section 5.6. This represents the un-improved base case or 'standard' configuration examined in this study to determine the limitations of the standard configuration.

9.2 Standard Configuration

The key process variables for the standard configuration are shown in Table 5 below. Note that the generating penalties from reboiler steam consumption and Post-Combustion Capture (PCC) plant electrical consumption are somewhat counteracted by reduced condenser duty in the power plant. Steam condensate from the amine reboiler can be returned directly to the Heat Recovery Steam Generator (HRSG) rather than passing through the condenser.

Table 5. Steady-state amine process outputs, single train basis

Parameter	Value	Units
Lean amine solution circulation rate	1500	kg/s
Amine rich loading	0.45	mol/mol
Amine lean loading	0.25	mol/mol
Reboiler temperature	125	°C
Stripper condenser temperature	50	°C
Reboiler heat consumption	336	MW.th
PCC auxiliary electrical consumption	44.9	MW.e (~25.1MW.e to compressor)
PCC plant heat rejection duty	537	MW.th (See Section 9.2.1)
CO ₂ design rate into PCC plant	85	kg/s
CO ₂ capture rate	95	%
CO ₂ residual emissions	4.1	kg/s

9.2.1 Standard configuration – heat rejection

The design basis for the PCC plant heat rejection is to share cooling duty with the power plant via mechanical draft cooling towers. Handling the extra 537MW.th heat rejection for the PCC plant in the CCGT cooling towers would be expected to increase net auxiliary electrical consumption for the site cooling by up to 3MW.e to account for the extra load on:

- Cooling water pumps (approximately 2MW.e net) and;
- Tower fan load to cool water returned from the PCC plant (approximately 1MW.e net).

Approximately 50% of the CCGT steam condenser duty would not be required during PCC operation, replaced instead by an increase in cooling water flow and increased cooling tower fan duty. The 3MW.e electrical consumption for PCC plant cooling represents approximately 0.3 absolute percentage points of generating efficiency. The application of different approaches for PCC plant heat rejection would explain much of the range of efficiency penalties calculated by other authors in open literature.

- Power plant cooling duty alone: approximately 414MW.th
- PCC plant cooling duty alone: approximately 537MW.th

PCC power plant combined cooling demand: approximately 673MW.th (HRSG condenser in combined plant has reduced load by 278MW.th)

For this process, the combined auxiliary electrical load attributed to the PCC process is approximately 44.9MW.e or 5.0 absolute percentage points at 100% load. In addition, 336MW.th of heat would be consumed, equivalent to approximately 74MW.e generation loss from the steam turbine.

9.2.2 Standard configuration overall generating efficiency

Net efficiency values for the 95% capture process are given in Table 6 below. PCC efficiency penalty is estimated at approximately 8.5 absolute percentage points. This value is broadly consistent with other works based on MEA investigated in the literature review ($\approx 10\%$) which are normally based on 80%-90% CO₂ capture rate rather than 95% as used in this study. This disparity is likely due to other authors not normally taking credit for sharing the power plant cooling solution and reduced steam condenser load, as well as normally considering 30wt% MEA, whereas this study has considered 35wt% MEA and allows for lower regeneration energy consumption per tonne of CO₂ captured. Note that efficiency penalties are expected to be lower if a proprietary or different solvent is used instead of a system based on MEA.

Table 6. Power plant performance with 95% PCC by 35wt% MEA, single train basis

Parameter	Value	Units
Normal generating capacity (before PCC) at site conditions	847	MW.e (870 MW.e at the generator terminals)
Site fuel consumption	1389	MW.th (LHV)
Normal net generating efficiency (before PCC)	60.9	% (LHV. 62.6% less Cooling towers, auxiliaries)
Site generating capacity with 95% PCC	722.7	MW.e
Site net generating efficiency with 95% PCC	51.9	% (LHV)

Source: Thermoflow material balance simulations

9.2.3 Amine inventory calculation for standard un-improved configuration

The standard configuration has been specified with approximately 30 minutes of process inventory at full circulation rate, as set in the Basis of Design (Ref. 2). 30 minutes of inventory is equivalent to:

$$1500 \frac{kg}{s} \times 30 \text{ min} \times 35\text{wt}\% \times \frac{1\text{kmol}}{61kg} = 15,492 \text{ kmol MEA}$$

At the initial acid loading of 0.25 mol/mol for the lean amine supplied from the storage tank ('fresh lean amine'), the quantity of CO₂ dissolved in the lean amine is given by:

$$0.25 \frac{\text{mol CO}_2}{\text{mol MEA}} \times 15,492 \text{ kmol MEA} = 3873 \text{ kmol CO}_2$$

During the first 30 minutes of operation, fresh lean amine is passed through the absorber from the lean amine storage tank, as shown in Figure 2 below. Rich amine is then returned to the tank and the conservative assumption has been made that the tank is always well-mixed, therefore the loading is recalculated at each Snapshot based on the total quantity of CO₂ absorbed.

Simplified process flow diagram of base case at start-up

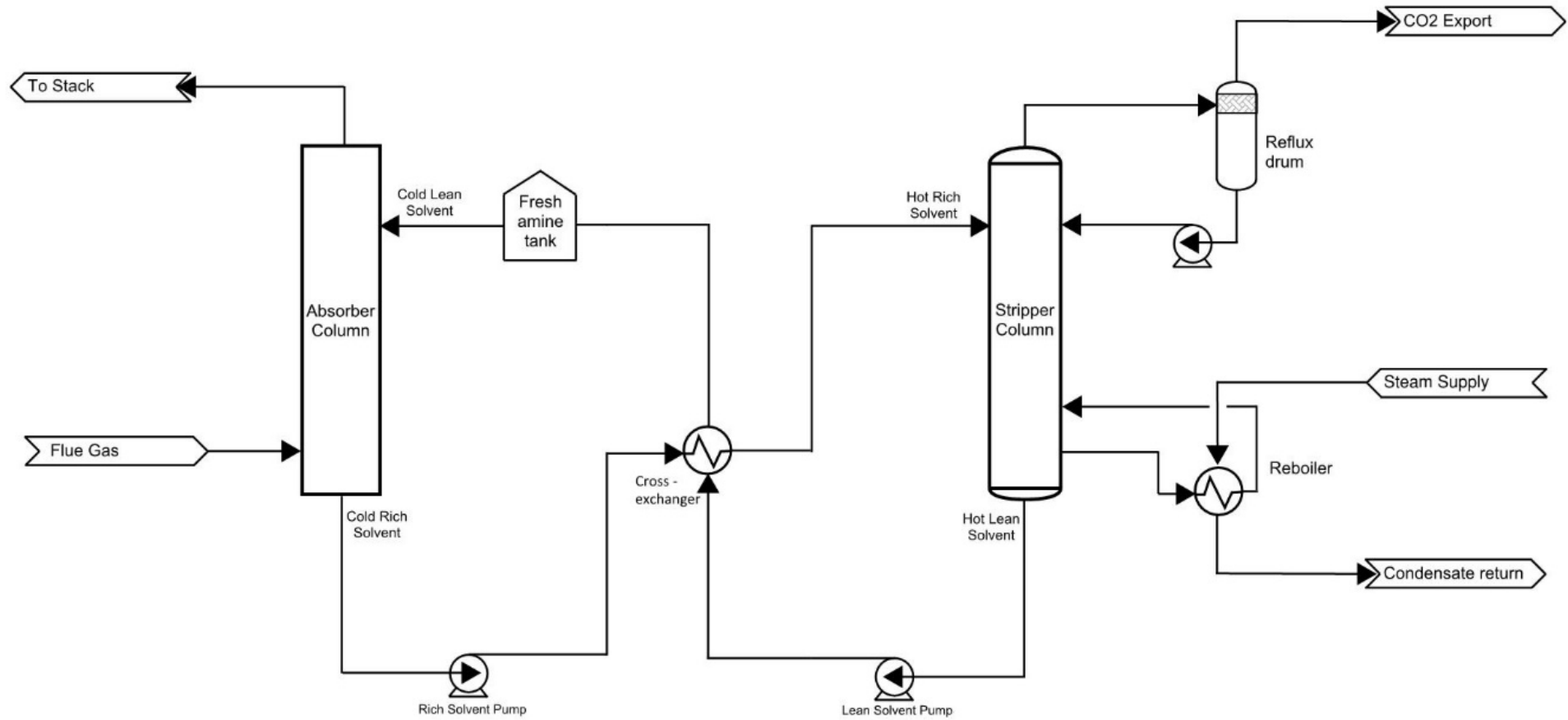


Figure 2. Post-combustion capture process considered for 'standard configuration'

9.2.3.1 Calculating amine loading rise through start-up

The loading in the amine tank throughout the initial period during the 30-minute rich amine collection period was calculated as a function of:

- Quantity of CO₂ already stored in the lean amine (3,873 kmol), plus;
- Quantity of CO₂ absorbed from the flue gas as the gas turbine is ramped from minimum load to load at 30 minutes.

Using the basis of 15,492 kmol total MEA inventory, the overall amine loading throughout the start-up snapshots is calculated as:

$$\text{Loading at end of Snapshot} = \text{Loading at start of Snapshot} + \frac{\text{kmols CO}_2 \text{ absorbed during Snapshot}}{15,492 \text{ kmol MEA}}, \text{ where:}$$

$$\text{Loading at start of Snapshot} = 0.25 \frac{\text{mol}}{\text{mol}} \text{ for Snapshot 1 and rises thereafter,}$$

$$\text{mols CO}_2 \text{ absorbed during Snapshot} = \frac{\text{mass CO}_2 \text{ absorbed during Snapshot}}{44 \frac{\text{kg CO}_2}{\text{kmol CO}_2}},$$

$$\begin{aligned} \text{mass CO}_2 \text{ absorbed during Snapshot 1} \\ = (\text{mass flow of CO}_2 \text{ from HRSG at GT loading} \\ - \text{mass flow of CO}_2 \text{ in treated gas to stack}) \times \text{duration of Snapshot} \end{aligned}$$

$$\begin{aligned} \text{mass CO}_2 \text{ absorbed during Snapshot 1} &= \text{GT taken as 25\%, so } \left(31.6 \frac{\text{kg}}{\text{s}} \text{ CO}_2 - 0.192 \frac{\text{kg}}{\text{s}} \text{ CO}_2 \right) \times 15 \text{ mins} \\ &= 31.4 \frac{\text{kg}}{\text{s}} \times 15 \text{ mins} = 28,267 \text{ kg or } 28.27 \text{ t,} \end{aligned}$$

$$\text{Loading at end of Snapshot 1} = 0.25 \frac{\text{mol}}{\text{mol}} + \frac{28,267 \text{ kg}}{15,492 \text{ kmol MEA} \times 44 \frac{\text{kg}}{\text{mol}}} = 0.29 \frac{\text{kmol}}{\text{kmol}}$$

Loading for the rest of the snapshots is given according to Table 6 below. The amine inventory is seen to saturate with CO₂ by the end of Snapshot 6 (0.45 mol/mol), indicating that the standard configuration is no longer able to capture CO₂ and continuing emissions from the GT are effectively unabated in CO₂.

Table 7. Calculating amine loading at the end of each Snapshot

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7
Time after start, mins	15	22	25	30	37	48	82
Duration, mins	15	7	3	5	7	11	34
Regenerator status	No steam	Pre-heat	Pre-heat	Pre-heat	Pre-heat	Pre-heat	Pre-heat
GT load	25%	50%	75%	100%	100%	100%	100%
CO ₂ rate from GT, kg/s	31.6	50	80	85	85	85	85
CO ₂ rate after PCC, kg/s	0.192	0.42	0.93	3.93	35	44.5	85
CO ₂ absorbed over Snapshot, t	28.27	20.82	14.23	24.32	21.00	26.73	0.00
Amine loading in tank at end of Snapshot, mol/mol	0.29	0.32	0.34	0.38	0.41	0.45	0.45

9.2.4 Stripper pre-heat energy requirement

The stripper heating time at start-up was calculated from the sum of sensible heat input required:

- To heat the amine inventory from ambient (9°C) to the stripper normal operating temperature (125°C)
- To heat the metal mass of the stripper, fittings, reboiler and interconnecting piping from ambient to the stripper normal operating temperature

For the standard (un-optimised) configuration, there will be 30 minutes of amine inventory circulation to be heated within the stripper column (2,700,000kg inventory at 1,500kg/s). Given a heat capacity of approximately

3.34kJ/kg.K from the material balance (Appendix E Stream 18) for lean amine at start-up (0.25mol/mol), the heat requirement, Q, was calculated as:

$$Q = 2,700,000 \text{ kg} \times 3.34 \frac{\text{kJ}}{\text{kg.K}} \times (125^\circ\text{C} - 9^\circ\text{C}) = 1,046,088,000 \text{ kJ, or } 1047 \text{ GJ}$$

The metal mass calculation comprised:

- Stripper column wall thickness calculation as outlined in the Basis of Design Section 5.8.2
- Stripper column mass of steel calculation given the wall thickness
- 30% design margin to allow for column dished ends, mass transfer packing, piping and associated mechanical equipment

Stripper wall thickness, t, was calculated as a low-pressure column where vacuum normally dictates the design metal thickness:

$$P_c = 2.2E_y \left(\frac{t}{D_0} \right)^3, \text{ where}^5:$$

$$P_c = 0.101325 \text{ MPa for vacuum - rated column}$$

$$E_y = 193 \text{ GPa for 316L}^6$$

$$D_0 = 10\text{m internal diameter} + 2t$$

$$\frac{t}{10\text{m} + 2t} = \sqrt[3]{\left(\frac{0.101325}{193000 \times 2.2} \right)} = 0.0062\text{m, rearranging gives:}$$

$$t = \frac{0.062\text{m}}{1 - 0.0124} = 0.063\text{m, or } 63\text{mm}$$

Given a minimum wall thickness of 63mm and an overall column height of approximately 40m to accommodate the fittings and sump in addition to the packing. The volume for a thin-walled cylinder is given by the annular area multiplied by the column height:

$$\text{Area} = \pi \times (R^2 - r^2) = \pi \times 5.063^2 \text{ m}^2 - 5^2 \text{ m}^2 = 1.99\text{m}^2$$

$$\text{Volume} = \text{height} \times \text{Area} = 40\text{m} \times 1.99\text{m}^2 = 83\text{m}^3$$

At a density of 7,990kg/m³, the mass of stainless steel used for the cylindrical section of the column is⁷:

$$83\text{m}^3 \times 7990 \frac{\text{kg}}{\text{m}^3} = 663\text{t, } +30\% \text{ margin} = 862\text{t}$$

The thermal mass and start-up heat requirement for the metal is calculated from a heat capacity of approximately 0.5kJ/kg.K⁸:

$$Q = 862,000\text{kg} \times 0.5 \frac{\text{kJ}}{\text{kg.K}} \times 116\text{K} = 49,996,000 \text{ kJ, or } 50\text{GJ}$$

The sum of the energy inputs for the standard configuration is therefore:

$$50\text{GJ} + 1047\text{GJ} \approx 1100\text{GJ}$$

9.2.4.1 Uncertainties

The pre-heat time of the stripper column was derived from the sum of energy required to heat the amine inventory and that required to heat the metal. Less than 5% of the total energy (1,100GJ) is required by the metal itself (50GJ). Therefore, even an error of 50% in the metal mass would give approximately 2% difference in heat requirement for the standard inventory.

⁵ Sinnott & Towler; Chemical Engineering Design; 5th Edition; Equation 13.52

⁶ AISI 316L datasheet, typical; AK Steel; https://www.aksteel.com/sites/default/files/2018-01/316316L201706_2.pdf; accessed Mar 2020

⁷ AISI 316L datasheet, typical; AK Steel; https://www.aksteel.com/sites/default/files/2018-01/316316L201706_2.pdf; accessed Mar 2020

⁸ AISI 316L datasheet, typical; AK Steel; https://www.aksteel.com/sites/default/files/2018-01/316316L201706_2.pdf; accessed Mar 2020

The method for calculating column metal mass is directly proportional to the column diameter. This method has been benchmarked against the stripper shipping mass given for the Kårstø FEED study report⁹ (6.67m diameter, 42m length for the cylindrical section and 271t, page 7-3) and found:

$$\begin{aligned} \text{Kårstø report mass} &= 271t, \\ \text{column method for Kårstø column} &= 447t, \text{ or } 65\% \text{ overestimate} \end{aligned}$$

The 65% overestimate in column mass is likely due to the wall thickness calculation being overly conservative as no credit has been taken for structural design features such as stiffening rings which offer some protection. The metal mass calculation is therefore most likely to be overly conservative and some reduction in column heat requirement would be required. However, in order to allow a margin for the mass of the piping, packing, fittings and mechanical equipment, the expected overestimate has been kept in this study.

The second part of the pre-heat time calculation for the stripper column depends on the liquid hold-up volume in the stripper and is a design choice depending on circulation rate, as well as the total solvent storage volume design basis for the plant. Both parameters are process design choices independent of the start-up procedure, not calculated variables. Therefore, no new errors are expected to be introduced, rather, any differences for different plant design should be estimated from the heat-up calculation given in Section 9.2.4.

9.2.5 Start-up steam extraction and steam ramping

The time required for the amine stripper to reach operation at start-up in the standard configuration is determined from the heat requirement (as calculated in Section 9.2.4) and the ramping heat extraction rate given by steam availability from the normal extraction point on the steam turbine. The normal extraction point has been set for the standard configuration in this study as the cross-over between the IP turbine outlet and the LP turbine inlet (i.e. the IP/LP cross-over), refer to the Design Basis (Ref. 2). In all configurations, the steam turbine capacity has been set as that for the unabated plant, without optimisation (i.e. without reduction in size) for PCC plant steam extraction in abated operation.

For the standard scenario, no credit has been taken for any fast start steam cycle equipment, as such technology has not been universally adopted for all OEM equipment. Manufacturers would only propose optional fast-starting steam cycle equipment where they see an advantage to do so and therefore fast-start capability for steam extraction has not been considered part of the standard H-Class configuration. Fast start of the steam cycle has been considered as a separate improvement option in Section 9.3.5 to directly compare the use of fast starting equipment.

Based on the snapshot outlines given in Table 3, the time at which first steam extraction is available has been conservatively assumed to be 25 minutes and 60 minutes for hot and cold starts, respectively. Note that certain plant configurations would be expected to have steam availability sooner as a result of fast start capability as an explicit capability (particularly during hot starts). However, while fast-start plants will have some steam available for extraction prior to the times adopted in this study, the exact interaction between the HRSG/ST stabilisation and extracting the quantities of steam necessary for PCC is not known at time of writing. The plant considered for the standard configuration in this study has therefore been based on a power plant with no measures taken to optimise fast-starting the steam cycle. The standard configuration PCC plant would wait to extract steam until available from the IP/LP interface, notwithstanding any improvement options which are considered explicitly later.

Predicting the start time for extraction will be an exercise in inferring power plant performance data from e.g. dump steam rate and pressure into the condenser by the ST bypass. Until some PCC plants are built at a scale appropriate to this study and data is available around the guarantees vendors are willing to offer, inferring performance introduces some inherent risks:

- Delaying credit for steam extraction being available would underestimate the performance of flexible PCC on power plant, missing out on modern developments in CCGT, and setting an overly pessimistic performance expectation for flexible operation of CCGT with PCC.
- Conversely, overestimating the performance of the plant by setting an extraction point too early would mean real plants may fail to meet the benchmarks set in this study as they seek to meet other competing performance guarantees or lead to infeasible design requirements. This risk is considered greater than underestimating plant performance.

⁹ CO2 Capture Facility at Kårstø, Norway; Bechtel; FEED Study Report; <https://ukccsrc.ac.uk/sites/default/files/documents/news/Karsto-FEED-Study-Report-Redacted-Updated-comp.pdf>; accessed Mar 2020

Therefore, the benchmarks used in this study have been taken to give reasonable estimates for steam extraction achievable by all modern plant (be it new-build or modernised retrofits), independent of particular technology choices or market drivers.

25 minutes after the NTS, credit has been taken for some steam being available. For a hot start, the quantity of steam available during the start-up snapshots has been taken to follow the GT load percentage. For example, 75% of full-load steam requirement has been considered available for extraction once the GT reaches 75% load; with 100% of steam available at 100% GT load. Table 8 and Table 9 show the CCGT steam extraction for hot and cold starts respectively, based on a normal heat extraction of 336MW.th for the base-line CCUS process, as discussed in Section 9.2.

Table 8. CCGT steam extraction rates following hot starts, based on 336MW.th normal steam duty in the reboiler

Time post-NTS, mins	GT load, %	GT load taken as, %	CCS heat extraction, %	MW.th to reboiler
0 to 15	Start and ramping to 25%	25%	0	None
15 to 22	Ramping to 50%	50%	0	None
22 to 26	Ramping to 75%	75%	Start and ramping	Assume none
26 to 30	Ramping to 100%	100%	75	252
30	100%	100%	100	336

Table 9. CCGT steam extraction rates following cold starts, based on 336MW.th normal steam duty in the reboiler

Time (post-NTS), mins	GT load, %	Heat to CCS, %	MW.th to reboiler
0	Start and ramping	0	None
60	50	Start and ramping	Assume none
61	50	50	168
180	100	100	336

For a cold start, Table 8 shows an extended period of running the GT at 50% until 180 minutes. This 50% load is a typical characteristic of power island operation for cold starts, with the GT held at part-load to warm the steam system at a controlled rate. The heat soak has been estimated as approximately 1400GJ to heat the steam cycle from ambient in a cold start. In comparison, as noted in Section 9.2.4, hot starts require minimal heat soak as the equipment is already warm. The extended part-load hold is not carried out in a hot start, as the steam system is already warm. Start-up calculations for the cold start have been performed assuming the maximum rate of heat extraction available in a cold start is 50% of the extraction that would take place with the plant at steady state with 100% GT load. 50% extraction of heat (168MW.th) continues until the GT ramps to 100% at approximately 180 mins.

9.2.6 Steam reboiler start-up time calculation

Given the reboiler start-up energy requirements for the standard case (1,100GJ, Section 9.2.4) and heat supply rate from the steam cycle (described in Table 8), the start-up time was calculated to achieve normal operation in the reboiler according to:

$$\begin{aligned} \text{Startup energy consumed} &= (\text{time at partial extraction} \times \text{partial extraction rate}) \\ &+ (\text{time at full extraction} \times \text{full extraction rate}) \end{aligned}$$

For 1,100GJ (1,100,000MJ) at hot start, the formula becomes:

$$\begin{aligned} 1,100,000MJ &= (5 \text{ mins} \times 252MW.th) + (x \text{ mins} \times 336MW.th), \\ x &= \frac{1,100,000MJ - 75,600MJ}{336MW.th} = 3048s = 51mins \end{aligned}$$

$$\text{Total start time} = 25\text{mins lag prior to extraction} + 5\text{mins at 75\%} + 51\text{mins at 100\%} = 81\text{mins}$$

Therefore, the hot start-up time (including the 25-minute initial delay) after Notice to Synchronise (NTS) for the standard configuration was calculated as 81 mins.

For cold start, the GT will be held at part-load for an extended time as part of the ST start-up heat-soak procedure and therefore heat is soaked into the HRSG at a lower rate than during a hot start (where the steam turbine is already hot). During the cold start, only 168MW.th of heat extraction (equivalent to PCC plant heat demand at 50% plant load) is taken to be available for the PCC plant as described in Table 9. The start-up time for the power + PCC plant from a cold power plant is calculated as:

$$1,100,000\text{MJ} = (x \text{ mins} \times 168\text{MW.th}),$$

$$x = \frac{1,100,000\text{MJ}}{168\text{MW.th}} = 6547\text{s} = 109\text{mins}$$

$$\text{Total start time} = 60\text{mins lag prior to extraction} + 109\text{mins at 50\%} = 169\text{mins}$$

The results of the start-up time calculation for both starts are presented in Table 10 below.

Table 10. Stripper start-up time calculation for standard configuration

Start type	Lag time post-NTS, mins	Part-load extraction duration, mins	Part-load rate, MW.th	Full-load extraction duration, mins	Full load extraction rate, MW.th	Total start-up time post-NTS, mins
Hot start	25	5	252	51	336	81
Cold start	60	109	168	N/A – start-up completed at part-load	N/A – start-up complete at part-load	169

9.2.6.1.1 Uncertainty

The stripper start-up time calculations given in Table 10 are calculated assuming instantaneous increments in steam rate, with fixed rate during each interval. It is noted that some steam extraction in the real plant would be available at some point before the 25 minute mark for hot starts and increase to the design extraction rate. The exact ramp rate and extraction start time are unknown and depend on equipment selection, instrumentation, piping and process dynamics. However, 25 minutes represent a reasonable conservative estimate by which point modern plant will be expected to support at least a part-load extraction (from the IP/LP cross-over) for hot starts. For cold starts, the corresponding figure would be approximately 60 minutes. Individual real plant would be expected to improve somewhat on the generic extraction benchmark steam extraction times used in this study.

A high-level sensitivity analysis was carried out to test the start-up time for a hot start based on:

- 0 to 25 mins: lag, any steam availability ignored including the ramping up of extraction
- 25 mins onwards: full steam extraction of 336MW.th (no discounting of extraction due to part-load GT i.e. without 5 mins at 252MW.th extraction per Table 8)

The calculated start time during a hot start was 80 mins (saving 1 minute of total pre-heating time) and represents a reduction of up to 2% on the overall plant start time.

During a cold start, the GT loading is held static at 50% until approximately 180 minutes. However, the stripper start-up time calculation shows only 136 minutes required as a maximum for starting the stripper and regenerating amine, significantly before the GT is ramped to 100%. Therefore, no significant reductions in start-up time would be expected during a cold start from considering a smaller time increment.

Note that real plant will have other options such as drawing from the HP bypass which would likely be available sooner than the IP/LP interface used in the process that is considered the standard configuration in this study. The standard configuration effectively requires much of the ST start-up and ramp to generation to be complete before extraction. HP bypass is considered as part of the improvement options in Section 9.3.5.

9.2.7 Standard configuration start-up emissions

Hot start performance for the standard configuration PCC power plant (un-improved process) is shown in Table 11 and Figure 4 below. Cold start performance and emissions are shown in Table 12 and Figure 5, respectively.

Note the decline in capture rate through both hot and cold starts as the solvent inventory is saturated, indicating that the standard configuration has a total CO₂ buffering capacity of approximately 140t CO₂. Once this quantity has been absorbed (approximately Snapshot 7 and 6 for hot and cold starts respectively), the solvent loading approaches 0.46mol/mol and further flue gas is effectively unabated until the stripper pre-heat is complete.

Once the stripper pre-heat is complete, the standard configuration has assumed that a bypass of the amine tank is used to send regenerated lean amine directly into the absorber feed line, rather than waiting for mixing the solvent into the tank. Figure 3 shows an indicative flow diagram showing the function of this bypass, which is only used as part of the PCC start-up sequence. Without this bypass, the recovery of the capture rate to 95% shown in the results would be significantly slower. The use of plant bypasses for optimising start-up is considered in detail in Section 9.3.2.

Simplified process flow diagram of standard configuration using tank bypass following stripper column start-up

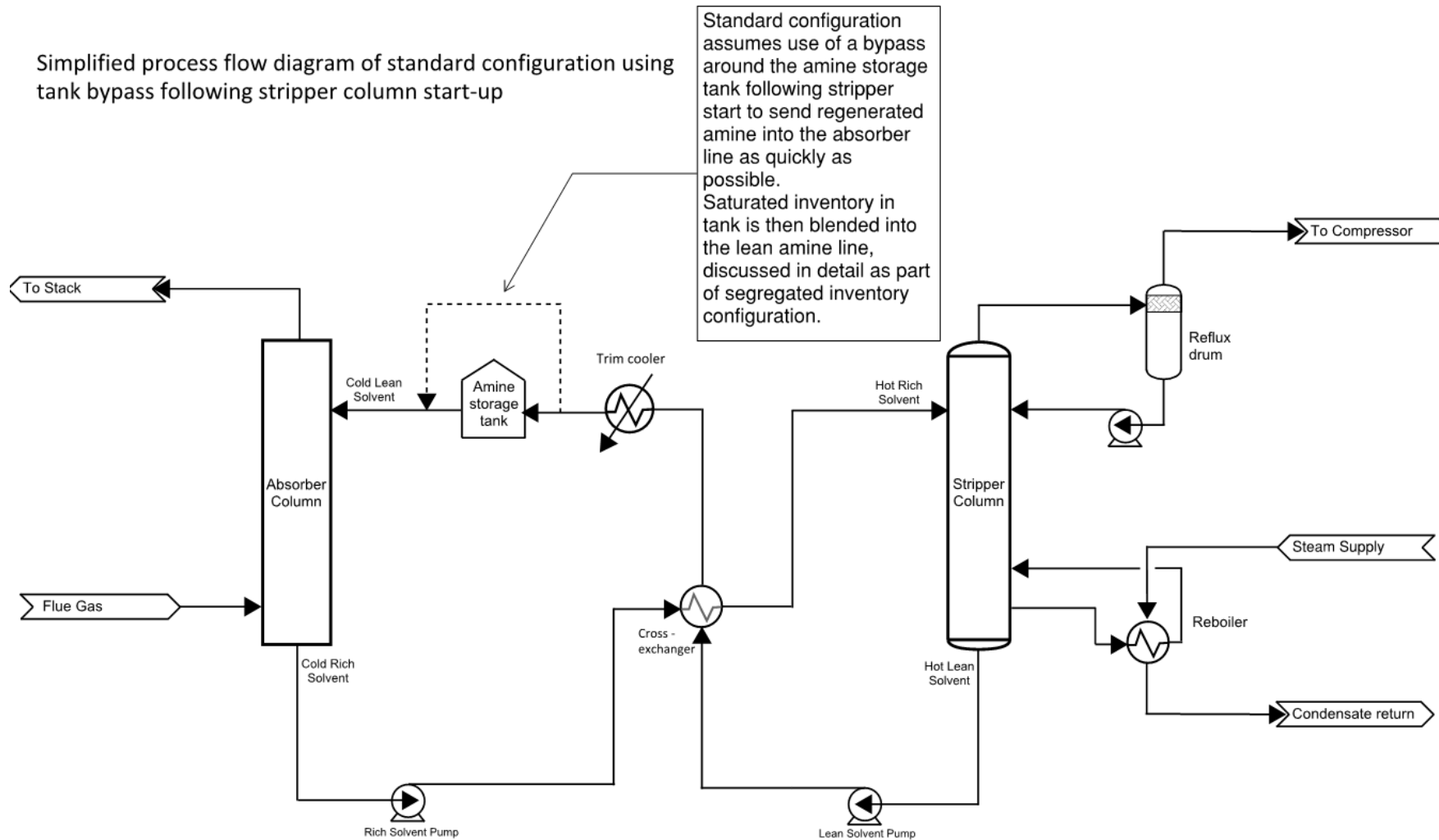


Figure 3. Standard configuration followed by tank bypass when stripper column start-up is complete

Table 11. Hot start performance for standard CCGT + 95% PCC (un-improved process)

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7	End	Totals
Time after start, mins	15	22	25	30	37	48	81	82	
Duration, mins	15	7	3	5	7	11	33	1	
Regenerator status	No steam	No steam	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	75%	100%	100%	100%	100%	100%	
CO ₂ rate from GT (inc. PCC design margin), kg/s	31.6	50	80	85	85	85	85	85	
CO ₂ quantity from GT during interval, t	28.4	21.0	14.4	25.5	35.7	56.1	173.4	5.1	
CO ₂ emissions rate after PCC, kg/s	0.192	0.42	0.93	3.93	35	44.5	85	4.1	
Residual CO ₂ emitted after PCC, t	0.17	0.18	0.17	1.18	14.7	29.37	173.4	0.25	219
CO ₂ absorbed, t	28.27	20.82	14.23	24.32	21.00	26.73	0.00	4.85	140
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.38	0.41	0.45	0.25	
Fuel burned, t	10.0	7.1	4.0	8.3	11.7	18.4	56.7	1.7	118
Fuel burned, GJ	501	355	198	417	584	918	2838	83	5894
Net generation rate, MW.e	217	387	549	723	723	723	723	723	
Electricity exported, MWh	54.3	45.2	27.5	60.2	84.3	132.5	409.6	12.0	826
Capture fraction	99%	99%	99%	95%	59%	48%	0%	95%	39%

The key characteristics of Table 11 are presented in Figure 4, showing the capture fraction, fuel burn and residual CO₂ emissions during the start-up scenario.

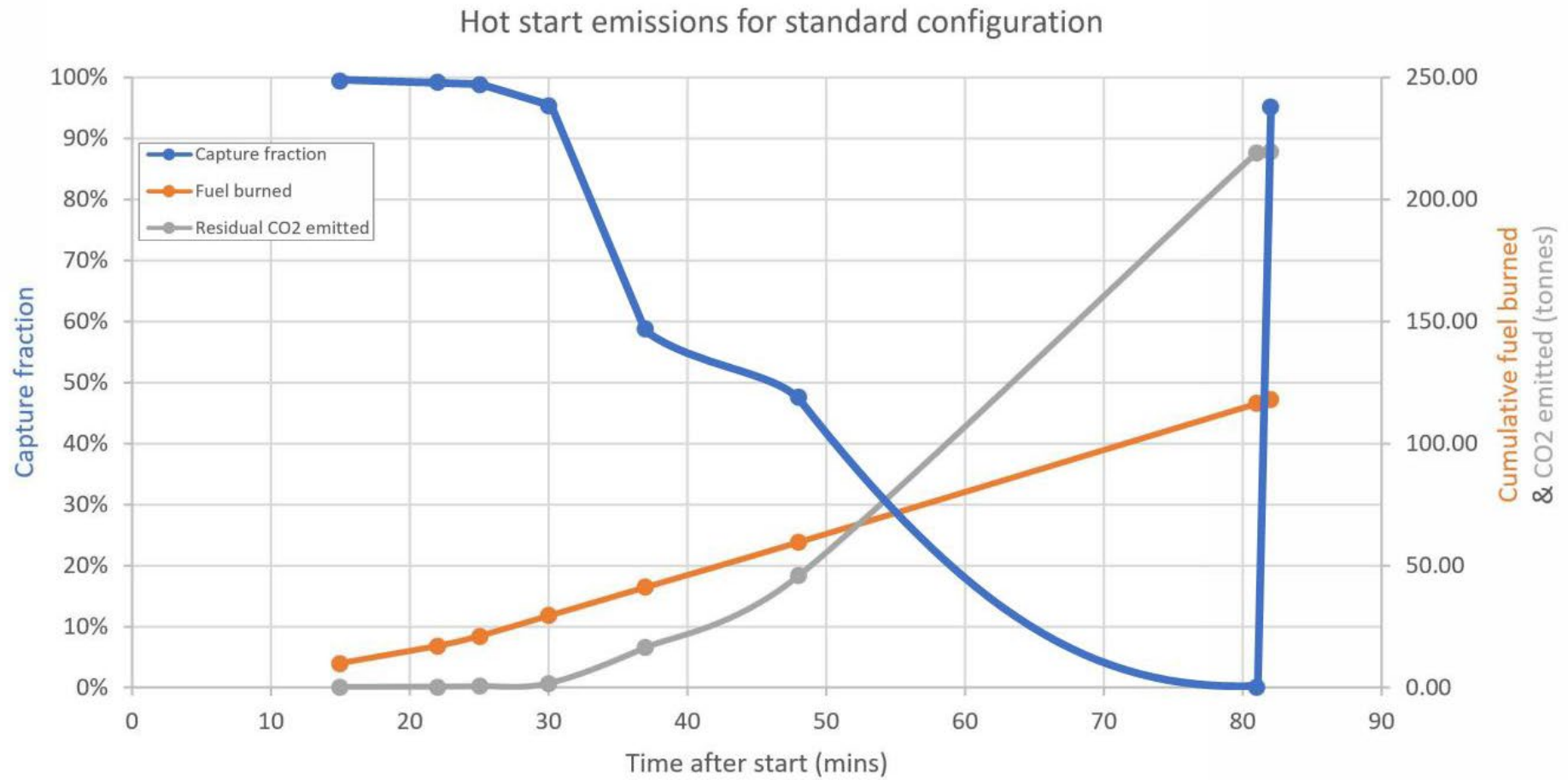


Figure 4. Hot start performance for standard CCGT + 95% PCC (un-improved process)

Table 12. Cold start emissions performance for standard CCGT + 95% PCC (un-improved process)

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7	End	Totals
Time after start, mins	15	22	25	30	55	60	169	170	
Duration, mins	15	7	3	5	25	5	109	1	
Regenerator status	No steam	No steam	No steam	No steam	No steam	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	50%	50%	50%	50%	50%	50%	
CO ₂ rate from GT (inc. PCC design margin), kg/s	31.6	50	50	50	50	50	50	50	
CO ₂ quantity from GT during interval, t	28	21	9	15	75	15	327	3	
CO ₂ emissions rate after PCC, kg/s	0.192	0.42	0.42	0.42	6.31	39.44	49.5	0.42	
Residual CO ₂ emitted after PCC, t	0.17	0.18	0.08	0.13	9.5	11.8	323.7	0.0	346
CO ₂ absorbed, t	28.3	20.8	8.9	14.9	65.5	3.2	3.3	3.0	148
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.36	0.45	0.46	0.25	
Fuel burned, t	10.0	7.1	3.0	5.1	25.4	5.1	110.7	1.0	167
Fuel burned, GJ	501	355	152	254	1270	254	5536	51	8373
Net generation rate, MW.e	217	387	387	387	387	387	387	387	
Electricity exported, MWh	54.3	45.2	19.4	32.3	161.4	32.3	703.9	6.5	1055
Capture fraction	99%	99%	99%	99%	87%	21%	1%	99%	30%

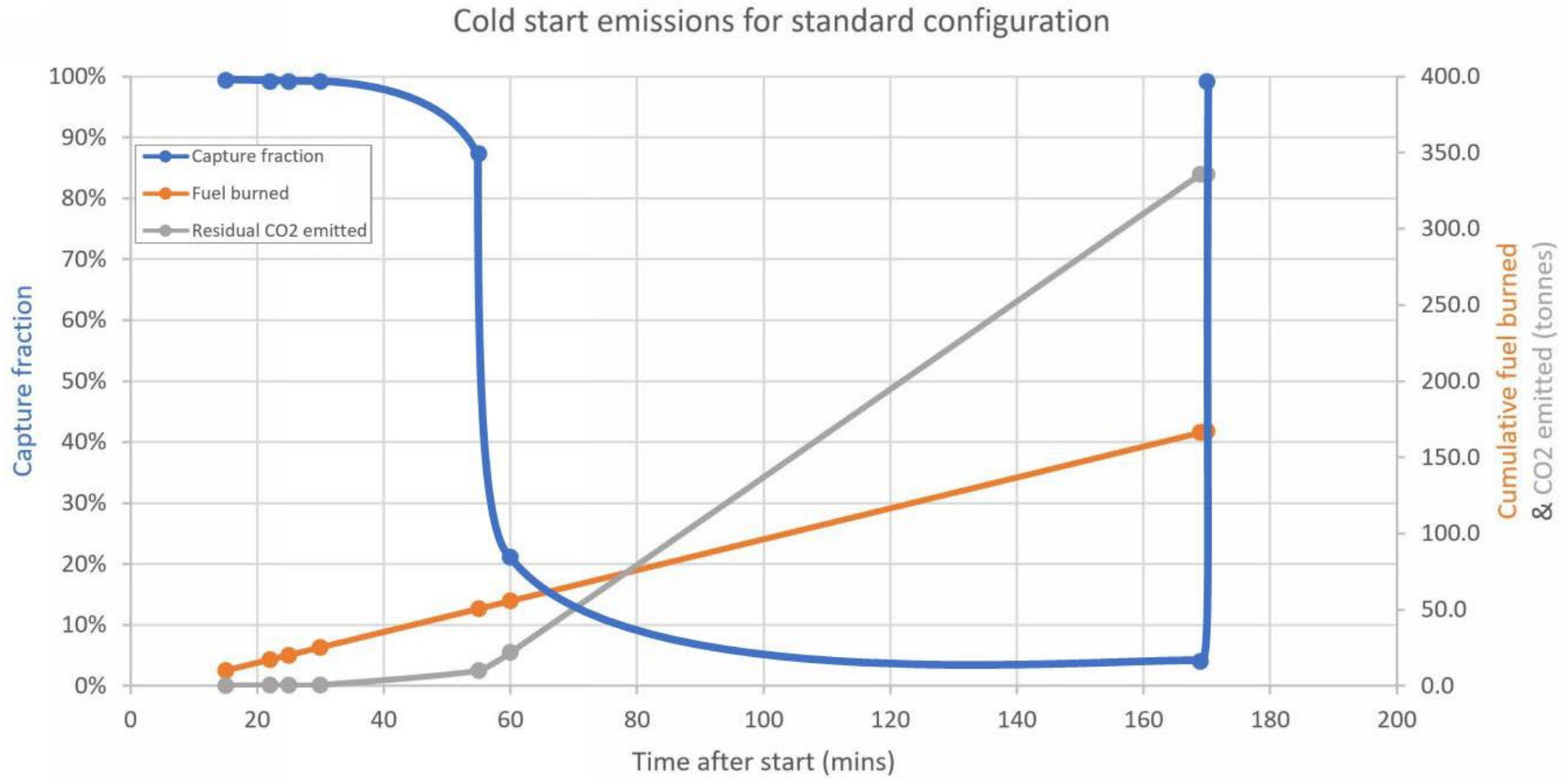


Figure 5. Cold start performance for standard CCGT + 95% PCC (un-improved process)

For both hot and cold starts, note that the initial snapshot periods with the gas turbine operating at part load (25% to 50% or 75%) show over-capture of CO₂ from the flue gas approaching 99%. Over-capture is seen at part-load due to lower gas flow than the column design basis, leading to absorption up to the equilibrium concentration of flue gas exiting the top of the packed bed and the lean amine entering the packed bed. The key results of the hot and cold start for the standard PCC plant are summarised in Table 13 below.

Table 13. Summarised outputs of the hot and cold starts for the standard configuration, for single train.

Parameter	Hot start	Cold start
Net fuel burned, t	118	167
Net fuel burned, GJ	5894	8373
Net electricity export, MWh	826	1055
CO ₂ emissions to atmosphere, t	219	336
Overall capture rate, %	39	32
Specific CO ₂ emissions, kgCO ₂ e/MWh	265	318

For two trains of abated CCGT, Table 13 has been recalculated with results shown in Table 14 below.

Table 14. Summarised outputs of the hot and cold starts for the standard configuration, recalculated for two trains of abated CCGT in standard configuration

Parameter	Hot start	Cold start
Net fuel burned, t	236	334
Net fuel burned, GJ	11,788	16,746
Net electricity export, MWh	1,652	2,110
CO ₂ emissions to atmosphere, t	438	522
Overall capture rate, %	39	32
Specific CO ₂ emissions, kgCO ₂ e/MWh	265	318

9.2.8 Standard configuration shut-down emissions

The standard configuration CCGT with PCC would be expected to shut down within 45 minutes as described in Table 4. Emissions expected during the shut-down process are shown in Table 15 below. Note that although 47.4t total carbon dioxide is captured during the shut-down period in total, Snapshots 1 and 2 happen while some steam is likely to still be available for extraction. Therefore, credit has been taken during shut-down for the first 10t (sum of Snapshot 1) of captured CO₂ to not contribute to accumulation in the amine during shut-down.

Snapshot 3 is therefore the only period of expected CO₂ accumulation in the solvent inventory, a total of 27.9t which corresponds to 635kmol of CO₂ or an increment of 0.04mol/mol to loading. Preliminary analysis of the stripper performance at part-load has found that operating with an increased stripper back-pressure of approximately 3.1bar allowed for a reboiler temperature of 137°C. Operating with elevated stripper pressure prior to shutdown would allow the stripper column inventory to store some heat and continue stripping for some time once the steam extraction is shut-down. It was also found that a lean amine production at 0.20 mol/mol during the 30 minutes preceding a shut-down was able to build up sufficient over-stripped amine and by the end of the shut-down process (45 mins), the amine will have a loading of 0.25 mol/mol ready for the next start-up process. The same calculation methodology was used to derive the required loading prior to shut-down as was used to derive start-up loadings (Section 9.2.3). It is noted that operating the real plant at 137°C reboiler temperature would accelerate the degradation of the solvent and alternative means of balancing column pressure and reboiler temperature should be explored for individual projects considering shut-down optimisation to avoid excessive periods running the reboiler at elevated temperature.

Table 15. Shut-down emissions calculation

Parameter	Snap 1	Snap 2	Snap 3	End	Totals
Time after initiation, mins	5	15	30	45	
Duration, mins	5	10	15	15	
GT load	30%	30%	5%	0%	
CO2 rate from HRSG, kg/s	35	35	4.25	0	
CO2 quantity from HRSG during interval, t	11	31.5	7.65	0	50
CO2 rate from stack, kg/s	1.58	1.58	0.2	0	
Treated CO2 emitted during interval, t	0.47	1.42	0.36	0.00	2
CO2 absorbed, t	10.0	30.1	7.3	0.0	47.4
Amine loading in amine feed to absorber	0.20	0.24	0.25	0.25	
Fuel burned, t	3.7	11.1	3.6	5.4	24
Fuel burned, GJ	185	555	180	270	1190
Net generation rate, MW.e	252	252	25	0	
Electricity exported, MWh	21.0	63.0	12.5	0.0	96
Capture fraction	95%	95%	95%	N/A	95%

9.2.9 Standard configuration conclusions

The standard configuration provides high-level indicative performance data for an un-improved PCC power plant during start-up and shut-down. The overall start-up capture rate was calculated to be approximately 39% and 32% in hot and cold starts, respectively (219tCO₂ and 336tCO₂ per hot and cold start, respectively). The un-improved configuration, having been developed on the assumption of base-load operation, cannot maintain 95% (or 90%) capture rates throughout the start-up process for either hot or cold start. The modelling results summarised above are presented as a reference case against which to assess the effectiveness of the various configuration improvement options outlined below.

Section 9.3 outlines general design options that would allow the plant to start and stop while still meeting 95% capture throughout.

9.3 Start-up improvement options

9.3.1 Introduction

Before considering the potential configuration improvement options of the capture plant, a number of main constraints were initially identified which limit the flexibility of the CCUS plant's operation. These include:

1. Lack of heat (normally supplied as extracted steam) availability to the rich amine reboiler for a period after the combustion cycle is started
2. Once heat can be supplied to the reboiler, significant sensible heat is required to heat the metal and liquid inventory from ambient before reboiling and amine stripping can begin.
3. A limited inventory of lean amine is available to operate the absorber while the regenerator is still warming up, leading to rapid increase in amine loading and an increase in emissions to atmosphere.
4. Lack of heat availability to the reboiler to maintain capture from residual flue gas flow once the power cycle is shut down, leading to emissions as the gas path is swept for shut-down as well as incomplete amine regeneration and elevated lean loading for next start-up

Based on these identified constraints in current CCUS processes, different options for the configuration of the carbon capture plant were discussed and reviewed within the Literature Review (Ref. 1) based on existing research conducted in the area of improving amine-based CCUS start-up and shut-down performance. Each of the options discussed aim to address at least one of the main constraints to improve the plant's flexibility.

The following subsections detail the chosen three configurations for simulation modelling detailed in the Basis of Design (Ref. 2), with an additional configuration option included ahead of the original options. Hence the option

numbers between the two documents do not comply and have been re-ordered according to an initial order of preference. The number of configuration options and their order within the Basis of Design has been preserved for historical reference and is in accordance with the ITT.

9.3.2 Improvement configuration 1 – segregated amine inventory

9.3.2.1 Introduction

The first configuration option segregates amine inventory between the absorber and stripper loop during start-up, without circulation between the two columns. This configuration option has been identified as a formal configuration since the original Design Basis and Literature Review works were carried out and is therefore not reflected in those reference documents. This scenario takes an initial distribution of solvent inventory identical to the un-improved process i.e.:

- Nominal hold-up in the absorber column and piping (approximately 5 mins for process safety surge time)
- Nominal hold-up in the stripper column and piping (approximately 5 mins for process safety surge time)
- Majority of inventory (30 mins) in lean amine storage tank

During the start-up process, the heating up of the stripper and use of amine in the absorber are carried out per the un-improved process, but in this case the solvent is recirculated in two shorter loops as shown in Figure 6 below. Note the use of bypasses around the cross-exchanger during the start-up, which are instead succeeded by the bypass around the storage tank once the stripper start-up is complete. This approach allows the stripper to heat up to its normal operating temperature more quickly, and hence reduce the time until regenerated amine is available to the absorber. Once amine regeneration is established, circulation is started by transitioning from segregated inventory per Figure 6 to circulating inventory as described in Figure 7.

Simplified process flow diagram of improved configuration during start-up

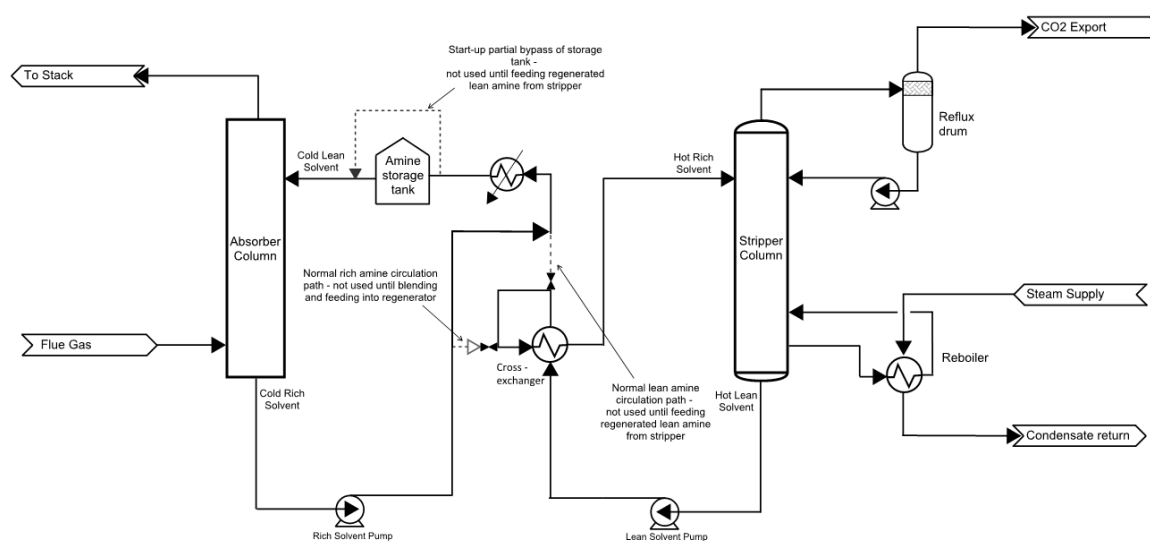


Figure 6. Flowsheet at start-up for segregated amine inventory scenario

The benefit of this option is that no new equipment is required, the improvements are instead given by modifications to the process control system and provision of start-up bypass lines (as well as associated instrumentation and controls) for use during start-up. This option can also be combined with other improvement configurations such as dedicated amine storage and combinations are discussed in each configuration option section below.

9.3.2.2 Description

This optimised configuration reduces the amount of amine inventory that must be heated at start-up. The minimum figure taken in this study is 5 minutes present in the stripper sump (450,000kg inventory) to allow surge process response time for pump safeguarding as discussed in the Basis of Design (Ref. 2) Section 5.8.1.

9.3.2.3 Start-up procedure

The initial steps (and therefore Snapshots) of the start-up procedure for Configuration 1 are similar to the un-improved process (see Section 8.4.1). During these Snapshots, the limited inventory in the absorber is used to treat the ramping flue gas. Rich amine is returned to the storage tank where it is assumed to immediately blend into the rest of the amine inventory, then the mixed stream is used to treat flue gas while the stripper inventory is heated with steam (once available). Once the stripper preheating is complete and reboiler boil-up is achieved, control valves on both the bypass streams act to gradually send amine into the normal circulation lines and bypass the storage tank. Once the stripper reboiler preheating is complete, the amine bottom product flows will be switched from the bypass to the main lines, as shown in the sequence in Figure 7 below.

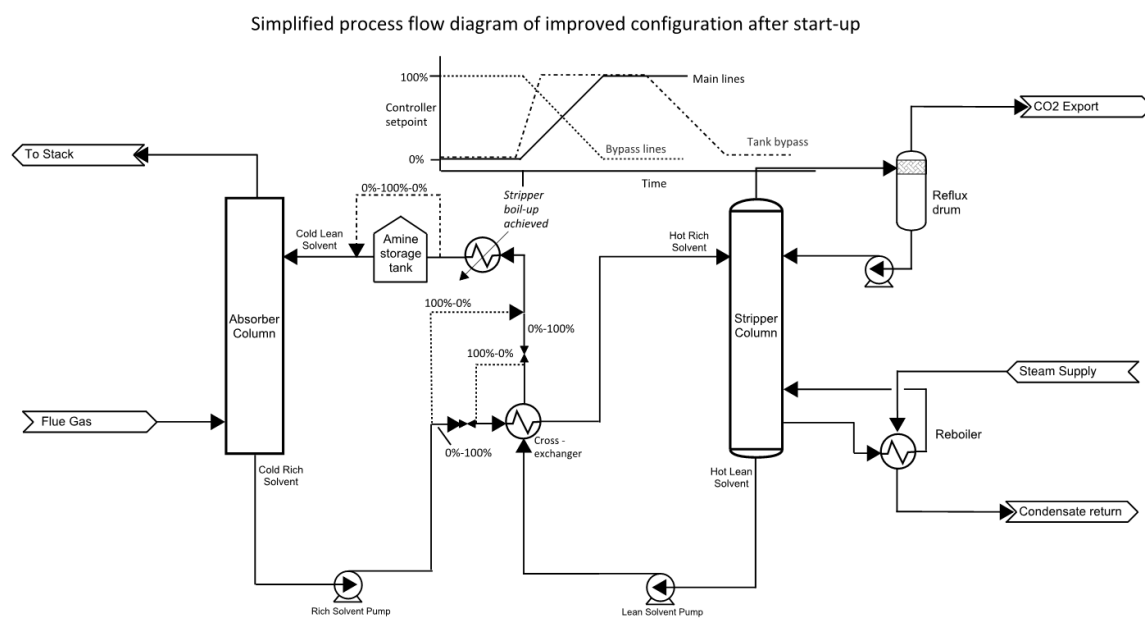


Figure 7. Segregated amine inventory configuration: transitioning from bypass flows to circulating flow once stripper boil-up is achieved

The switch-over process must balance disturbances in three main variables during the switch:

- Rich solvent temperature: introduction of colder-than-expected rich solvent to the top of the stripper caused by inadequate heat transfer into the rich amine through the cross-exchanger. This could lead to all the steam traffic in the column to condense, losing pressure in the column (activating the anti-surge controls on the compressor or potentially tripping the compressor). Solvent stripping would also be lost until vapour traffic could be re-established. Care must be taken to introduce new rich solvent to the column below the rate at which too much heat would be lost in the top stages of the column. The cross-exchanger will help to stabilise stream temperatures as flows increase.
 - An additional sub-category is introduction of richer-than-expected solvent into the top of the stripper causing an excess of vapour in the top section of the column. Noting that the increment in solvent loading is from a start-up scenario at leaner loading than the design case up to the design case, this slug of vapour would be expected to be dealt with by normal modulation of the column pressure controller and reflux controller to return condensed liquid back to the column.
- Stripper column level: loss of inventory in the stripper column caused by more flow of hot lean solvent out of the column than hot rich solvent entering the column. This could lead to loss of level in the stripper column and trip the lean solvent pump to prevent damage. Conversely, diverting more lean solvent to the main line through the cross-exchanger than the rich solvent entering the column would overflow the sump and trip the rich solvent pump to prevent damage to column internals. The rate at which solvent is diverted into the main line through the cross-exchanger must be kept controlled to maintain a relatively steady level in the stripper column
- Absorber column level: as with the stripper column, imbalances in the flows entering and leaving the absorber column can trip process pumps and must be balanced, taking advantage of the additional hold-up available in the lean amine storage tank.

For all three variables, a slow switch-over is the safest solution and can be carried out manually by an operator if carried out with appropriate time delays. However, a feed-forward controller informed with an appropriate model of the process would be able to optimise the switching procedure and directly instruct the various feedback controllers to achieve a significantly faster switch.

A feed-forward controller would still be limited by the three process variables described above (loss of boil-up, levels in absorber and stripper). However, a model of the process would allow simultaneous drawing back of the reflux flow and therefore condenser duty to compensate for the introduction of cold rich amine feed. While the stripper column is recycling with no new rich amine being added to the column (and therefore no new CO₂ to strip), the temperature of the liquid entering the top of the stripper rises and is balanced by an increase in condenser cooling duty i.e. with a fixed inventory under recirculation, the reboiler begins to evaporate more water which must be condensed rather than freeing CO₂ from the solvent, see Figure 8 below.

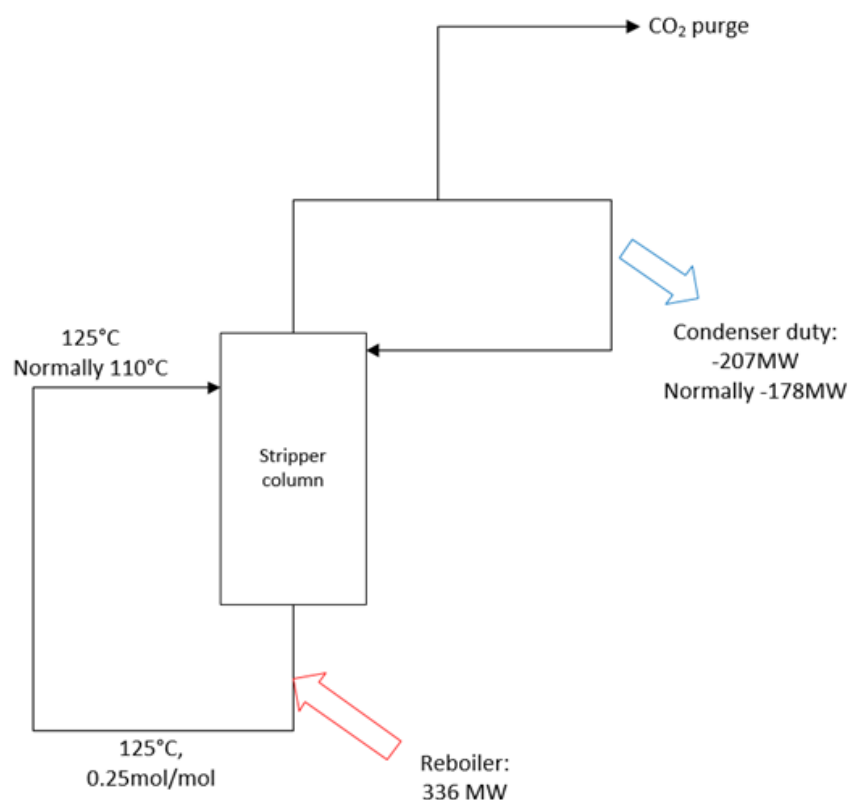


Figure 8. Recycling of stripper inventory leading to rising condenser duty

Indeed, stripping the same volume of amine continually increases the heat that must be removed by the condenser as successively less CO₂ remains in the inventory of lean amine being recycled into the rich amine feed to the column. Figure 9 describes the increase in condenser duty for a rich amine feed being recycled at the reboiler operating temperature of 125°C in orange below. Figure 9 also shows the trend in condenser duty for a rich amine feed at 110°C as during normal operation with circulation through the cross-exchanger. The condenser duty is lower by 50-80MW.th for all cases with a 110°C entry than at 125°C entry. For information, the increase in amine stream enthalpy from 110°C to 125°C is equivalent to approximately 80MW.th and explains much of the rise in overall condenser duty with excessive flashing of the amine feed entering the column, that then requires excessive cooling.

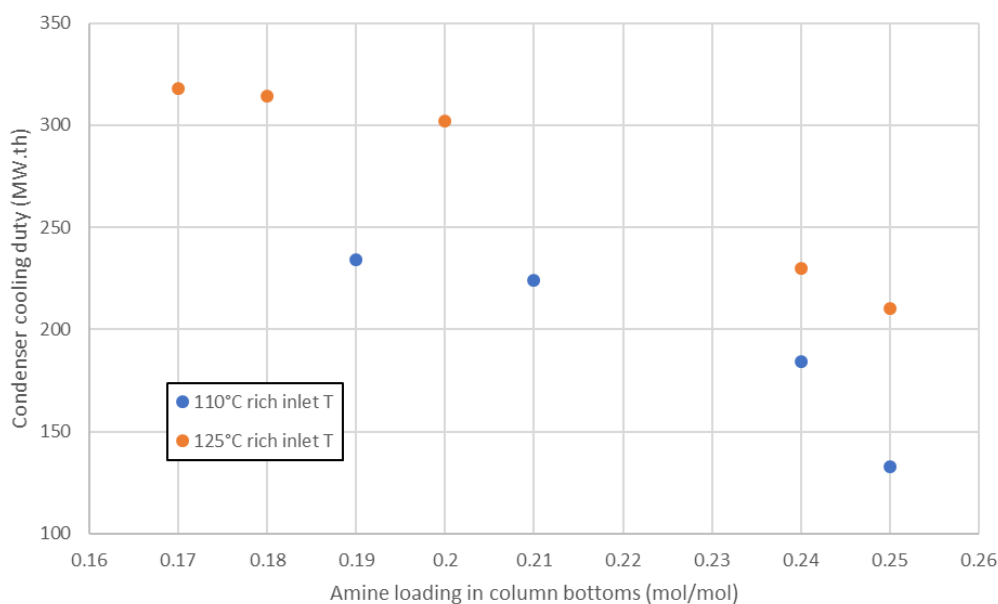


Figure 9. Increasing condenser duty as stripper amine loading drops from initial 0.25 mol/mol

As the simplified column diagram in Figure 8 shows, during the recycling period, the stripper column is not entirely in mass balance: a small flow of evaporated vapour leaves in the CO₂ purge at the top once boil-up is achieved. Introduction of new rich amine into the stripper feed at this time would help reduce condenser duty.

The issue with bringing new rich amine from the cross-exchanger into the stripper is an initial lack of pre-heating in the cross-exchanger and drop in amine feed temperature, see Figure 10 below. The rich amine from the absorber is fed at approximately 40°C but heat exchange in the cross-exchanger is initially limited as:

- The exchanger initially consumes some heat from both streams in heating the metal to operating temperature
- Initial heat transfer coefficients with low flows are potentially sub-optimal

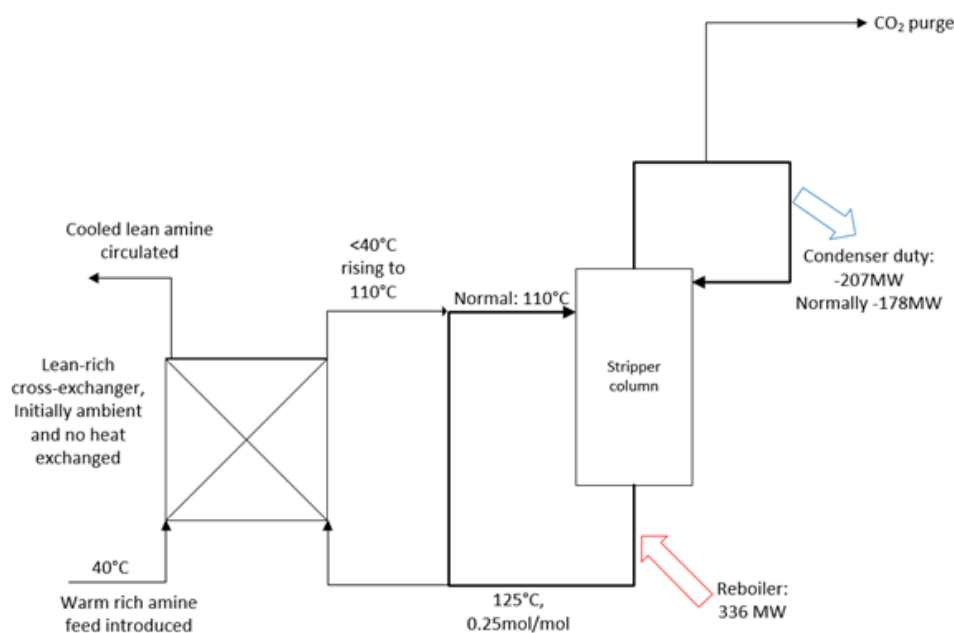


Figure 10. Introducing feed of new rich amine to cross-exchanger and extracting hot lean amine

The solution to achieve switch-over in less time would be to include the cross-exchanger within the recirculation loop by running the warming lean amine through both sides of the cross-exchanger, as shown in Figure 11.

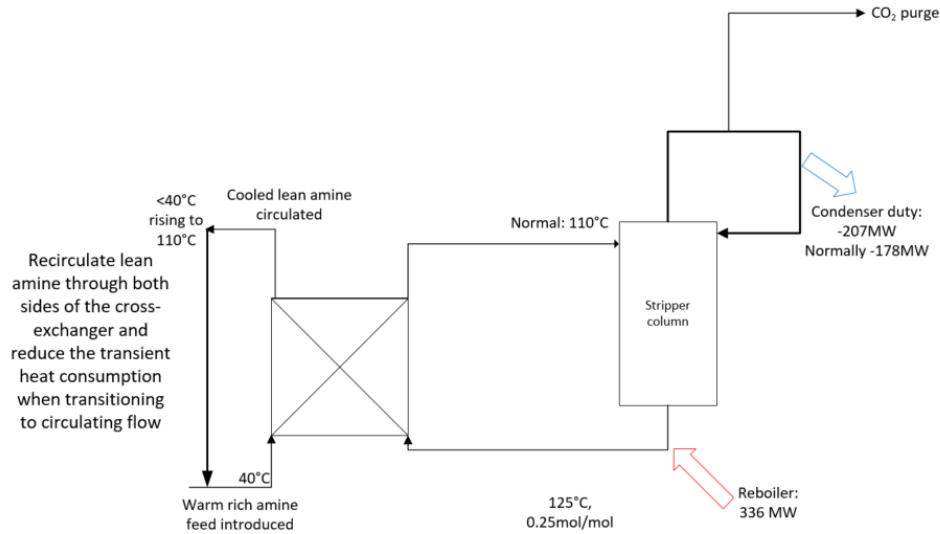


Figure 11. Introducing feed of new rich amine and extracting hot lean amine with cross-exchanger as part of the pre-heat loop

Further investigation of the stripper column performance shows the column would accept a reduction in overall feed temperature without losing the column vapour profile down to approximately 100°C for the combined feed stream (at approximately 35% new rich amine if supplied at 40°C), see Figure 12. Below an inlet temperature of 100°C , an inflection point is seen in the condenser duty and, although the overall trend is a reduction in condenser duty other indicators of poor stripping performance are present.

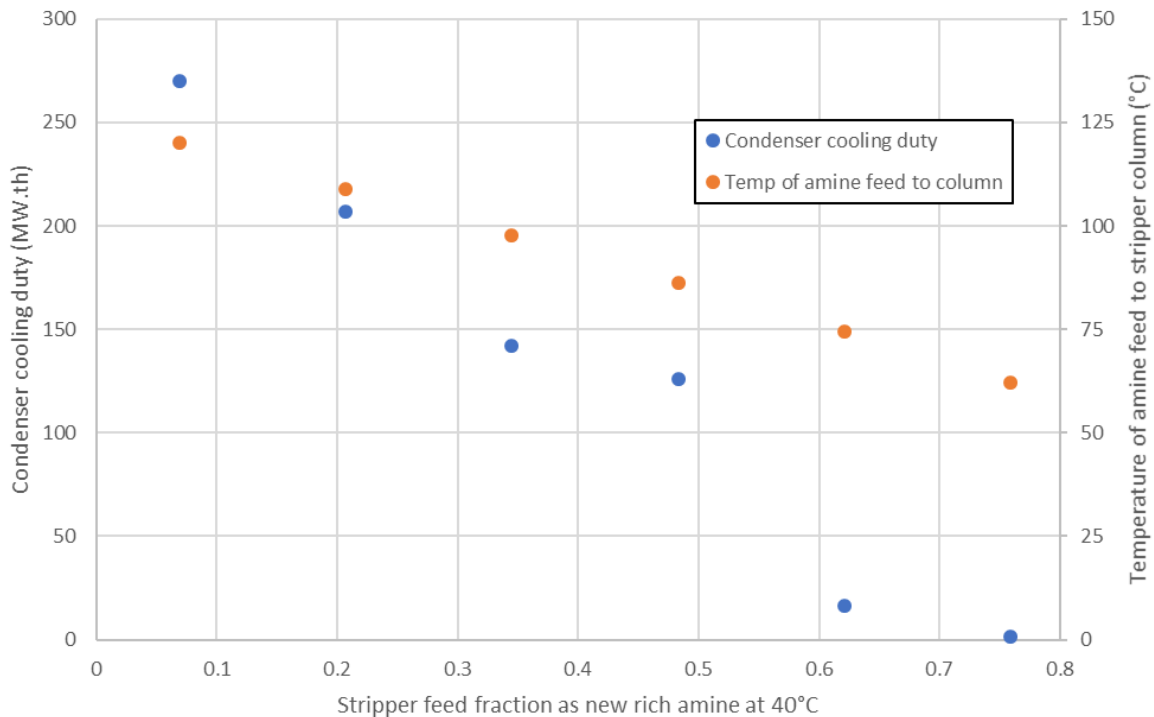


Figure 12. Effect on feed temperature and condenser duty by blending various fractions of rich amine at 40°C into stripper feed

Note that the rich amine feed temperature is itself not static at 40°C . The temperature of the rich amine leaving the cross-exchanger will rise to 110°C as more heat is exchanged with the hot lean amine. The increase in vapour generation as recirculated lean amine is gradually replaced by new rich amine, is expected to be managed by normal operation of the column reflux controls. No boundaries are expected implementing the switch from segregated recycling stripper flow to normal circulation as part of the overall column start-up procedure, pending a detailed dynamic process study on a defined configuration. This study would:

- Include selection of control valves and appropriate tuning of feedback controllers to work within the requirements of the feed-forward model
- Include estimates for dynamics such as heat consumption by warming up equipment
- Include estimates of sump and column hold-up volumes to ensure suitable suction head is available for pumps
- Identify overhead equipment and piping volumes to accurately predict and control the transient vapour flow

The findings of this dynamic study may recommend some changes to the process design (e.g. providing smaller parallel control valves for fine-tuning pump flowrates) and should be scheduled in time to feed findings back into the project development. The model could then be used to form the basis of the predictive process model informing the feed-forward start-up controller, with refinement during the testing phase targeted at equipment heat-up times and control response rates.

9.3.2.4 Stripper pre-heat energy requirement

Given a heat capacity from the material balance for lean amine at start-up, the heat requirement, Q , for this configuration was calculated using the method defined in Section 9.2.4:

$$Q = 450,000 \text{ kg} \times 3.34 \frac{\text{kJ}}{\text{kg.K}} \times (125^\circ\text{C} - 9^\circ\text{C}) = 174,348,000 \text{ kJ, or } 174 \text{ GJ}$$

Based on the earlier calculation of the thermal mass and start-up heat requirement for the metal stripper column of 44.4GJ in Section 9.2.4, the overall energy input for this configuration is shown below. The metal mass presents approximately 20% of the total heat requirement in this case (220GJ). Therefore, even an error of 50% in the metal mass would give approximately 10% difference in the heat requirement for this configuration.

$$44.4\text{GJ} + 174\text{GJ} \approx 220\text{GJ}$$

By comparing the stripper heat requirement of both the standard configuration against this configuration, the energy input for the optimised inventory configuration is approximately 20% of the value calculated for the unimproved configuration (1,100GJ).

9.3.2.5 Steam reboiler start-up time calculation

Using the calculation method described in Section 9.2.6, the start-up times for both hot and cold starts can be approximated using the required energy input value of 220GJ. Table 16 compares the results from the stripper start-up time calculations for the optimised inventory configuration with the standard case results for reference.

Table 16. Stripper start-up time calculation for both standard and optimised inventory configurations

Configuration	Start type	Lag time post-NTS, mins	Part-load extraction duration, mins	Part-load rate, MW.th	Full-load extraction duration, mins	Full load extraction rate, MW.th	Total start-up time post-NTS, mins
Standard	Hot start	25	5	252	51	336	81
Segregated	Hot start	25	5	252	7	336	37
Standard	Cold start	60	109	168	N/A	N/A	169
Segregated	Cold start	60	22	168	N/A	N/A	82

9.3.2.6 Start-up emissions

The performance of the configuration with segregated inventory during a hot start is captured in Table 17 and Figure 13 below.

Table 17. Hot start performance for CCGT+95% PCC with segregated amine inventory at start-up

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	End	Totals
Time after start, mins	15	22	25	30	37	38	
Duration, mins	15	7	3	5	7	1	
Regenerator status	No steam	No steam	Pre-heating	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	75%	100%	100%	100%	
CO ₂ rate from HRSG, kg/s	31.6	50	80	85	85	85	
CO ₂ quantity from HRSG during interval, t	28.4	21.0	14.4	25.5	35.7	5.1	130
CO ₂ rate from stack, kg/s	0.2	0.4	0.9	3.9	35.0	4.1	
Residual CO ₂ emitted during snapshot, t	0.2	0.2	0.2	1.2	14.7	0.2	17
CO ₂ absorbed from flue gas into solvent during snapshot, t	28.3	20.8	14.2	24.3	21.0	4.9	113
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.38	0.25	
Fuel burned during snapshot, t	10.0	7.1	4.0	8.3	11.7	1.7	43
Fuel burned, GJ	501	355	198	417	584	83	2140
Net generation rate, MW.e	217	387	549	723	723	723	
Electricity exported, MWh	54.3	45.2	27.5	60.3	84.4	12.1	284
Capture fraction	99%	99%	99%	95%	59%	95%	87%

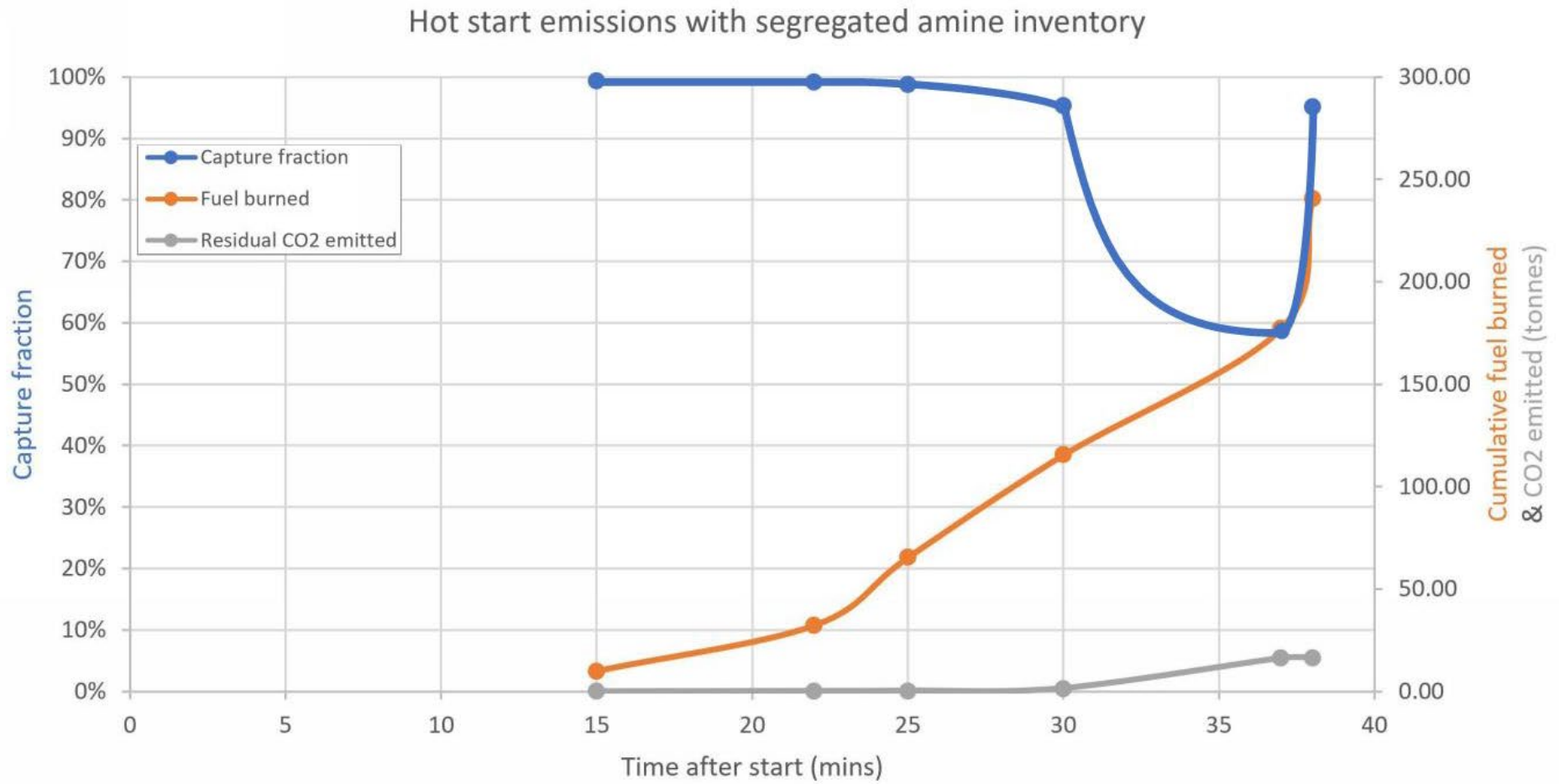


Figure 13. Hot start performance for CCGT + 95% PCC with dedicated rich amine storage and segregated amine inventory at start-up

Table 18. Cold start performance for CCGT+95% PCC with segregated amine inventory at start-up

Parameter	Snap 1	Snap 2	Snap 3	Snap 4	Snap 5	Snap 6	Snap 7	End	Totals
Time after start, mins	15	22	25	30	55	60	82	83	
Duration, mins	15	7	3	5	25	5	22	1	
Regenerator status	No steam	No steam	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Complete	
GT load	25%	50%	50%	50%	50%	50%	50%	50%	
CO ₂ rate from GT (inc. PCC design margin), kg/s	31.6	50	50	50	50	50	50	50	
CO ₂ quantity from GT during interval, t	28	21	9	15	75	15	66	3	232
CO ₂ emissions rate after PCC, kg/s	0.192	0.42	0.42	0.42	6.31	39.44	48	0.42	
Residual CO ₂ emitted after PCC, t	0.17	0.18	0.08	0.13	9.5	11.8	63.36	0.00	85
CO ₂ absorbed, t	28.3	20.8	8.9	14.9	65.5	3.2	2.64	3.0	147
Amine loading in amine feed to absorber	0.25	0.25	0.25	0.25	0.36	0.45	0.46	0.25	
Fuel burned, t	10.0	7.1	3.0	5.1	25.4	5.1	22.34	1.00	79
Fuel burned, GJ	501	355	152	254	1270	254	1119	50	3960
Net generation rate, MW.e	217	387	387	387	387	387	387	387	
Electricity exported, MWh	54.3	45.2	19.4	32.3	161.4	32.3	141.9	6.5	493
Capture fraction	99%	99%	99%	99%	87%	21%	4%	99%	64%

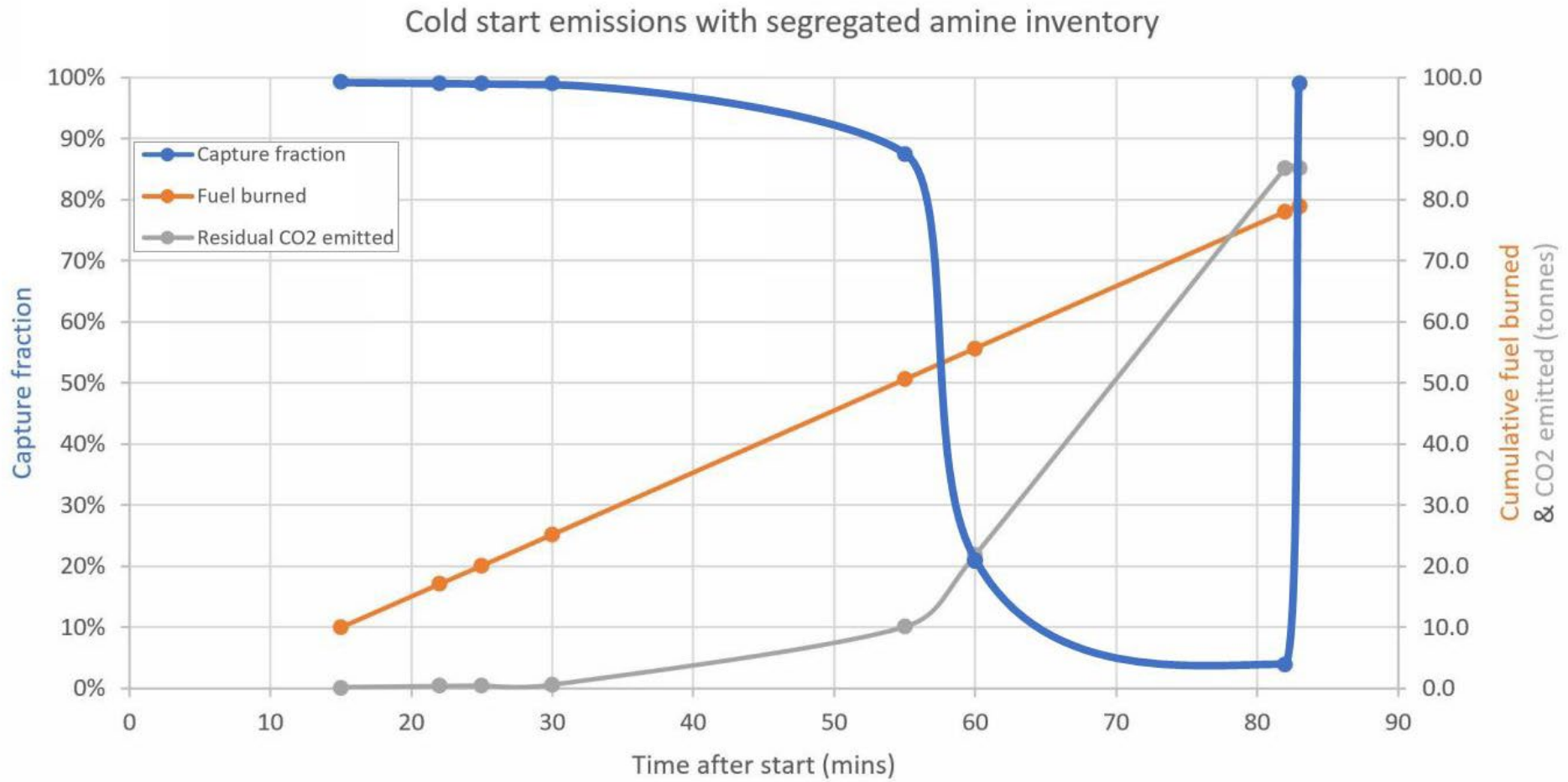


Figure 14. Hot start performance for CCGT + 95% PCC with dedicated rich amine storage and segregated amine inventory at start-up

The key results of the hot start for the PCC plant with the segregated inventory improvement option are summarised in Table 19. A total capture rate of approximately 87% was predicted for the hot start (Table 17) from the sum emissions to the PCC plant (219 t) and residual emissions (17 t). For the cold start with segregated inventory, calculated capture ratio was 64% (232t CO₂ total from the GT and 85t CO₂ residual emissions per Table 18).

Table 19. Summarised outputs of hot and cold starts with and without the segregated inventory improved configuration, for single train

Parameter	Hot start – standard	Hot start- segregated	Cold start – standard	Cold start - segregated
Time to complete PCC start, mins	81	37	170	83
Net fuel burned, t	118	43	167	79
Net fuel burned, GJ	5,894	2,140	8,373	3,960
Net electricity export, MWh	826	284	1055	493
CO ₂ emissions to atmosphere, t	219	17	336	85
Overall capture rate, %	39	87	32	64
Specific CO ₂ emissions, kgCO ₂ e/MWh	265	59	318	172

For two trains of abated CCGT, the key results of the PCC power plant with the segregated inventory improvement option are summarised in Table 20.

Table 20. Summarised outputs of the hot and cold starts for the configuration with segregated inventory, recalculated for two trains

Parameter	Hot start	Cold start
Net fuel burned, t	37	83
Net fuel burned, GJ	4,280	7,920
Net electricity export, MWh	568	986
CO ₂ emissions to atmosphere, t	34	170
Overall capture rate, %	87	64
Specific CO ₂ emissions, kgCO ₂ e/MWh	59	172

By comparing these results to the standard PCC plant, there is a significant improvement in the start-up capture rate as well as a reduction in the specific CO₂ emissions. During hot start of the standard configuration, the PCC plant was only able to capture 40% of the emissions during start-up. Using a segregated amine inventory increases the overall capture rate to 87% during hot start, more than doubling the capture rate. As for the specific CO₂ emissions, this improvement option reduces the level of emissions over a hot start by 206kgCO₂e/MWh from the standard configuration (265 kgCO₂e/MWh down to 59 kgCO₂e/MWh). For cold starts, the emissions are reduced by 146 kgCO₂e/MWh (318 kgCO₂e/MWh down to 172 kgCO₂e/MWh).

9.3.3 Improvement configuration 2 – dedicated lean and rich amine storage

9.3.3.1 Introduction

The second configuration variant proposed incorporates an increment of storage in addition to the normal process time already provided by the standard configuration. The increment volume is calculated to provide the shortfall in lean solvent circulation time during start-up. This ensures that lean amine is readily available as soon as the amine circulation in the absorber is established to fully treat the flue gas and continue treating until the stripper pre-heat time is complete.

Once the stripper pre-heat is complete and regenerated lean amine is ready for flow back to the absorber, the storage tank is partially bypassed to supply amine direct to the absorber for flue gas treatment. Rich amine produced and stored during start-up is blended into the circulation at a controlled rate without upsetting either capture rate (if bled into the lean line) or stripper performance (if blended into the rich line).

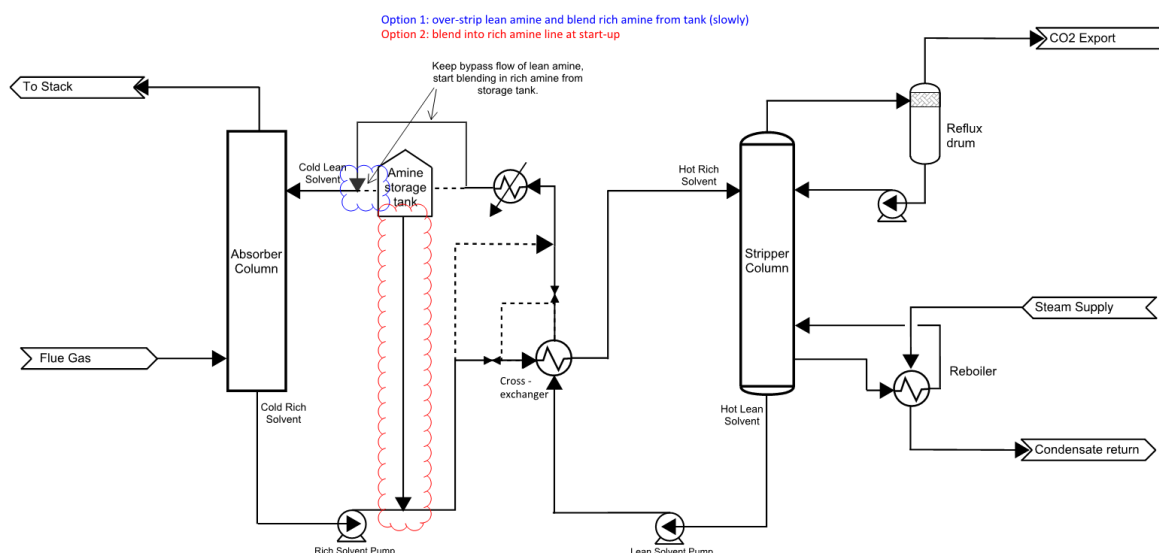


Figure 17. Using a single tank with varying bypass rates in combination with segregated solvent inventory

Prior to shut-down, the solvent inventory is then over-stripped to a lower lean amine loading than normal, to capture residual flue gas emissions during shut-down once steam is no longer available, coasting the plant to settle out with 95% capture throughout the shut-down. Shut-down would end with solvent loading of approximately 0.25mol/mol. Based on the MEA references identified in the Literature Review (Ref. 1), typical lean loading of MEA in carbon capture service is expected to range between 0.2-0.3 mol/mol. The target loading of the amine when it is being over-stripped is approximately 0.21 mol/mol and within the typical range of MEA lean loadings examined in literature.

The various configurations would all be designed to achieve the objective of maintaining the capture rate of 95% throughout start-up and shut-down. Solvent inventory is provided to ensure supply of lean amine for treatment throughout the start-up sequence until the regenerator can take over supply of lean amine. Once the regenerator supply is established, rich amine is worked off within the constraints of circulating pump sizing and stripper performance.

Estimated solvent volume is therefore given conservatively by providing hold-up to provide treatment at the solvent design rate (i.e. approximately 1500kg/s) for the full start-up time. Given the hot start-up time of 81 minutes for the standard configuration, the worst-case extra hold-up time required is calculated as:

$$\text{Standard configuration solvent storage} = 30 \text{ mins (in one tank)}$$

$$\text{Start - up time} = 81 \text{ mins}$$

$$\text{Inventory requirement for startup} = 81 \text{ mins at } 1500 \frac{\text{kg}}{\text{s}}, \text{ or } 7,290,000 \text{ kg}$$

$$\text{Density of lean amine} = 1099 \frac{\text{kg}}{\text{m}^3}, \therefore \text{inventory for start - up} = 6,633 \text{ m}^3$$

6633m³ storage includes the 30-minute storage provided in the standard configuration (2456m³, net increment for start-up is therefore 4177m³). Cost estimates for buffering the hot start and cold start options (169 mins per Section 9.2.6) are given in Table 21, comprising the cost of the tanks and solvent only, assuming a stainless steel 316-grade tank (see Appendix D).

Table 21. Additional amine storage volume calculation for design amine circulation rate of 1500kg/s, density 1099kg/m³, increment on 30 minutes storage provided by the standard configuration (2456m³), dedicated lean and rich storage for start-up

Solvent hold-up basis	Lean tank volume, m ³	Lean tank cost, £ ₂₀₁₈	Rich tank volume, m ³	Rich tank cost, £ ₂₀₁₈	Extra amine inventory, £ ₂₀₁₈	Cost increment for start-up storage, £ ₂₀₁₈
Un-improved, 30 mins	2,456	£155,000	N/A	N/A	N/A	-
81 mins, hot starts	6,633	£325,000	6,633	£325,000	£2,332,273	£2,982,273
169 mins, cold starts	18,840	£807,000	18,840	£807,000	£9,148,184	£10,762,184

Note that these cost estimates have not considered the other incremental cost effects from increased storage inventory e.g. instrumentation, piping and bund size. The cost differential on these options has been assumed to be negligible as the primary cost driver is clearly the solvent inventory. For the tank cost estimates, uncertainty in the cost estimates presented above is relatively low, the amine storage tanks would have similar metallurgy and design as that required for demineralised water. Costs are readily available for stainless steel tanks of the given sizes and some savings may be found if lower cost material selection is specified (e.g. glass reinforced plastics).

9.3.3.3 Working off rich inventory following completion of start-up

Working off the rich solvent inventory built up during start-up will clearly require supplementary energy to the normal heat consumption and can be estimated from the quantity of CO₂ held up in the solvent. The CO₂ hold-up is itself calculated from the total quantity of CO₂ produced by the GT during the full start-up time (thus giving the quantity of buffered CO₂ in storage), at 95% capture basis and the regenerator specific steam consumption. Note that the working off procedure would be carried out during full normal operation (i.e. by definition after start-up is complete), the full 336MW.th for 95% capture of 85kg/s CO₂ into the plant would be assumed to be available, or 4.2MJ.th/tCO_{2 product}). For a cold start:

$$\text{Quantity of CO}_2 \text{ held in solvent} = 493\text{t total from GT per } \times 95\% \text{ capture} \approx 468\text{tCO}_2$$

$$4.2\text{MJ steam per tCO}_2 \text{ product} \times 468\text{tCO}_2 \text{ to work off} \approx 1970 \text{ MJ}$$

Therefore, for a cold start, approximately 1970MJ of heat would be required from steam to work off all the CO₂ inventory built up during start-up. This energy will have to be provided alongside the normal regeneration heat input required by the reboiler. From the Basis for Design for this study (Ref. 2), the design margin applied on throughput in the capture plant is approximately 7% i.e. the reference flow from the GT is approximately 1020kg/s. However, the PCC plant mass balance has been carried out to treat 1100kg/s total flue gas. The normal heat consumption of the process for a flue gas of 1020kg/s would be approximately 312MW.th steam, leaving approximately 24MW.th design margin in the reboiler, plus the associated hydraulic margins in the regenerator system. Using the identified headroom of 24MW.th steam in normal operation, the built-up CO₂ would be expected to be worked off over 82 seconds:

$$\frac{1970 \text{ MJ}}{24 \text{ MW.th}} = 82 \text{ seconds}$$

Utilising the full design margin in the process would be an extreme scenario, dropping net cycle efficiency by up to 0.5 percentage points. It is likely that a more gradual blending would be pursued with a lower instantaneous penalty on a real plant and more immediately, on the amine circulation pumps. However, by inspection, the blending of the rich amine inventory would still be expected to be achieved within one hour and would not affect decisions regarding plant minimum up-time as the full solvent hold-up would be fully regenerated.

Note that the storage options incur a delayed 1970MJ regeneration requirement which must be repaid once the cold start-up is complete. In a hot start, the equivalent delayed penalty is approximately 1411MJ based on total 355tCO₂ to work off, see Table 11.

9.3.3.4 Combination with segregated inventory improvement

Evaluation of the solvent inventory options noted that storage can be readily combined with the segregated inventory improvement option and it is expected that projects given a start-up capture target may seek to deploy combinations of both. Therefore, using segregated inventory (detail in Section 9.3.2) in combination with start-up

storage has been considered and the corresponding stripper start-up times given as 37 mins and 82 mins for hot and cold starts, respectively, see Table 22.

Table 22. Storage cost increment in combination with segregated inventory allowing faster starts of 37 mins and 82 mins for hot and cold, respectively

Scenario description	Lean tank volume, m ³	Lean tank cost, £ ₂₀₁₈	Rich tank volume, m ³	Rich tank cost, £ ₂₀₁₈	Cost of additional amine, £ ₂₀₁₈	Cost above base case, £ ₂₀₁₈
Base case	2,456	£155,000	N/A	N/A	-	-
Hot start 37 mins	3,030m ³	£180,000	3,030	£180,000	£320,499	£680,499
Cold start 82 mins	6,715m ³	£330,000	6,715	£330,000	£2,378,059	£3,038,059

Note that the cost estimates given for deploying start-up storage together with segregated inventory have not considered the increment on control and hydraulic system complexity to deliver the switch-over from segregated to circulating mode. This area would be worth investigating on individual projects with dynamic simulation to consider the bottlenecks for a specific design and determine whether any further optimisation is possible. The findings from such a study would be specific to that project, although some generally applicable knowledge transfer may be possible between projects.

9.3.3.5 Amine storage option conclusions

The solvent storage requirement for achieving 95% capture during start-up was calculated as 51 mins or 139 mins to cover hot or cold starts, respectively. The volume would be in addition to the 30 mins of hold-up taken to be part of the reference configuration. By providing the extra hold-up, the plant would be expected to achieve 95% capture throughout start-up, buffering CO₂ in the solvent inventory for working off later once the start-up is complete. The time required for working off the solvent is expected to be less than one hour, depending on the rate at which the operator chose to blend rich start-up solvent into the stripper. The limit of the stripper and reboiler system itself to accept extra solvent was found to be approximately 2 mins, though in reality, the rate at which the circulation pumps could drive the rich inventory from storage would not allow such a fast transfer. Costs for the storage tanks and solvent inventory have been estimated as approximately £3,000,000 to £11,000,000, excluding pumping reconfiguration, foundations, bunds, pipework or other project works.

Projects considering start-up storage will likely also consider some means of segregating inventory for start-up optimisation, so the two options have also been considered together. The additional solvent inventory in this case was found to be approximately 7 mins to cover hot starts or 52 mins for cold starts. The costs for solvent inventory optimised by combination with segregated start-up have been estimated as £700,000 to £3,100,000 for tanks plus solvent approximately, excluding pumping reconfiguration, process instrumentation and controls, foundations, bunds, pipework or any other project works.

9.3.4 Improvement configuration 3 – heat storage

9.3.4.1 Introduction

The second configuration variant considered was the storage of thermal energy for instant availability to pre-heat the regenerator column and reboiler. This configuration would allow reboiler pre-heating to occur prior to steam availability from the HRSG, with the steam extraction taking over as soon as steam is available. Depending on the means of storage, the store could also be charged prior to power plant shut-down and continue reboiler operation to strip amine of residual flue gas. During periods of high renewable generation to the grid (coincident with times when the CCGT is likely not operating, by definition), one means may be to top the thermal store using an electric coil from the grid which would be relatively low in carbon intensity at that time. The storage unit would use hot oil to provide heat to the reboiler as the primary source of thermal energy. In case the heat storage at 130°C and required volume was found to be impractical for the hot oil storage tank, a separate backup hot water store option would be considered instead of the hot oil store if required.

This option would address the first and fourth main constraint of the Standard CCUS process: allowing heat to be readily available from the beginning of the start-up process and during the shut-down process. As this option would require a large working volume on the order of 10,000m³ depending on the selected configuration and reservoir type (hot oil or water), there is a greater commercial risk than solvent storage. Relatively few projects have been deployed at such scale and temperature level. However, a review by TES in 2016¹⁰ found at least one hot water thermal energy store of comparable scale in operation for district heating at Friedrichshafen, Germany. Further, the TES review found a general correlation for declining costs per unit volume as overall

¹⁰ Evidence Gathering: Thermal Energy Storage (TES) Technologies, 2016, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final_1_.pdf

installed volume increased. The technological risk of deploying a thermal energy store is low as the theory is well-defined¹¹, sharing design with the district heating industry.

9.3.4.2 Description

Given a worst case requirement of 1,100GJ to start the amine reboiler (calculated in Section 9.2.4), indicative sizing for a thermal energy store was carried out based on typical heat transfer fluid characteristics, as shown in Table 23.

Table 23. Typical oil characteristics

Parameter	Value	Units
Density	930	kg/m ³
Heat capacity	1.95	kJ/kg.K

Source: https://www.therminol.com/sites/therminol/files/documents/TF-8695_Therminol-66_Technical_Bulletin.pdf at approximately 130°C storage temperature

Temperature parameters used to inform the hold-up calculation include the starting temperature in the hot oil store and temperature drop: 140°C and 10°C respectively. The final temperature of the vessel would be 130°C and therefore meet the criteria in the Design Basis (Ref. 2) for 5°C minimum temperature difference between the store and the reboiler. The resulting hold-up was then calculated as:

$$\text{Mass of oil} = \frac{\text{Input thermal energy required}}{\text{Heat capacity of oil} \times \text{Temperature drop}} = \frac{1,100,000,000 \text{ kJ}}{1.95 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \times 10\text{K}} = 56,410,256\text{kg, or}$$

$$\text{Volume of oil} = \frac{56,410,256\text{kg}}{930 \frac{\text{kg}}{\text{m}^3}} = 60,656\text{m}^3$$

60,656m³ of storage would be expected to be required for this scenario which would be an order of magnitude larger than the largest existing current Tank Thermal Energy Store (TTES)¹² at 5,700m³. Note also that the largest existing TTES stores hot water at 95°C rather than oil at 140°C, without the additional heat losses introduced through insulation.

Another variant of this improvement configuration was considered in terms of storing a fraction of the start-up heat requirement in a hot water TTES. Based on the properties of water and heat transfer basis of 95°C hot side to 90°C, the calculated hold-up requirement was:

$$\text{Mass of water} = \frac{1,100,000,000}{4.18 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \times 5\text{K}} = 52,631,579\text{kg, or}$$

$$\text{Volume of water} = \frac{52,631,579\text{kg}}{1,000 \frac{\text{kg}}{\text{m}^3}} = 52,631\text{m}^3$$

The water option would be comparable in volume to the hot oil option: 52,631m³ and 60,656m³, respectively. A concept cost estimate (Appendix D) has been carried out according to a review of existing Thermal Energy Storage (TES) facilities for district heating¹³. The estimated cost for deploying tank thermal energy store was taken as the upper bound of Figure 2 in the Evidence Gathering report: €150/m³. This figure was reported in 2012 and has been escalated to approximately £2018124/m³ according to the latest Chemical Engineering Plant Index (CEPCI)¹⁴.

The preliminary cost of deploying either a water or oil thermal storage option is therefore calculated as shown in Table 24 below. Estimated costs of £6,600,000-£7,600,000 are comparable to the larger lean amine storage options once solvent supply costs are included and within the same order of magnitude as the other improvement configuration options.

¹¹ A Comprehensive Review of Thermal Energy Storage, Sarbu and Sebarchievici, Sustainability, January 2018

¹² The future of Thermal Energy Storage in the UK Energy System; UKERC; 2014; <http://www.ukerc.ac.uk/asset/82664E2B-6533-4019-BF5140CEB7B9894D/>

¹³ Evidence Gathering: Thermal Energy Storage (TES) Technologies; BEIS; 2016; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final_1_.pdf

¹⁴ Annual CEPCI reported as 584.6 in 2012 and 603.1; <https://www.chemengonline.com/tag/cepci/>

Table 24. Thermal store options cost calculations

Thermal Store Option	Volume of store, m ³	High-level cost estimate for store, £ ₂₀₁₈
Oil at 130°C	60,656	£7,612,333
Water at 95°C	52,631	£6,605,247

9.3.4.3 Uncertainties

There is significant uncertainty in the cost of deploying Thermal Energy Storage (TES) at the scale that would be necessary to store enough heat to pre-heat the reboiler. A figure of €₂₀₁₆150/m³ according to a 2016 Evidence Gathering report for BEIS. This is at the top end of the range the authors expected for the largest thermal stores (on the order of 10,000m³). Reductions on the €150/m³ cost rate are not expected due to the novelty behind the store size. Multiple smaller units in parallel may be required to meet the volume demand of 52,631m³-60,656m³ thermal storage if a specially designed tank was not considered. For reference, the largest standard size of storage tank for crude oil is approximately 24,000m³ gross volume, the plant may require up to 3 tanks in parallel without going out to a specialist design.

9.3.4.4 Combination with segregated inventory improvement

The heat storage requirement can be reduced by combination with segregated inventory, reducing the pre-heat requirement to 220GJ per Section 9.3.2.3. Table 25 summarises the results of the store volume and cost calculation using this reduced energy requirement. Reducing the pre-heat energy storage requirement would reduce the expected cost to approximately £1.5 million for either oil or water. However, the heat store requirement would still be significant (10,526m³ or 12,131m³ for oil and water, respectively) which must be accommodated on-site in an insulated storage tank.

Table 25. Thermal store options cost calculations for the combined improvement option

Thermal Store Option	Volume of store, m ³	High-level cost estimate for store, £ ₂₀₁₈
Oil at 130°C	12,131	£1,522,467
Water at 95°C	10,526	£1,331,049

9.3.5 Improvement configuration 4 – steam cycle improvements

9.3.5.1 Introduction

The initial proposal for this study was to consider a third option combining both amine and heat storage to optimise the sizing of both options. However, this was superseded by investigation of fast starting steam cycle technology which would significantly reduce the time lag before steam can be extracted to the PCC plant.

Fast-starting steam cycle technologies include:

- Operational procedures such as carrying out the combustion path purge at shut-down instead of start-up
- Feedback control and automatic adjustment of the gas turbine inlet guide vanes at start-up
- Once-through high-pressure boiler technology such as the Benson Boiler equipment (as originally installed in the UK at Cottam)¹⁵, allowing supercritical steam through the boiler and significantly increased allowable start-up steam cycle warm-up rates

Fast steam cycle starting technologies have the potential to impose extra fatigue on the steam cycle, with the connection between the high-pressure drum (for a fast drum boiler) and its steam riser being the component at most risk of failure in work by Foster Wheeler America¹⁶. The same report also proposed advanced plant controls to mitigate the impact on component life. Another report by VPI¹⁷ proposed a full inspection and monitoring program based on condition modelling for fast starting and cycling CCGT based on adapting sub-critical HRSG for fast starts. Sufficient measures to mitigate any impact on steam cycle lifetime are therefore expected to be available such that the net penalty in plant life for fast starting would be likely to be negligible. Note that a supercritical once-through boiler such as the Benson technology would avoid the high-pressure drum and therefore stress issue altogether, albeit imposing stricter water quality and operating procedure requirements than drum boilers.

¹⁵ UK sites with Benson Boilers include: Cottam; Lagange; Severn Power; Keadby 2 <https://assets.new.siemens.com/siemens/assets/api/uuid:a10a1319-3b9a-4265-bcd2-f95add4aa1e/version:1560384111/references-firedbensonsg-20180305.pdf>

¹⁶ Fast Start HRSG Life-Cycle Optimization; Power; 2013; <https://www.powermag.com/fast-start-hrsg-life-cycle-optimization/>

¹⁷ Economic Operation of Fast-Starting HRSGs; Power; 2010; <https://www.powermag.com/economic-operation-of-fast-starting-hrsgs/>

Alternative means of improving the steam cycle response and therefore PCC plant start-up time particularly during the cold start include diverting bypass steam into the amine reboiler. The bypass steam is normally dumped into the condenser and the heat rejected until steam quality is acceptable to use in the ST. However, the amine reboiler minimum requires only LP-grade steam. Therefore, the PCC plant can utilise heat that would otherwise be wasted into the condenser during start-up, completing the PCC start-up significantly sooner particularly in a cold start scenario. However, the diverted steam will be of continuously increasing quality during start-up, imposing requirements on let-down to LP to protect against introducing supercritical steam into a low-pressure system. The steam must also be appropriately de-superheated to avoid overheating the reboiler and amine inventory.

The impacts of using fast starting steam cycle options have been considered at a high level for Benson boiler technology and steam diversion, as well as in combination with the segregated amine inventory option.

9.3.5.2 Description: Benson boiler

For the fast steam cycle start-up improvement variant, credit was taken for specific fast-starting steam extraction (such as Benson boiler technology or other improvements specifically prioritising fast start of the steam cycle). Some slowdown in the start-up procedure of the steam turbine to facilitate early steam extraction would be expected. However, this slowdown would likely be relatively small and it is worth noting that the HRSG has significant excess heat which is otherwise dumped into the condenser during start-up. Fast start steam extraction technology improvements for the PCC plant comprise:

- Reduced lag time to approximately 40% of base case configuration for both cold and hot starts, as indicated possible for starting best-in-class fast-starting boilers¹⁸.
- Increased steam availability, taking credit for steam extraction for the PCC plant being prioritised and therefore full steam extraction being available immediately following lag time.

The improved start-up performance of the fast-starting steam cycle is shown in Table 26 below. The lag time after NTS for steam extraction in the standard configuration is approximately 25 and 60 minutes for hot and cold starts respectively (as shown in Section 9.2.6). Technology such as the Benson boiler would reduce the extraction time to 40% of the base case i.e. 10 and 24 minutes for both starts, respectively. Both hot and cold starts would then be followed by approximately 55 minutes of active heating time at 336MW.th, as calculated in Section 9.2.6. For cold starts, it is assumed that the full extraction rate of 336MW.th could be provided compared to an initial partial extraction in the standard configuration of 168MW.th (50%).

Table 26. Stripper start-up time calculations with fast steam cycle start

Start type	Lag time post-NTS	Extraction duration	Extraction rate	Total start-up time post-NTS
Hot start	10 mins	55 mins	336 MW.th	65 mins
Cold start	24 mins	55 mins	336 MW.th	79 mins

9.3.5.3 Description: steam diversion

The steam diversion option would connect by a take-off valve on the HP bypass line and require controls to be put in place for the rising upstream steam quality during start-up. Measures could include multiple parallel control valves of dissimilar trim sizes to cover the range of conditions encountered or other split-range control measures. This option would require rigorous analysis to ensure adequate safeguarding measures are put in place to protect the low-pressure equipment in the amine plant.

Once the steam cycle start-up is complete, steam extraction should switch over to the normal operating extraction point i.e. the IP/LP cross-over as prolonged operation on HP steam let-down would be inefficient for the plant.

Alternative means could be an arrangement with an intermediate back-pressure turbine such as investigated by Bechtel for Loy Yang A¹⁹. Under such an arrangement, steam extraction for the PCC plant would always be via the main ST HP bypass, with the intermediate back-pressure turbine also bypassed during start-up, with expansion through the back-pressure turbine once start-up is complete. Clearly, an additional turbine and generating equipment would be required in this scenario compared to the standard configuration and any other improvement configuration which would introduce cost and complexity. However, the incremental costs would likely be partly offset by less onerous extraction connection works required. In particular, the HP bypass line is

¹⁸ <https://www.acboilers.com/en/wp-content/uploads/2012/10/Heat-Recovery-Steam-Generators-for-large-combined-cycle-plants1.pdf>

¹⁹ Retrofitting an Australian brown coal power station with post-combustion carbon capture; Bechtel; 2018; http://www.co2crc.com.au/wp-content/uploads/2018/10/Retrofitting_Australian_Power_Station_with_PCC.pdf

more likely to be easily accessible on existing plants than the IP/LP cross-over. Existing plants considering retrofit of PCC may see more benefit from this option (providing suitable location can be provided for the back-pressure turbine).

Steam diversion would be of most benefit in cold starts when the standard configuration plant considered in this study would require approximately 60 minutes to begin steam extraction from the IP/LP cross-over. Diversion of some steam into pre-heating the amine reboiler could likely begin at approximately 25 minutes when the GT is held at 50% load for steam cycle heating. During the 35-minute long period from 25 minutes post-NTS to IP/LP cross-over extraction from the ST, the heat output from the GT and taken up by the HRSG would be:

$$\begin{aligned}
 GT \text{ exhaust @ 50\% load} &= 680 \frac{kg}{s} \text{ at } 670^{\circ}C, \\
 HRSG \text{ exhaust} &= 680 \frac{kg}{s} \text{ at } 118^{\circ}C \text{ and,} \\
 \text{average flue gas } C_p \text{ in the HRSG} &= 1.14 \frac{kJ}{kg.K} \\
 Q &= 680 \frac{kg}{s} \times 1.14 \frac{kJ}{kg.K} \times (670^{\circ}C - 118^{\circ}C) \approx 428 \text{ MW.th} \\
 35 \text{ minutes at } 428 \text{ MW.th} &= 898 \text{ GJ}
 \end{aligned}$$

The heat input to the HRSG during this period is approximately 898GJ and the estimated heat consumption to start the standard configuration amine plant is approximately 1100GJ, or a further 8 minutes of heating in the reboiler at 428MW.th. Clearly, this option is worth investigating in detail on an individual project basis for the potential to start the PCC plant purely on excess waste heat rather than waiting for the ST to come online and using energy that could be used for generating electricity. This option would potentially require over-sizing of the reboiler system to allow for increased steam flow at start-up (normal heat consumption in the reboiler is 336MW.th so approximately 30% overdesign on steam flow would be required).

Hot starts would not see such a dramatic improvement with steam diversion: the predicted delay before steam extraction from the IP/LP cross-over in the standard configuration in a hot start scenario without using bypass steam is already only 25 minutes. Reduction of the lag time would still be followed by active heating time and give smaller relative improvement than for cold starts. Without building a dedicated margin in the reboiler to accept extra steam for start-up, both hot and cold starts would require approximately 55 minutes of active heating time. It follows that in either hot or cold start, the PCC plant utilising steam diversion but without additional steam capacity would be ready within 79 mins after NTS (see Table 26).

9.3.5.4 Combination: Benson boiler with segregated amine inventory

As with the other improvement options, the optimised non-recirculating amine inventory can be combined with the fast-starting steam cycle technology to further optimise the start-up time.

Using the method presented above, the calculated extraction duration for the combined fast steam cycle option is shown below based on the stripper pre-heat energy requirement for the optimised inventory (220GJ) and full steam extraction.

$$\text{Extraction duration} = \frac{220,000\text{MJ}}{336\text{MW.th}} = 655\text{s} = 11\text{mins}$$

The stripper start-up time summary for the combined option is shown in Table 27, with the total start-up time for both start types reduced by 44 minutes.

Table 27. Stripper start-up time calculations with fast steam cycle start and optimised inventory

Start type	Lag time post-NTS, mins	Extraction duration, mins	Extraction rate, MW.th	Total start-up time post-NTS, mins
Hot start	10	11	336	21
Cold start	24	11	336	35

9.3.5.5 Fast starting steam cycle conclusions

The power CCUS plant start-up times for the scenarios shown in Table 26 and Table 27 range between 21 minutes for a hot start with segregated, optimised amine inventory at start and 79 minutes for cold start in the default, circulating mode at start. Clearly, significant reduction in start-up time of the CCS plant would be expected with the deployment of fast steam cycle starting technology over the base case (37-169 mins, respectively, see Table 10). With fast-start steam extraction, the PCC plant start-up process to reach steady-state regeneration and 95% capture would be expected to keep up with the power plant start-up.

High-level cost data for deploying once-through boiler technology is readily available from Thermoflow, estimated to be up to approximately £1,000,000 greater than a drum boiler per CCGT train (see Appendix D). This cost would be expected to allow economies elsewhere in the power plant and overall the power plant capital cost difference between once-through and drum boiler technology is expected to be negligible.

Costs of implementing steam diversion on its own have not been investigated, the required degree of over-design in the amine reboiler system and preceding engineering studies to confirm process details are a potential area for further study.

Current generating assets operating within the top half of the merit table have start times within the range of 55-80 minutes, based on discussion during a recent Open Access forum hosted by the UKCCSRC²⁰. Therefore, a modern plant equipped with fast starting steam technology will be expected to operate in the top half of the merit order in all cases. Further, with some CCS process control optimisation to segregate the amine inventories or some extra storage for start-up, the plant would be expected to be ready with 95% capture and operate at or near the top of the merit order.

9.3.6 Other improvement options not considered in detail

Other options for improving start-up and shut-down behaviour of PCC plant include fitting auxiliary gas-fired or electric heaters to heat the solvent in advance of start-up.

Gas-fired auxiliary heaters were excluded early in this study as being unlikely to be considered compliant with guidance on Best Available Techniques (BAT) for Large Combustion Plants. A case could be made for a BAT-compliant auxiliary heater used only for pre-heating the solvent before transitioning to steam extraction; if the heater exhaust was also connected to the absorber and emissions captured. This idea has not been tested in any planning applications at time of writing and was not considered in detail given that several other options were identified which would not be expected to be challenged on BAT.

An electrical auxiliary heater is worth noting as a further alternative option. Provided the necessary safeguarding on surface temperatures is put in place to protect the solvent from localised overheating, an electrical heater could be used to warm up the solvent ready for capture within the start-up process of the power plant. The heater would run when the power plant is offline i.e. when the majority of generation supplying the grid is from renewables so the carbon intensity of pre-heating with an electrical heater would likely be low.

²⁰ Notes taken during Open-access PCC Discussion, 19th March 2020, UKCCSRC

10. Conclusions

10.1 Standard configuration performance

From modelling the standard configuration of the PCC plant within Thermoflow and ProMax during transient phases, the following conclusions relating to the various performance indicators can be found.

10.1.1 Start-up and shut-down times

The standard configuration post-combustion capture plant designed for 95% capture was found to finish the start-up process within approximately 81 to 169 minutes for hot and cold starts, respectively (as shown in Table 10). For the power plant itself, start times would be expected to be within 30 minutes to 200 minutes for hot and cold starts, respectively. Note that, for the cold start, the PCC plant completing its start-up cycle and producing steady-state 95% capture within 169 minutes means the PCC plant start-up and pre-heating can be completed up to 31 minutes earlier than the power plant (which still requires ongoing heating until the 200 minute mark), due to extended time at part load in the gas turbine for reboiler heating.

10.1.2 Minimum up-time and down-time

As discussed in the Literature Review (Appendix A), the minimum plant up-time and down-time are economically-driven decisions, made by the operator based on their cost-benefit judgement of shutting down (and increasing start-up cost as well as increasing component fatigue). It is expected that an operator would only be inclined to shut down if they expected a minimum down-time of at least 2 hours.

Minimum up-time once started is also primarily an economic decision – an operator would normally prefer not to incur a start if they could not forecast at least 2 hours of operation in the case of a hot start or 4 hours 40 minutes of operation for a cold start. The durations of minimum up-time stated are based on an unabated plant. The times associated with an abated plant are expected to be similar as a similar regime is followed.

10.1.3 Carbon dioxide capture rates and residual emissions during start-up and shut-down

Capture rates during start-up have been estimated as 99% initially, falling to effectively 0% for a cold start, as shown by the blue line in Figure 4. Residual CO₂ emissions have been calculated as 336tCO₂ during the cold start. Overall capture rate for a cold start has been estimated as approximately 32%. The standard configuration presents a scenario where a PCC plant has been designed without any measures to maintain capture rates throughout start-up. The standard configuration is therefore a general worst-case scenario considering the degree to which an un-optimised plant might fail to meet the target of 95% capture rate during start-up and shut-down.

For a hot start, the minimum expected capture rate is approximately 10% at approximately 81 minutes. Overall emissions during a hot start were estimated as 213tCO₂ and correspond to an overall capture rate of 40%.

The standard configuration CCGT with PCC would be expected to shut down within 45 minutes as described in Table 4. Emissions expected during the shut-down process were estimated as 47t CO₂ total over a shut-down. However, snapshots 1 and 2 happen while some steam is likely to still be available for extraction. Therefore, credit has been taken during shut-down for the first 29.1t (sum of Snapshot 1 and 2) of captured CO₂ to not contribute to accumulation in the amine following shut-down.

Snapshot 3 is therefore the only period of expected CO₂ accumulation in the solvent inventory, a total of 27.9t which corresponds to 635kmol of CO₂ or an increment of 0.04mol/mol to loading. Preliminary analysis of the stripper performance at part-load has found that operating with an increased stripper back-pressure of approximately 3.1bar allowed for a reboiler temperature of 137°C and lean amine production at 0.21 mol/mol during the 30 minutes preceding a shut-down to build up sufficient over-stripped amine and allow the plant to complete the shut-down with amine at 0.25mol/mol loading.

10.1.4 Minimum stable generation

Minimum stable generation within environmental compliance limits for modern H-Class CCGT is driven by combustor technology and can be as low as 25% on the gas turbine for those deploying sequential combustors. Annular and can-annular combustors are limited to approximately 33%-50% turndown on the GT for steady lean burn at minimum emissions-compliant load.

10.1.5 Associated costs

Fuel consumption during hot and cold starts has been estimated as approximately 122t (5,680GJ) and 276t (12,841GJ), respectively.

10.1.6 Gross and net thermal efficiency

The standard configuration plant has an estimated thermal efficiency of approximately 61% net (LHV) prior to PCC (Table 6). With 95% PCC, the net efficiency is expected to drop to approximately 52% net (LHV). Gross efficiency for the standard configuration at the site conditions has been estimated as approximately 57% (LHV) at the generator terminals with 95% capture.

10.2 Performance with improvement configurations

The PCC plant performance with the four different improvement configurations, as well as the combination options examined, are detailed below. Comparisons between the improved configurations and to the standard configuration are made throughout to clearly identify the impact of the options introduced. The improvement configurations each consider how a real plant might be designed to meet the capture rate target at start-up as well as normal operation, with each option being contrasted against the standard configuration to highlight the main differences.

Note that the options considered in this study do not themselves interfere with the ability of the power plant to operate flexibly and are only ways to improve start-up and shut-down performance of the PCC plant. Once operating, the power plant would still be able to operate flexibly (e.g. with ramp rates), with the PCC plant following as an ongoing steam and auxiliary power consumer. In fact, the deployment of additional amine storage option for flexible operation would be expected to somewhat enhance the ability of the power plant with PCC to operate flexibly by shifting some regeneration to periods of low electricity cost, giving an extra degree of freedom for the operator to follow any variable electricity price.

10.2.1 Configuration 1 – segregated amine inventory

The first configuration variant considered was the de-coupling of the amine inventory for absorption and for stripper start-up. This option would require bypass of the lean-rich cross-exchanger on the absorber side during start-up and allow maximum lean solvent inventory to be stored in the absorber side of the PCC plant. It follows that this option allows the minimum inventory in the stripper to facilitate initial pre-heating of the stripper column, cross-exchanger and associated piping. This method was found to reduce the stripper start times for both hot and cold starts by approximately 50%, leading to 37 mins and 82 mins, respectively.

Note that this option did not maintain 95% capture throughout start-up. The overall capture rate in a hot start with segregated inventory was estimated as 87%. However, this option requires no major new equipment, only modifications to piping and instrumentation to facilitate the proposed mode of operation. It is anticipated that PCC plant design for flexibility would incorporate a combination of the options proposed in this report and this option has the potential to be combined with each of the other options to reduce the active heating time of the stripper..

10.2.2 Configuration 2 – dedicated lean and rich amine storage

This improvement option would replace the single 2,456m³ tank in the standard configuration with two tanks of 6,633m³, providing an additional 51 minutes of net amine circulation at start-up, with volume to store the rich amine without recirculating.

Corresponding cold start inventory requirements were for an additional 139 minutes of circulation, provided as a lean storage tank of 18,840m³ and rich amine storage tank (also 18,840m³) operating once-through from lean to rich storage at start-up. The tanks would then switch to holding rich amine in the rich tank, blending stored rich amine into the stripper feed at a controlled rate. At the same time, the lean amine tank could be either bypassed, or flowed through by the regenerated lean amine from the stripper depending on the particular configuration chosen. Other configurations could potentially remove the rich amine tank or seek to optimise inventory usage further, contingent on more sophisticated process control measures. It is expected that these tanks would be welded stainless steel and cost in the order of £495,000-£1,459,000 for hot and cold start basis per CCUS train respectively. The estimate cost of the additional solvent will cost in the region of £2,300,000 to cover capture during hot starts and £9,100,000 for cold starts.

Providing the additional amine storage inventory would allow the plant to continue generating low-carbon electricity with no decrease in capture rate throughout the start, depending on whether the capacity is available to treat throughout the cold start or only for hot starts.

Additional amine storage would allow 95% capture to be maintained through the plant start, with residual emissions calculated as approximately 17.7tCO₂ to 24.6tCO₂ for hot and cold starts, respectively.

By combining this improvement option with segregated inventory, the required increment on amine volume for start-up is significantly reduced, as are the associated costs of the tanks and additional solvent. The resultant amine tank sizes for hot and cold start for the combined option were 574m³ and 4,259m³ respectively. Applying the same cost estimate assumptions as before, the tanks would cost approximately £205,000-£505,000 for hot and cold start basis per CCUS train respectively. The required additional solvent in the PCC plant will cost in the region of £300,000-£2,400,000 for hot and cold starts respectively.

Clearly a trade-off exists between a developer seeking to cover capture during hot starts and the extra investment required to also cover cold starts. Given that a plant running at baseload would only be expected to have up to 20 cold starts per year, a developer may choose to install storage to cover capture during hot starts only. This would be a commercial decision driven by the cost of residual emissions and the number of cold starts. For example, a two-shifting plant may run 271 starts per year (of which approximately 50-55 may be cold starts). In this event, the incremental cost of emissions over the lifetime of the plant may drive the decision towards covering cold starts as well. Detailed commercial modelling will be required particularly given the expectation at time of writing for the first PCC power plants to initially run mostly baseload and eventually transition to the more flexible modes to work around growing renewables.

Solvent storage could be added later in the life of a plant when justified by operating economics, provided some provisions were made to do so when the plant is designed. These measures include reserving plot space for future operational rich amine storage (minimal pre-investment), and/or over-sizing the lean amine storage tank to allow additional inventory to be stored later (without purchasing the start-up inventory until required).

10.2.3 Configuration 3 – heat storage

Preliminary sizing estimated that 60,656m³ of storage would be expected to be required for a hot oil thermal store to provide sufficient heat to start the amine reboiler, which would be an order of magnitude larger than the largest existing current Tank Thermal Energy Store (TTES)²¹ at 5,700m³. Note also that the largest existing TTES stores hot water at 95°C rather than oil at 140°C, without the additional heat losses which can only be partially mitigated by insulation.

A cost estimation of required storage tanks can be found using the unit prices of the largest existing TTES and scaled up to the appropriate dimensions. Based on a reported unit cost value of €150/m³ in 2012, the estimated cost for the oil and water thermal store was approximately £7,600,000 and £6,600,000 respectively.

Storing heat would allow the plant to maintain 95% capture and therefore residual emissions rates would be approximately 17.7tCO₂ to 24.6tCO₂ for hot and cold starts, respectively, depending on the storage inventory basis.

Combining the thermal energy store improvement option with the non-recirculating inventory reduces the required volume of the water or oil store significantly. This is due to reduced stripper pre-heat requirement (1,100GJ down to 220GJ) as a result of the optimised level of inventory. For the thermal store using oil at 130°C, the required volume of the store is 12,131m³ with a high-level cost estimate of approximately £1,500,000. For the store using water at 95°C, the required volume of the store is 10,526m³ with a high-level cost estimate of approximately £1,300,000.

10.2.4 Configuration 4 – fast starting steam cycle technology

The power CCUS plant start-up times for the standard inventory shown in Table 26 range between 65 and 79 minutes for a hot and cold start respectively. Clearly, significant reduction in start-up time of the CCS plant would be expected with the deployment of fast steam cycle starting technology over the standard case (37-169 mins, respectively, see Table 10). With fast-start steam extraction, the PCC plant start-up process to reach steady-state regeneration and 95% capture would be expected to keep up with the power plant start-up.

²¹ The future of Thermal Energy Storage in the UK Energy System; UKERC; 2014; <http://www.ukerc.ac.uk/asset/82664E2B-6533-4019-BF5140CEB7B9894D/>

For the combined improvement option with non-recirculating inventory, the total start-up times for both hot and cold starts reduce by 44 minutes due to the reduced amine inventory in the stripper decreasing the overall duration of extraction. Therefore, for this configuration the total start-up time for a hot and cold start is 21 and 35 minutes respectively.

High-level cost data for deploying once-through boiler technology is readily available from Thermoflow, estimated to be up to approximately £1,000,000 greater than a drum boiler per CCGT train. This cost would be expected to allow economies elsewhere in the power plant and overall the power plant capital cost difference between once-through and drum boiler technology is expected to be negligible.

Costs of implementing steam diversion on its own have not been investigated, the required degree of over-design in the amine reboiler system and preceding engineering studies to confirm process details are worth further study.

Current generating assets operating within the top half of the merit table have start times within the range of 55-80 minutes, according to discussion during a recent Open Access forum hosted by the UKCCSRC. Therefore, a modern plant equipped with fast starting steam technology will be expected to operate in the top half of the merit order in all cases. Further, with some CCS process control optimisation to segregate the amine inventories or some extra storage for start-up, the plant would be expected to be ready with 95% capture and operate at or near the top of the merit order.

10.3 Overall study conclusions

All the improvement options considered have been found to effectively decouple the power plant from the PCC plant and allow the whole complex to maintain 95% capture through start-up and shut-down events, with the exception of segregated amine inventory alone (87% overall start-up capture). There are no incremental impacts expected on the overall process during normal operation and no strong reasons to prefer one option over another. The estimated costs to implement any of the flexibility improvement options identified are within the same order of magnitude. Therefore, the configuration of process options will likely be site- and project-specific rather than converging on any single approach and indeed most likely to tend towards a combination of options. For example, a fast-starting steam cycle (which would likely be an advantage in the current market even without PCC) would be complemented by segregated amine inventory and some additional dedicated start-up storage if found necessary during engineering work. This option would likely give a PCC power plant ready to respond quickly to grid demand, starting quickly and maintaining high capture rates through the start-up, operating phase and shut-down phases.

10.4 Further work

A future phase of development of this study should consider transient behaviour to optimise the process design including any start-up/shut-down improvement options being considered, as well as various combinations of improvement configurations. Once process parameters have been selected in detail, dynamic analysis of the integrated power CCUS facility would likely find significant savings possible from removing overly conservative assumptions. For this dynamic analysis, required parameters will include:

- Line sizing
- Column inventory estimates
- Preliminary process control valve specification
- Process control philosophy
- Pump and compressor preliminary specification

The above information would be expected to be available part-way through the Front End Engineering Design (FEED) of a power CCUS project, in which case, this study could be used to inform the activities to be carried out in a dynamic analysis towards the end of FEED.

Further work considering the steam heat extraction available at part load could also consider reducing the degree of conservatism in the cold start time calculation which likely underestimates the quantity of steam that could be made available for extraction to the steam cycle.

