CONTROL OF CARBON DIOXIDE CAPTURE FROM BIOMASS CHP PLANTS

Designing a suitable control system to realize the flexible operation of the CO2 capture system.

TANMMAY ROUT
ABSTRACT

This degree project studies the integration of carbon capture system into biomass fired combined heat and power (bio-CHP) plants. The key disturbances from bio-CHP plants include flue gas flow rate, carbon dioxide (CO₂) concentration and available heat for the reboiler because the use of versatile biomass and the dynamic operation of CHP plants results in large fluctuations in the properties of flue gas and the heat input for CO₂ capture. To clearly understand the impacts of these disturbances on the performance of CO₂ capture, a dynamic CO₂ capture model is developed in Aspen Plus Dynamics by using monoethanolamine (MEA) based chemical absorption. Proportional-Integral (PI) feedback controllers are then implemented to further study and compare the performance of the CO₂ capture process under different control strategies, the performance with general control settings and fine-tuned controllers are obtained and compared, including both the control performance and system performance. The control performance includes the maximum deviation and settling time, which could reflect only the performance of the controllers. The system performance includes Captured CO₂, reboiler duty and Energy penalty per unit CO₂ captured, which could reflect CO₂ capture system performance. An equilibrium stage steady state model is first developed for the key components in the CO₂ capture plant in Aspen Plus, consisting of the absorber, the stripper, and lean-rich heat exchanger. By sizing the components and employing the pressure driven mode, the steady state model is enabled to be a dynamic model. The disturbances about flue gas and reboiler heat are taken from a real bio-CHP plant in Sweden. Considering the higher flue gas flowrate, the model has been scaled up to meet the requirement of this bio-CHP plant. The addition of controllers are done for the flexible operation of the CO₂ capture system and the controlled variables considered in this study are the percentage of CO₂ absorbed in the absorber column, reboiler temperature and rich solvent flow in the stripper column.

The results show the effects of fluctuations in the key influencing factors on the control performance and the system performance. The fine-tuned controller implemented system showcases better performance when the quantity of CO₂ captured is compared with that of the system in the absence of controllers, where a 1.1% increase in the amount of captured CO₂ is observed when the flue gas flow rate is increased by 30%. The system also maintains a 1.8% higher capture rate when controllers are implemented. This showcases better system performance when controllers are implemented in the system. To further analyse the effects of control strategies two different control strategies are compared where controllers with general settings are compared to the controllers which are fine-tuning achieved by implementing tuning parameters which were obtained through Internal Model control (IMC) based on the system requirements. The fine tuning of the controllers results in improved system performance where the amount of captured CO₂ increases by 1.4% when the reboiler duty is increased by 30% and a 1.7% decrease in the energy penalty per unit CO₂ captured. Additionally, the results show that the settling time and maximum deviation are different for the two controllers where the controller which underwent fine tuning maintained the steady set point whereas the controller with general controller tuning showcases deviation before it attained stability. Therefore, the fine-tuned controller is more efficient to enable the flexible operation of CO₂ capture when facing disturbance. It is studied that the tuning parameters
implemented in the controllers affect the transient operation of the plant and improved the dynamic performance of the capture system. The tuned controllers offered more stability to the capture system while attaining their respective set points in a shorter time frame. It is also found that there exists a big difference between the system’s performance without controllers and that with finely tuned controllers. The difference in captured CO₂ amount is approximately 26 ton/h when flue gas flow rate increases by 30%. The percentage difference is 1.1%, 7.7% and 5.9% for Captured CO₂, reboiler duty and Energy penalty per unit CO₂ captured respectively. In conclusion the control of the transient operation of the CO₂ capture system needs the control system implemented and requires fine tuning parameters to achieve the desirable performance.

**Keywords:** Carbon capture, biomass fired combined heat and power plant, MEA based chemical absorption, flue gas, dynamic operation; PI controllers
PREFACE

This master's thesis work has been carried out by Tanmmay Rout as a fulfillment to the master's degree of Science in Sustainable energy systems at Mälardalen University in Västerås, Sweden. It is of great importance to acknowledge the project under Mälarenergi, Eskilstuna Energi och Miljö and VafabMiljö, within which this thesis work has been conducted.

The accomplishment of this work has been possible by dedicated support of supervisors Beibei Dong, Dr. Hailong Li. Their help and commitment to guide me with their knowledge and wisdom is highly appreciated.

I am also particularly grateful for the assistance and support provided by my examiner Valentin Scheiff. He made sure to steer me in the right direction regarding the content of the thesis and always provided valuable input.

Lastly, my gratitude towards my parents, Tamasa and Tapan is beyond measure. They have constantly believed in me and made sacrifices to ensure that I had the best opportunities possible throughout my entire life. Special thanks to the rest of my family and friends that are always supporting me.

Västerås October 2023

Tanmmay Rout
SUMMARY

The global community is currently facing two conflicting challenges: rapidly increasing global energy demand to meet the growing population of the world and the need to mitigate pollution and the factors that catalyse climate change. Globally, the largest source of CO₂ emissions which is one of the key greenhouse gases accelerating global temperature rise, is the power generation sector. There are significant efforts that are being made to focus on developing technologies suitable for CO₂ capture from the flue gas of power plants before they are released into the atmosphere. The objective of this thesis is to realize the implementation of a control strategy which enables for efficient and stable control of a CO₂ capture system, and ultimately enhances the performance of the CO₂ capture system when exposed to external disturbances in the key influencing factors. The study simulated the operation of a post combustion CO₂ capture system which uses MEA lean solvent for CO₂ absorption equipped with different control strategies to investigate (1) The impact of key influencing factors on the dynamic performance of the CO₂ capture system (2) Explore the performance of different control strategies on the dynamic operation of the CO₂ capture system and (3) highlight the performance of implementing control strategies on the CO₂ capture plant.

In order to meet the objectives of the work a dynamic model of a post combustion carbon capture system (CCS) was developed to study the effects of the fluctuations in the key influencing factors i.e., flue gas flow rate, flue gas composition which were obtained from Mälarenergi and reboiler heat. The variations in the influencing factors were studied by performing different case studies with increasing ramp changes over a period of time. These were used as the input parameters for the model. The control strategies implemented were categorized into two parts: (1) the control system with general controller tuning and (2) with the control system undergoing fine tuning. The results of both these strategies were compared to determine the best control strategy that could be implemented. Lastly, the control strategy chosen was compared under transient plant performance with no equipped control strategy and the positive impacts of the implementation of a finely calibrated and tuned control system was highlighted.

The result for the best strategy was achieved by implementing tuning parameters which were obtained through IMC control tuning which led to considerably shorter settling time and lower maximum deviation from the targeted set point when compared to the control strategy which was not tuned. Finally, the performance of CCS with the best control strategy determined through this work was much greater than the performance of the CCS without a control strategy in place. This was concluded by analysing the captured carbon amount over a period of 7 hours where the flue gas flow rate was ramp up increased by 30% for a span of 2 hours where the percentage difference was 1.1%, 7.7% and 5.9% for Captured CO₂, reboiler duty and Energy penalty per unit CO₂ captured respectively.

Hence, it is essential for CCS systems to implement efficient and effective control strategies to vastly improve the performance of the CCS when exposed to external disturbances and variations.
## CONTENT

1 INTRODUCTION ......................................................................................................................... 6

1.1 Background .......................................................................................................................... 7

1.2 Purpose/Aim .......................................................................................................................... 8

1.3 Research questions .............................................................................................................. 8

1.4 Delimitation .......................................................................................................................... 9

2 METHOD ..................................................................................................................................... 10

2.1 Literature review .................................................................................................................. 10

2.2 Data acquisition and case study .......................................................................................... 10

2.3 Model development and validation ..................................................................................... 10

2.4 Control implementation and performance evaluation ......................................................... 11

3 THEORETICAL FRAMEWORK/ LITERATURE STUDY .............................................................. 12

3.1 CO₂ capture and separation technologies .......................................................................... 12

3.1.1 CO₂ capture methods ...................................................................................................... 12

3.1.2 CO₂ separation technologies .......................................................................................... 16

3.2 Bioenergy conversion processes .......................................................................................... 17

3.2.1 Biomass fired combined heat and power plant ............................................................... 17

3.2.2 Biomass integrated gasification combined cycle power plant ......................................... 18

3.2.3 Biomass anaerobic digestion biogas plant .................................................................... 19

3.3 Capturing CO₂ from bio-CHP plants .................................................................................... 20

3.3.1 Bioenergy with carbon capture and storage (BECCS). .................................................. 20

3.3.2 Integrating CO₂ capture in bio-CHP plant .................................................................. 20

3.3.3 Amines based chemical absorption .............................................................................. 21

3.4 Dynamic modelling and simulation of CO₂ capture ............................................................ 22

3.4.1 Steady state modelling .................................................................................................... 22

3.4.2 Dynamic modelling .......................................................................................................... 22

3.4.3 Control strategies ............................................................................................................. 23

3.4.4 PID controller .................................................................................................................. 23

4 CURRENT STUDY ...................................................................................................................... 25
4.1 Case study: key influencing factors from bio-CHP plant

4.1.1 Case 1: Fluctuation of flue gas flowrate

4.1.2 Case 2: Fluctuation of CO$_2$ content (CO$_2$ vol%) in flue gas

4.1.3 Case 3: Fluctuation of both flowrate and CO$_2$ vol % in flue gas

4.1.4 Case 4: Fluctuation of available heat for reboiler

4.2 Model development and validation

4.2.1 Steady state simulation in Aspen Plus

4.2.2 Dynamic simulation in Aspen Plus Dynamics

4.2.3 Control implementation

4.2.4 Key performance indicators

5 RESULTS

5.1 Case 1: Control under the fluctuation of flue gas flowrate

5.1.1 Control performance

5.1.2 System performance

5.2 Case 2: Control for the fluctuation of CO$_2$ volume %

5.2.1 Control performance

5.2.2 System performance

5.3 Case 3: Control for the fluctuation of flue gas flow rate and CO$_2$ volume %

5.3.1 Control performance

5.3.2 System performance

5.4 Case 4: Control for the fluctuation of reboiler heat

5.4.1 Control performance

5.4.2 System performance

6 DISCUSSION

6.1 Impacts of various key parameters on the performance of CO$_2$ capture

6.2 Control strategy implementation

6.3 System controller design influence on CO$_2$ capture performance

7 CONCLUSIONS

8 SUGGESTIONS FOR FURTHER WORK
LIST OF FIGURES

Figure 1 Overview of method ................................................................. 11
Figure 2 Overview of pre-combustion ...................................................... 13
Figure 3 Overview of post-combustion .................................................... 14
Figure 4 Overview of a biomass plant ...................................................... 18
Figure 5 Main components of a biomass integrated gasification combined cycle power plant ................................................................. 19
Figure 6 Biomass anaerobic digestion power plant ...................................... 20
Figure 7 Overview of a CO2 capture system integrated in a Biomass CHP plant ................................................................. 21
Figure 8 Variation of Flue gas flow rate from May 1st, 2020, to May 31st, 2020 .... 26
Figure 9 Variation of Flue gas CO2 vol % rate from May 1st, 2020, to May 31st, 2020 .... 26
Figure 10 Variation ramp increase of FG flowrate in Case 1 ............... 28
Figure 11 Variation of FG CO2 vol % in Case 2 ....................................... 28
Figure 12 Variations in both flowrate and CO2 vol % in flue gas ................. 29
Figure 13 Variation of Reboiler heat duty in Case 4 .................................. 30
Figure 14 Simplified flowsheet of a CO2 capture by reactive absorption-stripping plant .... 31
Figure 15 Controller implementation in dynamic model ......................... 35
Figure 16 Model validation for the model developed against the PACT pilot plant model .... 38
Figure 17 Comparison of capture rate in different control strategies in Case 1 ........ 41
Figure 18 Comparison of reboiler duty in different control strategies in Case 1 ........ 42
Figure 19 Comparison of reboiler duty control performance for different controller tuning parameters in Case 1 ................................................................. 43
Figure 20 Comparison of lean solvent flow in different control strategies in Case 1 ........ 44
Figure 21 Comparison of lean solvent control performance for different controller tuning parameters in Case 1 ................................................................. 44
Figure 22 Comparison of capture rate in different control strategies in Case 2 ........ 46
Figure 23 Comparison of reboiler duty in different control strategies in Case 2 .......... 47
Figure 24 Comparison of reboiler duty control performance for different controller tuning parameters in Case 2 ................................................................. 48
Figure 25 Comparison of lean solvent flow in different control strategies in Case 2 ........ 49
Figure 26 Comparison of lean solvent control performance for different controller tuning parameters in Case 2 ................................................................. 49
Figure 27 Comparison of capture rate in different control strategies in Case 3 ........ 51
Figure 28 Comparison of reboiler duty in different control strategies in Case 3 ........ 52
Figure 29 Comparison of reboiler duty control performance for different controller tuning parameters in Case 3 ................................................................. 53
Figure 30 Comparison of lean solvent flow in different control strategies in Case 3 .... 54
LIST OF TABLES

Table 1 Stream characteristics for flue gas flow .......................................................... 33
Table 2 Stream characterization for lean solvent flow .................................................. 33
Table 3 Controller characteristics used for the control structure development .............. 36
Table 4 Controller characteristics for Lean solvent Flow controller ............................... 37
Table 5 Controller characteristics for reboiler duty controller ..................................... 37
Table 6 Controller characteristics for rich solvent flow controller ................................. 37
Table 7 Model validation parameters obtained from UKCCSRC PACT pilot plant ............... 37
Table 8 Scaled up estimations for the components of the CO2 capture plant ...................... 39
Table 9 Comparison of the system performance under different control strategies for Case 1 .................................................................................................................. 45
Table 10 Comparison of the system performance under different control strategies for Case 2 .............................................................................................................. 50
Table 11 Comparison of the system performance under different control strategies for Case 3 .............................................................................................................. 55
Table 12 Comparison of the system performance under different control strategies for Case 4 .............................................................................................................. 59
Table 13 Comparison of the amount of captured CO2 and energy penalty between the control strategies ........................................................................................................... 61

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Captured CO2</td>
<td>Dynamic amount of captured CO2</td>
<td>[ton/h]</td>
</tr>
</tbody>
</table>
### Symbol Description

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{n}e_{n}r_{g}y$</td>
<td>Average reboiler heat duty per unit captured CO$_2$</td>
<td>[MJ/kg]</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

With the effects of climate change on a constant rise and the desired transition towards sustainable energy trends and decarbonization, the reduction of greenhouse gas emissions is one of the primary goals for industries across various economic sectors. According to a report from the United Nations, it is essential to reach the climate goals which have been set by the Paris climate agreement and a concerted effort to capture CO₂ emissions is required.(UN Report Calls for Scaling-up Carbon Capture, Use and Storage | UN News, n.d.)

The goal to achieve net-zero emissions is essential to curb and control the rapid rise in global warming in the past decades, this has been extensively stated in the Paris Agreement on climate change. The technology brief from the agreement calls also for the rapid scale-up and development of carbon capture technology, use and storage. The global temperature target set by the Paris agreement is to limit global warming to significantly below 2 degrees, and preferably to 1.5 degrees Celsius, compared to pre-industrial levels.(The Paris Agreement | UNFCCC, n.d.) According to the United Nations Environment Program (UNEP), in order to achieve this goal, CO₂ emissions must be reduced by 7.6% every year between 2020 and 2030.(COP25 International, 2019)

The United Nations Economic Commission for Europe press release encourages and calls for the large-scale development and deployment of carbon capture use and storage (CCUS) technology in Europe, this would enable countries to effectively decarbonize their industrial sectors, which would help bridge the gap until the next generation of carbon capture use and storage technologies are established. (Carbon Capture, Use and Storage Is Needed Urgently to Meet Carbon Neutrality Targets, According to UNECE Report | UNECE, n.d.)

Carbon capture is essential for the efficient reduction of CO₂ emissions and plays a crucial role to combat climate change. CCS is necessary to achieve large-scale reduction of CO₂ emissions to achieve the rapid decarbonization. Carbon capture and storage is crucial to provide scalable means to achieve the necessary large scale decarbonization in sectors, which otherwise would have difficulties to do so quickly enough. Hence, exploring various carbon capture strategies would be beneficial to achieve the desired reduction of CO₂ emissions as directed by various climate control protocols and conventions.
1.1 Background

CCUS is the process of capturing CO₂ and either storing it permanently or utilizing it by converting it into valuable products, such as fuels, chemicals, or other by-products. There are various methodologies for the capturing of CO₂ and new technologies to capture and utilise the captured CO₂ are evolving rapidly. These methodologies for the CO₂ capture are already successfully applied to capture CO₂ from different sources. Currently various carbon capture technologies are used to prevent an estimated amount of 40 million tons of CO₂ every year from escaping into the atmosphere. (Climate Report Finds - Global CCS Institute, n.d.) This is achieved through hundreds of carbon capture projects that are currently being developed or are ongoing. (Carbon Capture and Storage Database | Netl.Doe. Gov, n.d.)

Bioenergy with CO₂ capture and storage (BECCS) is a carbon-negative technology that is instrumental to capture CO₂ from bioenergy conversion. BECCS involves an energy pathway for carbon capture where CO₂ is captured from a biogenic source. Currently only around 2 Mt of biogenic CO₂ are captured every year through BECCS removal of carbon dioxide, and an estimate of about 40 Mt of CO₂ every year by 2030 based on various projects currently in the early and advanced stages of deployment. (Bioenergy with Carbon Capture and Storage – Analysis - IEA, n.d.)

BECCS is the only CO₂ removal (CDR) technique which can also be utilised to produce energy. Biogenic sources used for BECCS can be process emissions resulting from biofuel and biohydrogen production, or combustion emissions from heat and power generation plants. (Bioenergy with Carbon Capture and Storage – Analysis - IEA, n.d.) Hence, retrofitting existing bioenergy facilities with carbon capture and storage could provide substantial decarbonization while reducing impacts on resources.

The carbon capture technologies can be divided into three main categories: (Meyer & Rubin, n.d.)

- Post-combustion – The exhaust gases released from industrial combustion or power plants is captured and the CO₂ is separated from the waste gases.
- Pre-combustion – This involves pre-treatment of fuels which enables the separation of CO₂ from the post combustion of the fuels.
- Oxy-fuel combustion – This involves combustion with pure oxygen instead of air. This results in a greater fraction of the CO₂ to be liberated from the waste gases which facilitates and makes it easier for the carbon capturing.

Post-combustion carbon capture has been implemented in large scale and several CO₂ capture and storage projects which are being developed around the world. Post combustion capture is considered as the most suitable option for retrofitting existing plants (Luis, 2016a), to provide scalable means to reach the decarbonization goals, which would have difficulties to do so quickly within the target of 2030 as set by the Paris agreement. (The Paris Agreement | UNFCCC, n.d.)
Post-combustion CO₂ capture using MEA is widely accepted as the most developed and researched CO₂ capture technology for power plants. (Kvamsdal et al., 2011) It is also essential to remove CO₂ as well as H₂S and other acid gases from natural gas because these impurities in the presence of water can form acids resulting in the corrosion of pipelines and other equipment. Furthermore, due to the nature of these acids and the combination of these impurities can affect the performance of the power plants.

Chemical absorption is a commercialized technology for CO₂ capture. In comparison to other CO₂ capture processes, CO₂ removal with the help of chemical absorption systems using chemical solvents offers higher capture efficiency. (Lin et al., 2010)

The performance of the same can be affected by many key parameters, such as the rate of flue gas flow, the percentage of CO₂ in the flue gas and available heat for solvent regeneration. Since the operation of the biomass fuelled power plant dynamically varies with fuel properties, heat and electricity demands, such dynamic changes can affect the performance of CO₂ capture. Therefore, it is important to design a suitable control system to realize the flexible operation of the CO₂ capture system and are crucial in the operational optimization of the CO₂ capture system when the system is exposed to disturbances. (Salvinder et al., 2019)

The benefits of flexible CO₂ capture and storage are understood; however, it is important to further evaluate the flexibility of the process at a plant scale to better analyse the impact of flexible operation on the performance of the CO₂ capture plant despite there being disturbances. Hence, dynamic pilot plant studies and process modelling work are crucial in assessing the feasibility of flexible operation in CO₂ capture plants.

1.2 Purpose/Aim

The objective is to develop efficient control strategies that can improve the dynamic performance of CO₂ capture and analysing the impacts of various key parameters on the performance of the CO₂ capture system, such as the flow rate of flue gas, concentration of CO₂ in the flue gas.

1.3 Research questions

- What are the impacts of various key parameters such as the flow rate of flue gas, concentration of CO₂ in the flue gas, on the performance of the CO₂ capture?
- How can different control strategies be implemented to handle different disturbances?
- How will the different control strategies design influence the dynamic performance of CO₂ capture?
1.4 Delimitation

- Flue gas data—the main compositions are obtained from plant, CO$_2$ and O$_2$, and the minor compositions such as NOX, SOX are neglected.
- Aspen Plus Dynamic is used for dynamic simulation, which is equilibrium-based model, and the control is based on PID controller principles.
- Cases are defined for the single variation of disturbance and combined disturbances, such as flue gas flowrate, CO$_2$vol% in flue gas, to investigate their influences on the CO$_2$ control mechanisms.
- Only the CO$_2$ capture process not the bio-CHP plant is considered and modelled, the operation of CHP is complicated on the basis of the variation of heat and electricity, and it makes the heat input for CO$_2$ capture vary with them, so the heat input for CO$_2$ capture is not directly taken from the plant due to no deployment of CO$_2$ capture.
2 METHOD

2.1 Literature review

A qualitative and quantitative literature study has been performed to obtain extensive knowledge about the theoretical and application aspects of carbon capture technologies and how they are implemented, with key focus on post combustion CO$_2$ capture technologies in combined heat and power plants. The literature study is carried out by researching and reading for scientific articles, research papers and publications containing information about carbon capture technology, BECCS, post combustion carbon capture, chemical absorption, previously implemented control strategies and impacts of these control strategies.

To acquire the relevant information for this literature study, different search engines such as DiVa, Google scholar and ScienceDirect were used. In addition to the search engines various books and publications were referred which are relevant to the scope of the thesis. Various pilot plant studies and the Aspen database was also referred to obtain extensive knowledge on the topic.

2.2 Data acquisition and case study

This paper investigates the impacts of various key parameters such as the flow rate of flue gas, concentration of CO$_2$ in the flue gas and available heat for solvent regeneration, on the performance of the CO$_2$ capture. Hence, the flue gas composition and the input parameters which influence the performance of the CO$_2$ capture system were provided by Mälarenergi, because this research paper is within the collaboration with Mälarenergi.

These input parameters include the flow rate of flue gas, concentration of CO$_2$ in the flue gas. The various case studies that have been studied in the paper are derived from the above-mentioned input parameters obtained.

2.3 Model development and validation

Aspen plus is a process modelling software used for process monitoring, optimization, and conceptual design of manufacturing facilities and processes in biochemical industries. Aspen plus is used for the modelling of the CO$_2$ capture system, due to the software’s ability to simulate various key processes involved in a CO2 capture system both in steady state and dynamic (real time). The modelling process can be categorized into three parts: (1) Steady state modelling, (2) Dynamic modelling and (3) Control strategies.

The steady state model is first developed with the help of the input parameters. Then the dynamic model is developed, and controllers are implemented to understand the behaviour of the control strategies. A sensitivity analysis to understand the impact of varying the
parameters affecting the CO₂ capture would be performed on the dynamic model. The control strategies will also be analysed to handle disturbances.

Model validation is an essential step to determine the credibility of the performance of the CO₂ capture system. Without validation against real experimental data, the validity of modelling findings is unreliable. The validation for the model developed in Aspen plus is done by comparing the model with other similar models obtained from the literature.

2.4 Control implementation and performance evaluation

The dynamic model is developed based on the influencing factors from the bio-CHP plant such as flue gas flow rate, CO₂ vol% and available heat from the reboiler. The implementation of controllers is done to alter the influencing factors in the dynamic model. Based on the influencing factors and the behaviour of the model with respect to the disturbances, key indicators such as the amount of CO₂ captured, CO₂ capture rate and energy penalty per unit CO₂ captured are used to determine the performance of the CO₂ capture system, these performance indicators are used to determine the performance of the CO₂ capture system.

*Figure 1 Overview of method*
3  THEORETICAL FRAMEWORK/ LITERATURE STUDY

3.1 CO₂ capture and separation technologies

To prevent the ongoing rise of global warming, it is crucial to reduce the concentration of greenhouse gases in emissions from power plants, mainly carbon dioxide. This can be done through various methodologies such as emitting less carbon dioxide or by specifically reducing CO₂ emissions. Many CO₂ capture and reduction technologies have been developed over the last few decades and various other CO₂ capture technologies are undergoing research to recapture the carbon dioxide produced and make it usable. (Kammerer et al., 2022)

3.1.1 CO₂ capture methods

The capturing of carbon dioxide in power plants is done using various methods. The CO₂ separation systems can be divided into three different categories: Pre-combustion, post-combustion, and oxy combustion. These three strategies to capture the CO₂ emissions are described in the sections below.

Pre-combustion

Pre-combustion carbon capture refers to removing CO₂ from gas mixtures before combustion. This is a process in which the fuel is oxidized using a gasification process which involves the production of syngas with a composition of hydrogen (H₂) and carbon monoxide (CO). The produced CO is converted into CO₂, which is captured before combustion. (Feron & Hendriks, 2005) In a subsequent shift reaction, the CO interacts with the steam to produce more H₂ and CO₂. The CO₂ is then separated, typically through a physical or chemical absorption process, producing a stream that is hydrogen-rich and useful for a variety of devices, including boilers, furnaces, gas turbines, motors, and fuel cells. Pre-combustion capture allows for the use of physical solvent for CO₂ removal, which uses a lot less energy than post-combustion capture due to the greater CO₂ concentration and pressure. (Meyer & Rubin, n.d.)

Gasification, partial oxidation, or steam reforming technology are all options for turning fossil fuels into syngas. For solid fuels, partial oxidation is most frequently used, for liquids partial oxidation, and for vapours steam reforming. An example of this technology is the integrated coal gasification combined cycle facility.
Shijaz et al. in their work performed a comparison between the power generation using coal gasification without a CO₂ capture system, pre-combustion CO₂ capture system. The results from their work showed that the overall efficiency of a power plant with pre-combustion carbon capture is reduced when compared to a power plant without CO₂ capture. It is further explained that the CO₂ captured from the fuel prior to burning in a combustor reduces the fuel volume sent to the turbine which results in the reduction of power generation.

However, due to the environmental implications of CO₂ emissions, including a CO₂ capture system in a power plant is inevitable. (Shijaz et al., 2017)

This procedure is expensive because of the fuel conversion. Hence it is ideal for implementing this CO₂ capture system in new power plant projects. (Meyer & Rubin, n.d.)

**Post-combustion**

The separation of CO₂ from flue gas created by the combustion of biomass, fossil fuels or waste is the basic principle for post-combustion capture. There are two major steps in post-combustion processes. A power-generating energy conversion comes first, then a CO₂ separation procedure that results in the creation of a concentrated stream of CO₂. (Feron & Hendriks, 2005) Integrated pollution control and waste management systems are additional post-combustion technology requirements for both retrofits and new power stations. Many CO₂ capture and storage projects are being developed globally, and post-combustion carbon capture has been applied on a large scale in these projects.

Using physical or chemical adsorption/absorption mechanisms, the post-combustion CO₂ capture approach can remove CO₂ and other gases from burning fossil fuels or biomass resources. Adsorption, absorption, membrane separation, and chemical processes are the classifications that can be made based on the principles of the capture process.
Although post combustion hasn't been completely considered in big power plants, the most popular post combustion process involves an absorption process using amine-based solvents.

Because of the large volume of gas at low CO$_2$ concentration that needs to be handled, the post-combustion capture method using the amine scrubbing process has the disadvantage of requiring big equipment sizes, which results in high capital costs. The substantial energy needed for solvent regeneration is a major hurdle for this technique. This heat typically comes from the steam cycle, which significantly lowers the power plant's overall efficiency. (Liang et al., 2011)

Based on the foregoing, it is necessary to enhance the existing solvents or create new solvents that could lower the capital expense and energy penalty of post-combustion capture. Integrated pollution control and waste management systems are additional post-combustion technology requirements for both retrofits and new power stations.

The power plant output such as the flue gas flow rate and its composition, and the steam rate supplied by the steam cycle, are constantly changing which are a result of the demands of the power grid, so controllability of the post combustion process is crucial. These factors will unquestionably have an impact on how a CO$_2$ capture facility operates.

**Oxy fuel combustion**

One of the top technologies being explored for CO$_2$ capture from power plants with CCS is oxygen fuel combustion. Instead of using air for the combustion of the fuel, this method uses almost pure oxygen. A portion of the flue gas is recycled back into the burner or boiler to regulate the flame temperature.
The primary goal of using this technology to capture CO₂ from a power plant is to produce a flue gas with a high concentration of CO₂ and water vapor. The CO₂ is then separated from the flue gas by dehydration and low temperature purification processes.

The following main units make up oxyfuel combustion for electricity generation: (Stanger et al., 2015)

- Air Separation Unit – oxygen production
- Boiler – combustion of fuel and generation of heat
- Flue Gas Processing Unit – flue gas cleaning
- CO₂ Processing Unit – Purification of the CO₂ for transportation and storage

The supply of oxygen must be made at high pressure, and various cycles are presently being examined. Only a few projects are presently underway or are about to be commissioned for larger scale tests of the technology, which is currently being developed at a small pilot scale. The upcoming decade will be crucial for oxyfuel technology to build on this foundation and demonstrate its viability on a large scale. Technical readiness, financial incentives, political will, and public acceptance of CCS will eventually decide its viability as a CO₂ mitigation technology. (Stanger et al., 2015)

Oxy-fuel's biggest obstacle is reducing the energy penalty and, consequently, the penalty cost associated with producing significant amounts of oxygen. It is anticipated that the operating, maintenance, and capital expenses of this emerging technology will be comparable to those of post-combustion technology. Another significant issue is that the oxy-fuel combustion process necessitates significant modifications to combustion equipment and materials because the equipment and materials are currently configured and cannot function at high temperatures.
3.1.2 CO₂ separation technologies

Systems for capturing CO₂ currently employ a number of well-known techniques for gas separation, including adsorption, membrane separation, cryogenic separation, physical and chemical absorption. The following parts provide a brief summary of these separation techniques.

Adsorption

Adsorption is a CO₂ separation technique employed in industry primarily for the recovery and purification of gases, i.e., the isolation of CO₂, H₂, and air. The process involves using molecular forces to cause vapor and gases to condense on the surface of a solid adsorbent, and it makes use of variations in the adsorption capacities of various components of the separated gas combination on a given adsorbent. (Czarnota et al., 2019)

The most widely used adsorbents are zeolite and carbon, which, when used to fill an adsorption tower, form an adsorption bed. At least two adsorption towers must be present for the process to be ongoing. Multi-bed systems are actually used in practice, which increases the process's efficiency. Through chemical or physical sorption, CO₂ is absorbed. (Czarnota et al., 2019)

Chemical absorption

Chemical absorption involves converting CO₂ from its gaseous state to its liquid state. A chemical reaction then takes place in the liquid phase, shifting the absorption balance in favour of the product, which is carbon dioxide linked to other substances. (Czarnota et al., 2019) Due to the low partial pressure of CO₂ in the exhaust gas, chemical absorption processes are presently the favoured method for post-combustion CO₂ capture. The CO₂ is taken during chemical absorption, where it then chemically reacts with the solvent. Processes involving chemical absorption can be used to remove CO₂ that is present at low concentrations (low partial pressure).

MEA, dietanoloamine, methylodietyloamine, and trietanoloamine are the most popular absorbents. (Shakerian et al., 2015) Despite some obvious drawbacks, MEA is the most widely used chemical sorbent due to its low purchase prices and availability. (Czarnota et al., 2019)

Physical absorption

Adsorption is a CO₂ separation technology that utilizes solids called adsorbents to capture CO₂ from gas streams. The CO₂ molecules adhere to the surface of these materials and can be released through desorption, usually by changing physical conditions such as temperature or pressure conditions. Rectisol is a methanol-based low-temperature physical CO₂ absorption method. The method was initially created for integrated gasification combined cycle and synthesis gas wash from sour components in facilities such as coal to liquids as well as coal to substitute natural gas.
The Rectisol process is flexible and can be set up to meet any particular requirements for the downstream product as well as the upstream syngas condition. It enables a variety of CO$_2$ and H$_2$S separation ratios. (Czarnota et al., 2019)

**Membrane absorption**

A membrane is a selective permeable barrier that separates components from the flue gas stream to the permeate at different speeds. (Czarnota et al., 2019)

The pace at which specific components diffuse from one side of a membrane barrier to the other is the basis for the membrane separation process. Due to the concentration difference, the CO$_2$ dissolves into the membrane and then diffuses through it. More suited to this technique are membranes with high selectivity and permeability for the component to be separated. Because membrane separation processes can be carried out continuously at room temperature, they can be used to separate materials that cannot withstand the circumstances of other processes, such as distillation or crystallization. Furthermore, it is not essential to use additional environmentally hazardous substances. (Czarnota et al., 2019)

**Cryogenic CO$_2$ capture**

Phase shift is used by Cryogenic CO$_2$ Capture to separate CO$_2$ and other pollutants from exhaust or process gases. Compression, cooling, condensation, and distillation are steps in the air separation process known as cryogenic distillation that can be used to separate CO$_2$ from other components and create liquid CO$_2$. (Czarnota et al., 2019)

### 3.2 Bioenergy conversion processes

Quereshi et al (Quereshi et al., 2020) explains how various renewable sources of energy such as solar, wind, hydropower and marine sources are capable of producing energy, they are unable to directly produce fuel and chemicals. Thus, cannot be considered as a complete replacement of fossil fuels. This is where Bio renewable energy resources show promising potential to produce energy and can be used to produce fuels and chemicals.

Biomass conversion technologies are processes and techniques which are used to convert organic material or biological matter into energy, fuels, chemicals, and products which can be utilised. These technologies can play a vital role in the reduction of greenhouse gas emissions and help promote sustainable energy production. They are trivial for the utilization of renewable resources efficiently. This section explains some of the key biomass conversion technologies that are implemented in power plants to convert biomass into energy.

#### 3.2.1 Biomass fired combined heat and power plant

A combined heat and power (CHP) plant is a type of power plant that generates both electricity and heat by the combustion of a common energy or a fuel source. (Mertzis et al., 2014)

(Thorin et al., 2015) explains that with the integration of heat and power production from a
combined heat and power plant, it is possible to use the energy source more efficiently. Additionally, this would result in the reduction of the environmental impact and in the substantial reduction of the CO₂ emissions. Furthermore, the CHP plant while producing electricity can also supply heat for the heating demand of residential buildings in regions with colder climates or can provide industrial process heat. A bio-CHP also known as biomass cogeneration plant, is a CHP plant that uses biomass as its fuel source.

The main components of a bio-CHP as described by (Rezaei et al., 2021) consists of feedstock receiving and preparation also known as biomass fuel handling, biomass conversion and power and heat production.

![Figure 4 Overview of a biomass plant](image)

**3.2.2 Biomass integrated gasification combined cycle power plant**

A method to resolve the challenges posed by a conventional steam boiler power plant is the addition of a gas turbine between the combustion and steam turbine. In natural gas fired power plants combining the gas turbine and steam turbine systems forms a combined cycle system.

(Yap, 2004) in their paper describe how the addition of a combined cycle system would result in higher efficiency, although fuel cleanliness is essential to extend the lifetime of a gas turbine. Since direct combustion of biomass fuel has its environmental consequences, gasification is necessary to provide gaseous fuel that can be used for combustion in a gas turbine. The combined cycle, flue-gas cleaning and gasification are the technologies that are integrated together to provide an environmentally sustainable, efficient, and highly reliable system. This is seen in the biomass integrated gasification combined cycle power plant. Contrary to conventional steam-boiler turbine system, where the exhaust gases are cleaned after the boiler or no cleaning performed at all, in biomass integrated gasification combined
cycle power plant the fuel is cleaned before entering the gas turbine system, resulting in the reduction of emissions, and increasing the efficiency of the facility.

The main four components of the biomass integrated gasification combined cycle power plant as described by (Yap, 2004) are fuel handling and feedstock, gasification through the gasifier, the gas clean-up unit (GCU), and the combined power system.

3.2.3 **Biomass anaerobic digestion biogas plant**

Biomass anaerobic digestion biogas plant which is also known as an anaerobic digester is a system that produces renewable energy by converting organic matter into biogas through a biological process called anaerobic digestion. Anaerobic digestion is a biological process in which biomass is converted to methane and CO₂ in the absence of oxygen with the help of microorganisms. Anaerobic digestion mainly consists of four major stages known as hydrolysis, acidogenesis, acetogenesis and methanogenesis (Fedailaine et al., 2015).

Fedailaine in their paper explains the steps involved in the process of anaerobic digestion, the first step which is the hydrolysis step is to make the substrate more soluble, this is done through extracellular enzymes excreted by certain bacteria, due to the lack of metabolism this is not a biological process. Acidogenic, acetogenesis and methanogenesis are metabolic steps where the organic substrate is consumed and converted by bacteria, and during this stage, the microorganisms convert the hydrogen and acetic acid to biogas.

The biogas which is produced from the anaerobic digestion can then be utilized to produce energy, the main steps involved in the Biomass anaerobic digestion plant are show in the figure,
3.3 Capturing CO₂ from bio-CHP plants.

3.3.1 Bioenergy with carbon capture and storage (BECCS)

A worldwide energy system transformation on a scale unprecedented since the industrial revolution is necessary to keep global warming well below 2 °C. In order to achieve this 2 °C objective, 87% of integrated assessment models choose to BECCS. The models predict that without BECCS, achieving the objective will either be impossible or significantly more expensive. Although there is a large amount of modelling research, there are few studies that examine how important climate policy actors evaluate and view BECCS. (Fridahl, 2017)

BECCS, however, is still in the early stages of creation. Estimates of storage capacity, the availability of biomass, conflicts with objectives for biodiversity and food security, prices and financing options, and competition for land, fertilizer, and water are all subject to substantial uncertainty. (Fridahl, 2017)

3.3.2 Integrating CO₂ capture in bio-CHP plant.

Shahbaz et al. reviewed and analysed the status and potential of integrating CO₂ capture with different biomass conversion processes, including combustion, gasification, pyrolysis, and liquefaction (Shahbaz et al., 2021). It was concluded that the combustion process within combined heat and power (CHP) plants shows great opportunities for the commercial operation of BECCS. Integrated CO₂ capture in a bio-CHP plant refers to the integration of CO₂ capture technology to capture the CO₂ emissions emitted during the combustion of biomass for electricity and heat generation.

This process is aimed at reducing greenhouse gas emissions and mitigating climate change while utilizing a renewable source of energy as its fuel, in this case biomass. Biomass and waste are commonly used as fuel for CHP plants (Anca-Couce et al., 2021) especially in northern Europe.
Therefore, integrating BECCS with bio-CHP and waste fired CHP plants is a promising solution to reduce CO₂ emission and its reduction potential is huge.

The integrated CO₂ capture in biomass fired CHP plant can be divided into two major parts, the biomass fired CHP plant and the CO₂ capture system. The energy generation takes place in the biomass fired CHP plant due to the combustion of biomass which results in the emission of flue gas which is rich in CO₂ which then is captured using the CO₂ capture system. The CO₂ capture system is dependent on the power plant for reboiler heat which is obtained from the extracted steam after the energy generation takes place from the turbine. The figure below is a schematic representation of the integrated CO₂ capture in biomass fired plant.

![Figure 7 Overview of a CO₂ capture system integrated in a Biomass CHP plant](image)

### 3.3.3 Amines based chemical absorption

In the gas processing industry, amine scrubbing technology for CO₂ separation has been used for decades and is regarded as the most effective method for large-scale post-combustion CO₂ capture. (Rochelle, 2009)
Due to its commercial availability, cheap cost, quick absorption rate, and extensive experience in industrial applications, MEA is the most common solvent in the early stages of post combustion CO\(_2\) capture in power plants. Despite MEA being generally regarded as a benchmarking amine solvent, its high capital cost and ancillary energy consumption still prevent the widespread use of MEA-based post combustion CO\(_2\) capture. (Luis, 2016b)

However, the high energy requirements for solvent regeneration and solvent degradation make this technique for CO\(_2\) capture from power plants difficult to implement. Through chemical processes in the absorption column, the solvent, such as amine solution, aqueous ammonia, and carbonate, removes CO\(_2\) from the gas stream.

When it comes to their physical, chemical, and sorbent properties, the specific amines vary greatly from one another. Because of the complicated amine characteristics, choosing the correct sorbent can be challenging. Primary amine circulation in the system is reduced as a consequence of the higher reaction rate of primary amines compared to tertiary amines. (Czarnota et al., 2019)

**3.4 Dynamic modelling and simulation of CO\(_2\) capture**

**3.4.1 Steady state modelling**

Steady-state simulation is important for the design and simulation because it helps realize the processes involved in the CO\(_2\) capture system. These processes which occur in steady state can be used to realize the performance and definition of parameters involved in the CO\(_2\) capture system. Steady-state studies for the MEA process usually consider the performance of CO\(_2\) capture process at a constant output of flue gas from the power plant. Additionally, the steady state model would be a foundation to develop the dynamic model which will be utilized to implement the control strategies.

In a steady-state system, certain key variables remain constant over time, and the system is not experiencing significant changes or fluctuations. This is essential to calibrate, define the simulation environment and define the composition and chemistry of the components involved in the different processes in the system.

**3.4.2 Dynamic modelling**

Dynamic simulation has become an increasingly important tool in the recent years to analyse and develop the various industrial processes for multiple reasons: defined operability studies, analysis of startup and shut-down procedures, efficient operability studies and process optimization. Additionally dynamic simulation is the basis for the design and implementation of control strategies and observe their behaviour with respect to time and fluctuations in the parameters in the system.
The dynamic process model must sufficiently characterize the transient behaviour in order for steady state validation to be effective. Key process information, such as reaction performances, plant reaction time, and process dynamics such as plant response to disturbances in process can only be obtained from dynamic simulations. Therefore, in order to obtain credible plant performances and results it is important for dynamic simulations to be studied and optimized based on disturbances with respect to time.

The dynamic model should ideally be validated with multiple sets of dynamic data describing various types of dynamic behaviour in order to guarantee that the results of the dynamic model are reliable for a broad variety of conditions. To study disturbances in the process operations such as flue gas fluctuations due to flow rate changes or fluctuations in the heat produced for the reboiler the knowledge of the dynamic process behaviour is required.

In recent years the study of plant behaviour and simulations are performed in various dynamic simulation software such as ASPEN Dynamics, ASPEN HYSYS and MATLAB.

3.4.3 Control strategies

As mentioned above, the importance of dynamic modelling in simulating plant behaviour while exposed to disturbances in key parameters is essential to gauge the performance of the plant. The key performance indicators need to be studied and control strategies need to be implemented accordingly. Control strategies are implemented through the following steps:

(1) Defining control variables: The control variables are the process variables such as temperature, pressure, and flow rates that are needed to control to achieve the desired process objectives.

(2) Selection of controller types: Proportional-Integral-Derivative (PID) controllers are a type of controller that can be used for the control of the process variable chosen.

(3) Control Strategy Design: The design of control strategies involves specifying setpoints for the control variables and configuring the controllers to obtain the desired output.

Finally, (4) Controller Tuning: Tuning is the process of optimizing controller parameters to ensure stable and responsive control.

3.4.4 PID controller

A PID controller is a type of feedback control system. It is widely known both in engineering and industrial applications and is used in order to regulate a great variety of structures and procedures. The shortened form PID stands for Proportional, Integral, and Derivative, which are the three terms used to describe the three fundamental control actions utilized by a PID controller in order to maintain a particular setpoint during a process.

The following is an explanation of the terminologies and essential elements of PID controllers:

Process Variable (PV):

The process variable, frequently shortened to PV, is the parameter or variable that we want to manage or regulate within a structure or procedure. It represents the current condition or
metrics of the system, such as temperature, pressure, speed, level, or any other quantifiable characteristics.

**Setpoint (SP):**

The targeted or goal value for the process variable is known as the setpoint, which typically appears as SP or reference value. It stands for the objective or target value at which we wish to keep the process variable. The PID controller's task is to manage the control output in order to achieve and maintain a process variable as close to the setpoint as possible.

**Output Variable (OP):**

The output variable, often denoted as OP or control output, is the signal generated by the PID controller that is used to control the system or process. It is the action the controller takes to adjust the process variable.
4 CURRENT STUDY

4.1 Case study: key influencing factors from bio-CHP plant

Flue gas flow rates and composition of the flue gas in the biomass CHP plant vary due to various factors like feedstock quality and load demands. These fluctuations occur due to variations in the biomass feedstock quality, load demands, and combustion efficiency.

Biomass Feedstock: The quality, composition and moisture content of the biomass feedstock can vary significantly. This affects the combustion efficiency and the flue gas composition and flow rates. Load Demands: Due to variations in the power demand, biomass CHP plants need to adjust their power generation and heat production. These adjustments result in fluctuations in combustion conditions. Hence, resulting in variations in the flue gas composition and flow rates. Combustion Efficiency: Factors such as boiler performance, air-to-fuel ratios, and temperature control can impact the efficiency of the combustion process and, subsequently, flue gas characteristics. These fluctuations can adversely affect the performance of the CCS system, which leads to reduced capture efficiency and increased operational costs.

Data treatment

The flue gas composition and the input parameters which influence the performance of the CO$_2$ capture system were provided by Mälarenergi, because this research paper is within the collaboration with Mälarenergi. The data provided over various time steps and has various input parameters and hence needs to be treated to selectively chosen based on the relevance of the scope of this research paper.

The data used for this report is from the month of May 2020. The average daily flue gas compositions are derived from the data provided and analysed for each case before the implementation of controllers and the control strategies.

Implementing PID controllers in the carbon capture system of the bio-CHP plant is an effective strategy for mitigating variations of flue gas fluctuations. The implementation of the controllers provides precise control over critical parameters which results in improved efficiency of the CCS. This case study demonstrates the feasibility and benefits of employing efficient control strategies using PID controllers in bio-CHP plants with CCS systems. To implement efficient control strategies, it is important to analyse different cases with different parameters that need to be controlled. The following cases describe the fluctuations in the flue gas characteristics based on the data provided from the literature review and the data treated. A case study is essential to understand the behaviour of the input parameters on the CO$_2$ capture process.

As previously mentioned, it is essential to understand and analyse the response of the MEA absorption process over a function of time due to the change in the flue gas flow rate. This case study was performed to approach the dynamic behaviour of this process when there is a change in the flue gas flow rate and CO$_2$ vol% over a period of time which is typically observed.
on a periodic basis in the power plant flue gas outputs. The fuel for bio-CHP plants mainly consists of household waste, industrial waste, and recycled wood. FG data collected from a real bio-CHP plant from 2020/01/1 to 2020/05/31 are used as input for simulations, which are illustrated in the figures which show the variation in the flue gas flow rate and CO$_2$vol% respectively.

The data collected for the month of May is used as an input for simulations as the FG data for the month of May shows the highest amount of significant fluctuations in the FG data when compared to that of the data obtained for other months in this period. Hence using the data for the month of May as input simulations would help analyse the performance of the control strategies implemented in the presence of such fluctuations in the FG data, the advantages of the results obtained from the simulations which are performed on the input data from the month with higher fluctuations in FG data can be used as a reference while designing a control system for the overall system.

![Figure 8 Variation of Flue gas flow rate from May 1st, 2020, to May 31st, 2020](image)

![Figure 9 Variation of Flue gas CO2 vol % rate from May 1st, 2020, to May 31st, 2020](image)

In general, the variation of flue gas flow rate and CO$_2$vol% ranges from 235.07 ton/h to 490.94 ton/h and 7.6 and 14.98 volume percentage respectively. The average values of the
flue gas flow rate and the CO$_2$ vol% are taken as the initial base case conditions which are 315.15 ton/h and 12.3 volume percentage respectively. Depending on the availability of data, either real data or fabricated data are used as inputs. For Case 1 to Case 3, it is assumed that there is always enough heat in the reboiler. Harun (Harun et al., 2012) found that the dynamic variations in the operation were different for the decrease and increase of the FG flowrate. Considering the workload for calculation, simulations are performed for a period of 7 hours. To achieve the best possible control strategies and understand the influence of high flue gas variation flow rates the study will only concentrate on the increasing aspects of flue gas characteristics. Due to the workload which is a result of the high input values the 7-hour period is chosen after various attempts with different time frames, the 7-hour time frame enables for better accuracy of results and stable simulation runs without any compromise on the quality of results and ensures that the simulations are smooth. The simulations for a period of 7 hours is divided into 3 parts, the first 1 hour is for the system to reach stability after the input of the initial FG parameters, then a ramp up of 2 hours is chosen for the system and then the remaining 4 hour is to observe both the control performance and the system performance. The 2 hours ramp up period is chosen to analyse the impact of the implementation of the controllers on the system performance, it is also essential to observe and compare the performance of the different control approaches within the ramp up time frame. The 2 hours is adequate amount of time for the system to implement the ramp up and for the controllers to then function after the ramp up is implemented.

4.1.1 Case 1: Fluctuation of flue gas flowrate

The maximum flue gas flow rate which the plant attains over the month of May can be seen to be 490949.3 kg/h and the minimum flue gas flow rate is 235070.6 kg/h from figure 8. This gives us an idea about the maximum peak and the minimum peak the CO$_2$ system might be exposed to and provides us with the range. The average flue gas flow rate is taken for this study which is 315152 kg/h. The following figure 10 shows the ramp percentage increase in the flue gas flow rate to determine the performance of the controller that is to be implemented in the system. A 30% increase in the flue gas flow rate is chosen where the flue gas flow rate increases from 315152 kg/h to 409697 kg/h for a period of 2 hours. The CO$_2$ vol% is taken as the average which is 12.3%. The CO$_2$ vol% in this case is assumed to be constant because the CO$_2$ volume percentage is not constant in actual plant data. It also assumed that there is always enough heat in the reboiler.
4.1.2 Case 2: Fluctuation of CO\textsubscript{2} content (CO\textsubscript{2} vol\%) in flue gas

From figure 9 the minimum CO\textsubscript{2} vol\% output data in May was measured at 7.67261982, while at its highest point the CO\textsubscript{2} vol\% output data reached 14.98857377. These measurements provide us with an average value which is 12.3 \%, and therefore the value range that can be expected. A 30\% increase is introduced for a duration of 2 hours where the CO\textsubscript{2}vol\% increases from 12.3 \% to 16\% to determine the performance of the plant under the variation of the CO\textsubscript{2}vol\%. The figure 11 illustrates the ramp up increase used for the case 2. The flue gas flow rate is assumed to be constant at 315152 kg/h as the as the flue gas flow rate is always changing when it leaves from the bio-CHP plant. It also assumed that there is always enough heat in the reboiler.
4.1.3 Case 3: Fluctuation of both flowrate and CO₂ vol % in flue gas

The Case 3 is a combination of both flue gas flow rate and flue gas CO₂ vol% to study the impacts of the disturbances of the flue gas characteristics on the performance of the system. The figure 3 illustrates a more realistic flue gas input as obtained from a bio-CHP plant where the composition and flow rate both change over time. The case 3 also gives us an indicator on how the system with the control strategies behaves in a setting where the flue gas characteristics change over a period of time. A 30% increase in the flue gas flow rate is chosen where the flue gas flow rate increases from 315152 kg/h to 409697 kg/h for a period of 2 hours with a simultaneous increase in the CO₂ vol% from 12.3% to 16% for the ramp up duration of 2 hours.
4.1.4 Case 4: Fluctuation of available heat for reboiler

The reboiler heat duty is essential for the solvent heat regeneration process. The available heat in this case increases from the base value as shown in the figure 13. Due to the lack of data provided from the bio-CHP plant, the base value for the reboiler heat is assumed from the model development process to achieve 90% removal rate, which is 560 GJ/h after which the ramp up increase by 30% is implemented to study the impacts of the change in reboiler heat on the performance of the system. The ramp up increase is implemented for a period of where the reboiler heat increases from 560 GJ/h to 728 GJ/h.

4.2 Model development and validation

CO₂ post-combustion capture using MEA.

Using amine aqueous solutions, CO₂ post-combustion is captured through reactive absorption-solvent regeneration method. The plant can be divided into two major parts: the absorption, which moves carbon dioxide from the vapor phase to the liquid, and the stripping, which regenerates the solvent.

The reaction between the solvent and the CO₂ transmitted in the liquid phase specifically helps the absorption process. The opposite reaction, however, takes place in the stripper to separate the amine from the CO₂, which is then returned to the atmospheric phase. A cross heat-exchanger links the two parts together. (Madeddu et al., n.d.)

A simplified flowsheet of the system is shown in figure 14.

The absorber's bottom is where the CO₂-rich flue gas enters and moves against the direction of the liquid solvent. The discharge gas leaves the top of the column after the absorption process is complete, and after solvent recovery, it is sent to the stack. The cross heat-
exchanger heats the rich liquid before pumping it to the top of the stripper, which is located at the bottom of the absorber.

Figure 14 Simplified flowsheet of a CO₂ capture by reactive absorption-stripping plant

The liquid in the second section of the CO₂ capture system the liquid moves in opposition to the vapor flow produced by the reboiler. A gaseous combination of carbon dioxide and water is introduced from the top of the stripper to a partial condenser, where the CO₂ is concentrated in the gas phase before being compressed, while the water is recovered in the liquid phase. The regenerated solvent is then sent from the bottom of the stripper to the heat-exchanger, where it gives the rich solvent its sensible heat before being recycled back to the absorber’s top. The two columns are typically packed ones rather than plate ones because packing can increase the contact area between the gaseous and liquid phases and reduce pressure loss.

4.2.1 Steady state simulation in Aspen Plus

As explained in the previous section, there are various components that comprise of the standard CO₂ post-combustion capture using amine aqueous solutions. The scope of the current research is condensed into studying the behaviour and control of the absorber and the stripper column, hence, to reduce computational time of the simulation which also use various key influencing factors and solely concentrate on the effects of these key parameters this study concentrates only on the model development and study of the absorber and the stripper column. The process flow for steady state modelling and simulation is further explained below. The CO₂ post-combustion capture using amine aqueous solutions consists of a definitive reactive absorption-solvent regeneration process which consists of two main processes which can be further classified as: the absorption section, where the CO₂ is transferred from the vapor/gas phase to the liquid one with the help of the lean solvent, and the stripping section, which involves the solvent regeneration process.

To further explain this, the absorption process is occurring due to the reaction between the CO₂ in the flue gas flow into the absorber and the solvent, and the reverse reaction happens
in the stripper to strip the rich amine from the CO₂ which is then transferred to the gaseous phase.

**Steady state modelling in Aspen Plus®**

Aspen Plus® from Aspen Tech is one of the most widely used steady-state process modelling and simulation software in process and chemical engineering. As explained in the previous section, the CO₂ post-combustion capture using amine aqueous solutions consists of a reactive absorption and stripping process. Aspen Plus® is the ideal software to simulate and study this process which can be modelled using the RadFrac™ model, which enables users to model absorbers and strippers with chemical reactions.

The following sections describe the modelling essentials used for the steady state simulation.

**Thermodynamics and kinetics**

ENRTL-RK, the electrolyte-non-random-two-liquid-based thermodynamic package is used to describe the thermodynamics in the CO₂ capture process. It is beneficial to run dynamic simulations and steady state simulations due to the electrolyte solutions used in the MEA absorption process and computation of vapor properties. (Madeddu et al., n.d.)

The chemistry used for the model development is represented by the equations given below, where the equation 1-7 are equilibrium reactions.

These reactions have been widely used in the study and modelling of CO₂ capture plants in research papers such as (Lin et al., 2010) and (Salvinder et al., 2019)

1. **Equilibrium** 2.0 H₂O ↔ H₃O⁺ + OH⁻
2. **Equilibrium** CO₂ + 2.0 H₂O ↔ HCO₃⁻ + H₃O⁺
3. **Equilibrium** HCO₃⁻ + H₂O ↔ CO₃²⁻ + H₃O⁺
4. **Equilibrium** MEAH⁺ + H₂O ↔ MEA + H₂O⁺
5. **Equilibrium** MEACOO⁻ + H₂O ↔ MEA + HCO₃⁻
6. **Equilibrium** H₂S + H₂O ↔ HS⁻ + H₃O⁺
7. **Equilibrium** HS⁻ + H₂O ↔ S²⁻ + H₃O⁺

**Components**

The specification of components is essential to study the behaviour of chemical reactions that occur in the process that is to be modelled. The two phases that are involved in the modelling process are gaseous and liquid. The gaseous phase, nitrogen, oxygen, and water vapor are present together with CO₂. This specific case also consists of the presence of other components such as H₂S which are the impurities in the flue gas. (Cau et al., 2014)
Alongside MEA which is used as the target solvent for the absorption process, other components in the liquid phase comprise of CO$_2$- H$_2$O-Amine which is characterized by the presence of ions due to their ionic dissociation.

**Feed streams characterization**

The stream characterization is done by providing various parameters such as the temperature, pressure, flow rate which is provided in mass flow and the composition which is provided in mole fraction. The specification is done only through the apparent composition of the main components, which as discussed previously are CO$_2$, MEA, and H$_2$O. The compositions of the ions are determined by Aspen Plus® after solving a system of equations that includes the equilibrium reactions defined earlier. It is also assumed that other pollutants such as (SO$_2$, NOx, etc.) have been removed and will not be studied and they are not considered because they don’t change the behaviour of the capture process and can be negated. The characterizations of the main streams Flue gas and Lean solvent that are used in this research study are provided in the tables below,

The initial stream characterization for flue gas flow is given in the table below,

**Table 1 Stream characteristics for flue gas flow**

<table>
<thead>
<tr>
<th>FLUE GAS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>45.2 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>114,325 kPa</td>
</tr>
<tr>
<td>Total Flow Rate</td>
<td>315152 kg/hr</td>
</tr>
<tr>
<td>H$_2$O Mole-Fraction</td>
<td>0.01</td>
</tr>
<tr>
<td>CO$_2$ Mole-Fraction</td>
<td>0.123</td>
</tr>
<tr>
<td>N$_2$ Mole-Fraction</td>
<td>0.677</td>
</tr>
<tr>
<td>O$_2$ Mole-Fraction</td>
<td>0.182</td>
</tr>
</tbody>
</table>

The initial stream characterization for lean solvent flow is given in the table below,

**Table 2 Stream characterization for lean solvent flow**

<table>
<thead>
<tr>
<th>LEAN SOLVENT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>40.2 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>107,325 kPa</td>
</tr>
<tr>
<td>Total Flow Rate</td>
<td>528100 kg/hr</td>
</tr>
<tr>
<td>H$_2$O Mole-Fraction</td>
<td>0.86</td>
</tr>
<tr>
<td>CO$_2$ Mole-Fraction</td>
<td>0.01</td>
</tr>
<tr>
<td>N$_2$ Mole-Fraction</td>
<td>0</td>
</tr>
<tr>
<td>MEA Mole-Fraction</td>
<td>0.11</td>
</tr>
</tbody>
</table>

**Equilibrium RadFrac™ model**
To simplify the calculation and simulations that are to be studied in this research the equilibrium stages model is preferred over the rate-based model as Aspen Plus® requires equilibrium stages model to be able to transfer the steady state model to a Dynamic one. This is a certain shortcoming of Aspen Plus® as the equilibrium stage approach is often inadequate to study the actual behaviour of the CO₂ capture system due to the presence of intricate material transfer and rate changing chemical reactions but enables us to run simulations more smoothly. The equilibrium stages approach assumes that the liquid and the gaseous phases are in intimate contact for sufficient time which enables for thermodynamic equilibrium between the streams exiting each stage of the RadFrac™ columns.
4.2.2 Dynamic simulation in Aspen Plus Dynamics

The dynamic model for the CO₂ capture system was developed by converting the steady state simulation developed into a dynamic simulation using a pressure driven dynamic simulation in Aspen Plus® and convert it to an Aspen Plus® dynamics model. In order to achieve the targets such as removal rate and capture rate, 3 integral controllers have been integrated into dynamic model which are shown in figure 15 with green lines. The control implementation is explained in the next section.

The time control parameters such as time communication, display updates and time now are added to the simulation to make the simulation responsive to the time steps which are added after data treatment.

![Figure 15 Controller implementation in dynamic model](image)

4.2.3 Control implementation

This section explains the development and implementation of a control strategy to maintain the operation of the CO₂ capture process while it is exposed to disturbances which arise due to the fluctuations from the bio-CHP plant in the form of fluctuations from the flue gas flow rate, changes in the CO₂ vol% and the changes in the heat supplied to the reboiler.

As explained and understood from the case study and the data analysis, the CO₂ capture process is an inherent dynamic system that is affected by the fluctuations that occur due to the functioning of the bio-CHP plant. The objective is to develop and implement a decentralized control configuration that enables the system to maintain CO₂ absorption rate and the reboiler temperature while it is exposed to disturbances.

Figure 15 depicts the control structure for CO₂ capture process in this study. The green line represents the control signal that carries the respective signals from components of system to the controllers which in this system are the ratio controller and the PID controller.
The control structure is directly dependent on the manipulated variable and the controlled variables. The controllers used in this study have the following manipulated and control variables displayed in the table below.

<table>
<thead>
<tr>
<th>Controller name</th>
<th>Lean solvent flow controller</th>
<th>Reboiler duty controller</th>
<th>Rich solvent flow controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller type</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
</tr>
<tr>
<td>Controlled variable</td>
<td>Removal rate</td>
<td>Stage reboiler temperature</td>
<td>Rich loading</td>
</tr>
<tr>
<td>Setpoint</td>
<td>10%</td>
<td>119.5°C</td>
<td>0.129 mol/mol</td>
</tr>
<tr>
<td>Manipulated variable</td>
<td>Lean solvent flow</td>
<td>Reboiler Specific heat duty</td>
<td>Rich solvent flow</td>
</tr>
</tbody>
</table>

The ratio controller is used to calculate the ratio between the \( \text{CO}_2 \) flow rate from the outlet vent gas and the \( \text{CO}_2 \) flow rate in the flue gas inlet of the system. The percentage of \( \text{CO}_2 \) absorbed is determined by simultaneously measuring the ratio between the \( \text{CO}_2 \) flow rate in the vent gas and the \( \text{CO}_2 \) flow rate in the flue gas. This is the desired \( \text{CO}_2 \) capture rate that is defined to maintain the \( \text{CO}_2 \) absorption of the \( \text{CO}_2 \) capture system. The ratio of \( \text{CO}_2 \) flow rate is calculated with the help of the ratio controller, and it is used as an input for the Set point SP of the PID controller. The SP of the PID controller is then used by the PID controller to manipulate the Process variable so that the \( \text{CO}_2 \) capture rate is maintained near the Set point value.

As shown in table 3 the control variable for the lean controller is set as the removal rate which is 0.1 and the manipulated variable is the lean solvent flow rate which is manipulated to achieve the specified control variable. Similarly, for the reboiler duty controller the control variable is specified to be the stage reboiler temperature which is set at 119.5 degrees C and is to be used as the set point by the controller to manipulate the specific heat duty of the reboiler, which is the manipulated variable.

The Rich solvent flow controller as shown in the table 3 manipulates the rich solvent flow entering the stripper based on the rich loading value which is 0.129 mol/mol. When the reboiler duty changes the controller manipulates the rich solvent flow to provide for the target rich loading which exits the reboiler of the stripper column.

**Controller tuning**

Controller tuning is performed to adjust the parameters of the control system, in this work the PID controllers are tuned to optimize the performance of the system being controlled. The goal of control tuning is to ensure that the control system can effectively regulate the process variable and maintain it as close as possible to the desired setpoint SP while minimizing undesirable effects like overshoot, settling time, and steady-state error.
The control tuning is also used to compare the system performance while comparing it to a controller which is not tuned. Hence, providing better control strategies. The following tables 4, 5 and 6 show the controller tuning parameters used.

**Table 4 Controller characteristics for Lean solvent Flow controller**

<table>
<thead>
<tr>
<th>Controller type</th>
<th>General settings</th>
<th>Fine tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>1%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Time</td>
<td>20 min</td>
<td>0.26 min</td>
</tr>
<tr>
<td>Derivative time</td>
<td>0 min</td>
<td>0 min</td>
</tr>
</tbody>
</table>

**Table 5 Controller characteristics for Reboiler duty controller**

<table>
<thead>
<tr>
<th>Controller type</th>
<th>General settings</th>
<th>Fine tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>1%</td>
<td>305%</td>
</tr>
<tr>
<td>Time</td>
<td>20 min</td>
<td>0.27 min</td>
</tr>
<tr>
<td>Derivative time</td>
<td>0 min</td>
<td>0 min</td>
</tr>
</tbody>
</table>

**Table 6 Controller characteristics for rich solvent flow controller**

<table>
<thead>
<tr>
<th>Controller type</th>
<th>General settings</th>
<th>Fine tuning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>1%</td>
<td>12.8%</td>
</tr>
<tr>
<td>Time</td>
<td>20 min</td>
<td>8.58 min</td>
</tr>
<tr>
<td>Derivative time</td>
<td>0 min</td>
<td>0 min</td>
</tr>
</tbody>
</table>

**Model validation**

For the validation of the model the Key process parameters for steady state case, the data is chosen from the August 2016 test campaign at the UKCCSRC PACT pilot plant. This data is obtained from the research of (Bui et al., 2018) and the mode is validated using the temperature in the absorber from the bottom of the absorber height.

**Table 7 Model validation parameters obtained from UKCCSRC PACT pilot plant**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Case A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas flow rate (Nm3 /h)</td>
<td>199.2</td>
</tr>
<tr>
<td>Feed flue gas CO₂ concentration (vol%)</td>
<td>12.3</td>
</tr>
<tr>
<td>Lean solvent flow (kg/h)</td>
<td>974.3</td>
</tr>
<tr>
<td>Absorber solvent inlet temperature (°C)</td>
<td>40.2</td>
</tr>
<tr>
<td>Absorber flue gas inlet temperature (°C)</td>
<td>45.2</td>
</tr>
<tr>
<td>Stripper solvent inlet temperature (°C)</td>
<td>100.5</td>
</tr>
<tr>
<td>Stripper pressure (kPa abs)</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Reboiler temperature (°C)</td>
<td>118.1</td>
</tr>
<tr>
<td>Lean CO₂ loading (mol CO₂/mol MEA)</td>
<td>0.129</td>
</tr>
<tr>
<td>Rich CO₂ loading (mol CO₂/mol MEA)</td>
<td>0.37</td>
</tr>
<tr>
<td>PACT plant CO₂ capture rate (%)</td>
<td>91.2</td>
</tr>
</tbody>
</table>

**Figure 16 Model validation for the model developed against the PACT pilot plant model**

The model validation results are displayed in the figure 16 as shown above where the developed model for this study is compared to the temperature in the absorber from the bottom of the absorber height. The validated curve shows some amount of deviation from the PACT pilot plant data because it was developed while using equilibrium stages model development parameters to perform dynamic simulations. Hence there is some deviation observed.

**Model scale up.**

To meet the requirement of large FG input and lean solvent flow rate due to the input parameters and the scope of this research where the studied waste-CHP has a higher FG flowrate than the case used for model validation, the CO₂ capture system needs to be scaled up.

The scale up for the composition of the lean solvent remains the same while the flowrate of the scales up lean solvent stream was estimated to be enabled for 90% CO₂ capture rate. The scale up of the lean solvent was done with the help of the Aspen Plus® design specification which utilizes the solver to estimate the target which in this case is 90% capture rate of CO₂ and
varying the lean solvent flow rate. The cyclic capacity and packing types are the same as those in the validated model as they don’t need to be scaled up.

Due to the required operational capacity and the dynamic simulations that need to be run, it is essential to scale up the components such as sump and the reflux drum of the absorber and the stripper to be able to hold up the streams entering the columns and for effective functioning. The dimensions of the absorber and stripper were estimated based on the method proposed by Otitoju. (Otitoju et al., 2023)

The scale up estimations were performed to calculate the diameter and height of the packed columns. The results are listed in the table below.

The estimated volume of the packed columns is determined based on a residence time of 10 minutes.

Table 8 Scaled up estimations for the components of the CO₂ capture plant.

<table>
<thead>
<tr>
<th>Component</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>Diameter: 8.7m; Height 17.4m</td>
</tr>
<tr>
<td>Stripper</td>
<td>Diameter: 4.3m; Height 10.9m</td>
</tr>
<tr>
<td>Reboiler</td>
<td>352m³</td>
</tr>
</tbody>
</table>

4.2.4 Key performance indicators

System performance

The amount of CO₂ captured indicates the overall performance of the CO₂ capture system. The controller implementation is done to target 90% CO₂ captured. The capture rate is calculated as the percentage of CO₂ obtained from the system at a given function of time and is the ratio of the CO₂ which exits the stripper after the stripping process and the CO₂ which goes into the system through the flue gas. The captured CO₂ is the CO₂ regenerated from the stripper and is shown in the equation where,

\[
\text{Captured } CO_2 = \int_{0}^{300} CO2_{product}(t)\,dt \quad (8)
\]

\[
\text{Heat duty} = \int_{240}^{300} Heat_{reboiler}(t)\,dt \quad (9)
\]

\[
\text{Energy penalty} = \frac{\int_{0}^{300} Heat_{reboiler}(t)\,dt}{\int_{0}^{300} CO2_{product}(t)\,dt} \quad (10)
\]

Heat duty is the consumed heat duty, Captured CO₂ (t) is the dynamic amount of captured CO₂ at the time t, ton/h; Heat_reboiler(t) is the reboiler duty at the time t, GJ/h; Energy penalty is the average reboiler heat duty per unit captured CO₂, MJ/kg. Captured CO₂ is the accumulated amount of captured CO₂ over the time t.

Control performance

Controller performance for PID (Proportional-Integral-Derivative) controllers which are the chosen controller for this research paper can be evaluated using several key metrics. Two
main controller performance metrics that can be implemented are settling time and maximum deviation. These metrics are used to assess the controller response to fluctuations in the input parameters such as flue gas flow rate and flue gas vol % in the system it is controlling.

The two important controller performance indicators are explained,

Settling Time (TS): Settling time is the time it takes for the Process variable PV to settle within a specified range of the desired setpoint after a step change in the setpoint. The settling time is estimated as the time it takes for the PV to attain the final steady-state value.

Maximum Deviation (MD): Maximum deviation is the measure of how far the process variable deviates from the desired setpoint during the transient response, specifically the maximum absolute difference.

Both these performance indicators can be studied by plotting the data with respect to time and comparing the deviation between the SP and the PV when there is some amount of disturbance in the system, in this case the disturbance is caused due to the fluctuation in the flue gas flow rate and CO₂ vol% in the flue gas.

To compare the control performance, two controller strategies are included. The performance without controllers is also included as the base case for comparison. They are defined below,

\[ CASE_{\text{without}} = \text{No controllers are implemented. Base conditions are used for the same.} \]

\[ CASE_{\text{general}} = \text{Control strategies are implemented but the controllers have the general settings.} \]

\[ CASE_{\text{tuned}} = \text{Control strategies are implemented with fine tuning curated to achieve the desired system performance.} \]

The tuning parameters are provided in table 4,5 and 6.
5 RESULTS

5.1 Case 1: Control under the fluctuation of flue gas flowrate

5.1.1 Control performance

The transient change achieved through different control strategies on the capture rate due to a 30% ramp up variation in the flue gas flow rate is illustrated in the figure 17, where the flue gas flow rate is increased for a period of 2 hours. The capture rate of the system without a control strategy implemented is observed to be the lowest whereas the capture rate of the system with the implementation of controllers is higher. When the capture rate of the tuned controller is compared with the capture rate of the system without any controllers it can be seen that the capture is higher by approximately 2%. The tuned controller shows better stability in maintaining the capture rate when compared to the controller with general settings implemented. It is also observed that the capture rate of CO₂ is higher in the controller which undergoes fine tuning compared to the controller with general settings, resulting in better capture rate performance overall.
The performance of the control strategies implemented on the reboiler duty of the system is shown in the figure 18, since there are no controllers to govern the reboiler duty in the CO$_2$ capture system without controllers the reboiler duty remains the same throughout the simulation time. While there is transient change in the reboiler duty where controllers are implemented. The controller which undergoes fine tuning, shows much higher consumption of reboiler duty, which is expected as the controllers are added to manipulate the reboiler duty to ensure stable stage temperatures in the reboiler. The reboiler duty curve is a steady increase when the system has controllers with general settings which showcases no stability in the reboiler duty and a constant increase is seen. Whereas the controller equipped with fine-tuned parameters showcases an increase in the reboiler duty throughout the ramp up increase which last for 2 hours and steadily maintains the reboiler duty once the flue gas flow rate is a stable 30% increased from its base value.

To further investigate the performance of the control strategies a comparison between the CASE$_{general}$ and CASE$_{tuned}$ is performed to determine the superior control strategy. The maximum deviation and the settling time for the two control cases are shown in figures 21 and 22.
Figure 18 demonstrates a rise in the reboiler duty, indicating an increase in the necessary work required to maintain the SP temperature. This is further highlighted in the Figure 19, where the SP is set at 119ºC. As expected, when there is a ramp increase in the flue gas flow rate, the reboilers workload increases in its effort to maintain the stage SP temperature of 119ºC. This reboiler duty increase in both the controller cases can also be seen in the figure 19.

The reboiler temperature control system is illustrated in the Figure 19 where the setpoint SP is established at 119.5ºC. In this setup with general controller setting, the process PV experiences a decrease in response to the optimization of reboiler duty necessary to uphold the SP input. This decrease is also seen to achieve maximum deviation from the set point to achieve a maximum deviation of 118.7 º C and struggles to attain stability over the period of the simulation but can be seen to be achieving stability towards the end of the simulation. Notable, it can also be seen with the fine tuning implemented the controller shows very high stability and the reboiler temperature is maintained at the SP as the PV doesn’t undergo a major change.
The change in the lean solvent flow is showcased in the figure 20, where over the course of 7 hours of the simulation as it can be evidently seen in the presence of controllers the lean solvent flow increases with the increase in the flue gas flow rate due to the functioning of the lean solvent flow controller.

The behaviour of the lean solvent control flow system under $CASE_{general}$ and $CASE_{tuned}$ is depicted in the figure 21. Here, the SP is configured to target the removal rate of $CO_2$ in the
absorber, ensuring that the absorber receives an adequate amount of lean solvent for CO₂ absorption. The PV, which is the variable adjusted to maintain the SP, deviates from the SP due to the increase in the flue gas flow rate and CO₂ vol%. As the PV increases, it showcases the maximum deviation it experiences before stabilizing at the setpoint. Due to the fine tuning which was implemented in tuning \(CASE_{tuned}\), the SP is finely tuned to target the removal rate of CO₂ within the absorber, ensuring that the absorber consistently receives a sufficient quantity of lean solvent to facilitate CO₂ absorption. The \(CASE_{tuned}\) in comparison to \(CASE_{general}\) showcases no deviation and has a near perfect value of the SP.

### 5.1.2 System performance

Table 9 Comparison of the system performance under different control strategies for Case 1

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Captured CO₂ (ton)</th>
<th>Reboiler Heat Duty (GJ)</th>
<th>Energy penalty MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CASE_{without})</td>
<td>384.8</td>
<td>3893</td>
<td>10.1</td>
</tr>
<tr>
<td>(CASE_{general})</td>
<td>386.3</td>
<td>4040.2</td>
<td>10.4</td>
</tr>
<tr>
<td>(CASE_{tuned})</td>
<td>389.3</td>
<td>4193.6</td>
<td>10.7</td>
</tr>
</tbody>
</table>

The calculated system performance for the different control strategy approaches used in Case 1 is showcased in table 9. Where the captured CO₂ for a simulation time of 7 hours is the highest for \(CASE_{tuned}\) with higher reboiler heat duty and energy penalty per unit captured CO₂. The increase in the reboiler duty is due to the reboiler duty control which manipulates the reboiler duty to maintain the reboiler temperature as a response to the increase in the flue gas flow rate. This increase in the reboiler duty results in the higher energy penalty per unit CO₂ captured. The amount of CO₂ captured also increases with the implementation of controllers and with the fine tuning of the controller as the controllers manipulate the lean solvent flow into the absorber with the increase in the flue gas flow rate to maintain the SP.

The percentage difference between the cases \(CASE_{without}\) and \(CASE_{tuned}\) was 1.1%, 7.7% and 5.9% for captured CO₂, reboiler duty and energy penalty respectively.
5.2 Case 2: Control for the fluctuation of CO₂ volume %

5.2.1 Control performance

The transient changes achieved through various control strategies in the capture rate of CO₂ due to a 30% ramp up variation in the flue gas CO₂ vol% is depicted in the figure 22. This variation involves a 2-hour period during which the flue gas CO₂ vol% increases.

The capture rate of the system without any implemented control strategy is observed to be a little higher in comparison to the capture rate of the system with controllers in place. When comparing the capture rate of the fine-tuned controller to the capture rate of the system without any tuning for the controllers, it becomes evident that the capture rate is approximately the same.

Furthermore, the fine-tuned controller demonstrates superior stability in maintaining the capture rate compared to the controller with general settings implemented. Notably, the controller that undergoes fine tuning exhibits a much more stable CO₂ capture rate when compared to the controller with general settings, resulting in stable capture rate performance.

Figure 22 Comparison of capture rate in different control strategies in Case 2
The performance of various control strategies on the reboiler duty within the system can be examined in the figure 23. In the absence of controllers governing the reboiler duty in the CO₂ capture system, the reboiler duty remains constant throughout the simulation period. However, when controllers are introduced, we observe transient changes in the reboiler duty. Notably, the controller undergoing fine tuning exhibits a lower consumption of reboiler duty. This outcome aligns with the predictions, as controllers are introduced to manipulate the reboiler duty in order to ensure stable stage temperature within the reboiler.

The reboiler duty curve takes on a distinct pattern when controllers are employed with general settings. It displays a steady decrease in the duty continues and the reboiler duty is much higher in contrast to the system when controllers are equipped with fine-tuned parameters where the reboiler duty is much lower. In the case of the fine-tuned control system the reboiler duty decreases steadily during the 2-hour ramp-up period and then declines even further once the flue gas CO₂vol% stabilizes at a 30% increase from its base value. This shows the controller controls the reboiler duty to do much lesser work to maintain the SP temperature.

This figure 23 highlights the effectiveness of controller tuning in achieving stable and controlled reboiler duty, contributing to the overall performance and stability of the CO₂ capture system. To further investigate the performance of the control strategies a comparison between the CASEgeneral and CASEtuned is performed to determine the superior control strategy. The maximum deviation and the settling time for the two control cases are shown in figures 24 and 25.
As shown in the Figure 23 which provides a visual representation of the decreased workload on the reboiler duty, which is essentially due to the lower work required to maintain the setpoint temperature of 119.5 °C, as detailed in Figure 23. As anticipated, when there is a gradual rise in the flue gas CO₂,vol%, the reboiler duty must decrease in order to effectively sustain the stage SP temperature at 119.5 °C. This reduced reboiler duty is evident in both controller cases, as illustrated in Figure 23.

Now, shifting our attention to Figure 24, it offers insights into the reboiler temperature control system, where the SP is set at 119.5°C. In the scenario with general controller settings in $CASE_{general}$, the process PV experiences an increase in response to the optimization of reboiler duty necessary to maintain the SP input. This increase in PV is also observed to reach its maximum deviation from the setpoint, registering a peak deviation of 119.7°C approximately, and it struggles to attain stability over the simulation period. However, toward the end of the simulation, some degree of stability is achieved.

On the other hand, it's noteworthy that with fine tuning implemented in $CASE_{tuned}$, the controller demonstrates remarkable stability, effectively maintaining the reboiler temperature at the setpoint. In this case, the PV undergoes minimal variation and does not experience significant deviations from the desired setpoint temperature.

This figure highlights the effectiveness of controller tuning in achieving stable and controlled reboiler duty, contributing to the overall performance and stability of the CO₂ capture system.
The comparison of lean solvent flow over the simulation period as shown in the figure 25, the implementation of controllers results in the manipulation of the lean solvent flow which is manipulated as a result of the control action. To further investigate the performance of the controllers of the lean solvent flow controllers we analyse the performance in the figure 26.

The behaviour of the lean solvent control flow system in two distinct scenarios: $CASE_{\text{general}}$ and $CASE_{\text{tuned}}$ is depicted in the figure 26. In both cases, the setpoint is configured to
regulate the rate at which CO₂ is removed in the absorber, ensuring that the absorber receives an optimal supply of lean solvent for effective CO₂ absorption.

In the : \textit{CASE}_{general} scenario, the process variable, which is adjusted to maintain the SP, deviates from the SP due to increase in the flue gas flow CO₂ vol%. As the PV increases, it demonstrates the maximum deviation it experiences before eventually stabilizing back at the setpoint. The maximum deviation is approximately 0.104 and the settling time is 3.5 approximately hours. In comparison the fine-tuning implementation results in precise adjustment of the SP to target the desired CO₂ removal rate in the absorber. This ensures that the absorber consistently receives an optimal quantity of lean solvent for efficient CO₂ absorption. In comparison to exhibits an absence of deviation and maintains a nearly perfect alignment with the SP, highlighting the effectiveness of tuning in achieving precise and stable control of the lean solvent flow system.

### 5.2.2 System performance

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Captured CO₂ (ton)</th>
<th>Reboiler Heat Duty (GJ)</th>
<th>Energy penalty MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{CASE}_\textit{without}</td>
<td>351</td>
<td>3893</td>
<td>11.1</td>
</tr>
<tr>
<td>\textit{CASE}_\textit{general}</td>
<td>350</td>
<td>3882</td>
<td>11.1</td>
</tr>
<tr>
<td>\textit{CASE}_\textit{tuned}</td>
<td>350</td>
<td>3871</td>
<td>11.06</td>
</tr>
</tbody>
</table>

The calculated system performance for the different control strategy approaches used in Case 2 is showcased in table 10. Where the captured CO₂ for a simulation time of 7 hours is the highest for \textit{CASE}_\textit{tuned} with higher reboiler heat duty and energy penalty per unit captured CO₂.

The percentage difference between the cases \textit{CASE}_\textit{without} and \textit{CASE}_\textit{tuned} was -0.2%, -0.5% and -0.3% for captured CO₂, reboiler duty and energy penalty respectively.
5.3 Case 3: Control for the fluctuation of flue gas flow rate and CO\textsubscript{2} volume %

5.3.1 Control performance

The dynamic changes in CO\textsubscript{2} capture rates resulting from various control strategies in response to a 30\% ramp-up variation in the flue gas flow rate and CO\textsubscript{2}vol\% can be analysed from the figure 27. This variation occurs over a 2-hour period, involving an increase in the flue gas CO\textsubscript{2} concentration under a total simulation time of 7 hours.

Interestingly, the system’s capture rate, with control strategy in place becomes slightly higher compared to the capture rate when controllers are not implemented, and the controlled systems showcase much higher stability in maintaining the capture rate. When we compare the capture rate of the fine-tuned controller to the system with general controller settings, it becomes apparent that the capture rates are roughly the same with the CASE\textsubscript{general} being lower than the CASE\textsubscript{tuned}.

Furthermore, the fine-tuned controller demonstrates much better stability in maintaining the capture rate when compared to the controller with general settings. Notably, the fine-tuned controller consistently delivers a much more stable CO\textsubscript{2} capture rate than the controller with general settings, resulting in consistent and stable capture rate performance.
Figure 28 illustrates an insightful view on the performance of control strategies on the reboiler duty within the CO₂ capture system when a 2-hour ramp up increase in the base value of both the flue gas flow rate and flue gas CO₂ vol% is added to the system at the 1-hour mark. In the absence of controllers governing the reboiler duty, the system maintains a consistent reboiler duty level throughout the simulation period. However, when controllers are introduced, we observe dynamic changes in the reboiler duty. As expected, the controller undergoing tuning exhibits significantly higher consumption of reboiler duty. This aligns with the predictions made, since the controllers are introduced to manipulate the reboiler duty to ensure stable stage temperatures within the reboiler.

When the system employs controllers with general settings, the reboiler duty curve shows a steady increase which indicates a lack of stability in the reboiler duty, and a continuous increasing trend is shown. In contrast, the controller equipped with fine-tuned parameters exhibits a different pattern. The reboiler duty increases steadily during the 2-hour ramp-up period of the flue gas flow rate and CO₂ vol% and maintains a stable level once the flue gas flow and CO₂ vol% rate stabilizes at a 30% increase from its base value. The reboiler duty is also much higher in the CASE tuned.
Figure 29 Comparison of reboiler duty control performance for different controller tuning parameters in Case 3

Figure 29 provides valuable insights into the control system for regulating the reboiler temperature, where the SP is established at 119.5°C. In the presence of controller with general settings, the PV experiences a decline in response to the optimization of reboiler duty required to maintain the SP input. This decline is also associated with reaching its maximum deviation from the setpoint, with a peak deviation of 118.9°C. The system struggles to achieve stability over the course of the simulation in this case there are no signs of the PV attaining stability. On the other hand, it’s important to note that with controller fine tuning implemented in CASE_tuned, the system exhibits remarkable stability. The controller effectively maintains the reboiler temperature at the setpoint, resulting in minimal variations in the PV.
The change in the lean solvent flow in the different control strategies is showcased in the figure 30, in comparison to the previous cases the case 30 shows a clear difference in the performance of the controllers to manipulate the amount of lean solvent entering the system, with the finely tuned controller resulting in providing for higher lean solvent flow to the system with the increase in both flue gas flow rate and flue gas CO$_2$ vol%.

The trends of the lean solvent control flow system in two controller scenarios: \textit{CASE}$_{\text{general}}$ and \textit{CASE}$_{\text{tuned}}$ is illustrated in the figure 31. In both cases, the setpoint is configured to
regulate the rate at which CO₂ is removed in the absorber by providing the controller variable to be the removal rate, ensuring that the absorber receives adequate amount of lean solvent for effective CO₂ absorption.

In the \( CASE_{\text{general}} \) scenario, the process variable, which is adjusted to maintain the SP, deviates from the SP due to increase in the flue gas flow and CO₂ vol\%. As the PV increases, it demonstrates the maximum deviation it experiences before eventually stabilizing back at the setpoint. The maximum deviation is observed to be 0.112 and the settling time is approximately 3.2 hours.

In comparison the fine-tuned controller results in the precise manipulation of the SP to target the desired CO₂ removal rate in the absorber. This ensures that the absorber receives a consistent amount of lean solvent for efficient CO₂ absorption. This can also be seen in the figure 30 where the finely tuned controlled system consumes higher amounts of lean solvent to capture carbon. In comparison to exhibits an absence of deviation and maintains a nearly perfect alignment with the SP, highlighting the effectiveness of tuning in achieving precise and stable control of the lean solvent flow system.

The lower maximum deviation and faster response time to the disturbances while ensuring adequate lean solvent flow as seen in the figures 30 and 31 highlights the importance of fine-tuning control parameters.

### 5.3.2 System performance

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Captured CO₂ (ton)</th>
<th>Reboiler Heat Duty (GJ)</th>
<th>Energy penalty MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CASE_{\text{without}} )</td>
<td>387</td>
<td>3893</td>
<td>10</td>
</tr>
<tr>
<td>( CASE_{\text{general}} )</td>
<td>386</td>
<td>4037</td>
<td>10.4</td>
</tr>
<tr>
<td>( CASE_{\text{tuned}} )</td>
<td>389</td>
<td>4178</td>
<td>10.7</td>
</tr>
</tbody>
</table>

The calculated system performance for the different control strategy approaches used in Case 3 is showcased in table 11. Where the captured CO₂ for a simulation time of 7 hours is the highest for \( CASE_{\text{tuned}} \) with higher reboiler heat duty and energy penalty per unit captured CO₂. The amount of captured CO₂ is higher in the case of the system where the controller which undergoes fine tuning as the amount of lean solvent flow increases as a result of the controller manipulating the flow of lean solvent flow. The increase in both flue gas CO₂ vol\% and flow rate requires for more lean solvent.

The percentage difference between the cases \( CASE_{\text{without}} \) and \( CASE_{\text{tuned}} \) was 0.5\%, 7\% and 6.7\% for captured CO₂, reboiler duty and energy penalty respectively.
5.4 Case 4: Control for the fluctuation of reboiler heat

5.4.1 Control performance

The comparison of the change in the reboiler temperature as a result of the increase in the reboiler duty in case 4 is depicted in the figure 32. It can be seen that the reboiler temperature increases throughout the ramp up period of the reboiler duty in the three different control strategies. This is expected as higher reboiler duty results in higher reboiler temperatures.

But while comparing the three control strategies it can be seen that in the absence of controllers the reboiler temperature experiences a high increase and reaches a maximum of 125.5 °C which is much higher than the desired 119 °C. It can also be seen that the reboiler temperature does not attain stability and experiences a steady increase even after the ramp up increase ends at hour 3.

On the other hand, the implementation of controllers results in lower reboiler temperatures and the reboiler temperature can be seen to attain stability after the ramp up increase ends at hour 3, with the finely tuned controller showing the best stability out of all the three control strategies. The finely tuned controller also reaches the lowest stage temperature during the ramp up increase before attaining stability.
The comparison between the rich flowrate entering the stripper over the course of the simulation period is illustrated in the figure 33. Due to the absence of the controller the rich solvent flow into the stripper remains the same. But on the other hand, due to the implementation of the controllers where the manipulated variable is the rich solvent flow into the stripper, there is an increase in the rich solvent flow rate as the reboiler duty increase. The rich loading being the SP in this case requires for higher amount of rich solvent flow into the system as the reboiler duty and reboiler temperature increases. It can also be seen in the figure 33 that the finely tuned controller showcases much more stability and responsiveness to the transient change in the reboiler duty and the increase in the rich solvent flow rate is almost synonymous with the reboiler duty increase. While the controller equipped with general control settings takes much longer to attain stability.

Figure 34 Comparison of lean loading control performance for different controller tuning parameters in Case 4
The comparison of the control performance of the different controller tuning parameters implemented in case 4 can be seen in the figure 34. As expected and based on the previous figure 33 we can realize that the fine tuning of the controller showcases faster responsiveness to the disturbance in the system and reaches stability much sooner when compared to the controller with the general controller settings.

It is also interesting to note that the controller with the general controller settings does not attain stability throughout the time of period of the simulation while the controller equipped with fine tuning attains stability and maintains stability.

![Figure 34: Comparison of captured CO\textsubscript{2} change](image)

Finally, the comparison of the change of the amount of CO\textsubscript{2} captured is illustrated in the figure 35. The increase in the reboiler temperature as seen in the figure 32 it can be speculated that the capture rate of the system would be much higher in the case of the system in the absence of the controller, but due to no change in the rich solvent loading there is no significant increase in the amount of captured CO\textsubscript{2}. As the amount of rich solvent remains the same throughout the system. The temperature change does result in increase in the amount of CO\textsubscript{2} captured but it isn’t as significant due to the stable rich solvent entering the stripper in the absence of the controller.

Whereas, in the presence of controllers the captured amount of CO\textsubscript{2} increases in both the controller equipped with general settings and the controller fine-tuned for the system. This is due to the increase in both the reboiler temperature and the increase in the rich solvent flow in the stripper. The fine-tuned controller shows better stability and higher amounts of captured CO\textsubscript{2} due to better control performance as shown in figure 34.
### 5.4.2 System performance

Table 12 Comparison of the system performance under different control strategies for Case 4

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Captured CO₂ (ton)</th>
<th>Reboiler Heat Duty (GJ)</th>
<th>Energy penalty MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE_without</td>
<td>366.8</td>
<td>4751.5</td>
<td>13</td>
</tr>
<tr>
<td>CASE_general</td>
<td>422</td>
<td>4751.5</td>
<td>11.2</td>
</tr>
<tr>
<td>CASE_tuned</td>
<td>428.1</td>
<td>4751.5</td>
<td>11</td>
</tr>
</tbody>
</table>

The calculated system performance for the different control strategy approaches used in Case 4 is showcased in table 12. Where the captured CO₂ for a simulation time of 7 hours is the highest for CASE\_tuned with higher reboiler heat duty and energy penalty per unit captured CO₂. With the increase in the rich solvent flow rate, which is the manipulated variable in the case, the amount of captured CO₂ also increases. Hence the implementation of the controller with fine tuning results in higher captured CO₂ and since the total reboiler duty increases and remains the same for all the cases the energy penalty is the lowest when the fine-tuned controller is implemented in the system.

The percentage difference between the cases CASE\_without and CASE\_tuned was 16.7% and -15% for captured CO₂ and energy penalty respectively.
6 DISCUSSION

6.1 Impacts of various key parameters on the performance of CO₂ capture

Fluctuation of flue gas flow rate

From the case study performed on the CO₂ capture system without the presence of control strategies it can be observed that the variation in flue gas flow rate in Case 1 increase and vastly affect the system performance and the capture rate of the system. Where the total CO₂ captured is 384.8 ton which is the lowest when compared to the system when control strategies are introduced.

The increase in the flue gas flow rate in the system decreases the capture rate as observed in figure 17 where the capture rate becomes the lowest which is approximately 78 %. This is due to the lack of control for the lean solvent flow rate which is underestimated with the incoming ramp up increase in the flue gas flow rate of 409607 kg/h after ramping up increase. The initial lean solvent flow rate was determined based on achieving the target 90% capture rate when the flue gas flow rate was 315152 kg/h.

Hence the variation in the flue gas flow rate can adversely affect the capture rate of the system and can cause poor control of the system. This also means that there are considerable larger amounts of CO₂ that is released in the vent gas and lower amount of CO₂ that is being captured. This results in environmental consequences and poor functioning of the capture system.

Fluctuation of flue gas CO₂ volume percentage

In the case study conducted on the CO₂ capture system in the absence of control strategies, it becomes evident that increase in CO₂vol% has a profound impact on system performance and the capture rate.

When the CO₂vol% decreases, as demonstrated in Case 2, we observe a consistent decline. This is due to the fact that the lean solvent becomes overwhelmed and cannot adequately react with the escalating volume of CO₂ introduced into the system through the higher CO₂vol% in the flue gas. in the capture rate over the time frame the capture rate subsequently decreases to approximately 71 % that can decrease the effective control of the dynamic operation of the CO₂ capture system.

In essence, fluctuations in CO₂vol% can significantly and adversely affect the capture rate of the system, leading to difficulties in maintaining control. Furthermore, this fluctuation results in more CO₂ being released into the vent gas and less being captured which is a similar trend as case 1.
Fluctuation of both flue gas flow rate and CO2 volume percentage

Case 1 and Case 2 provide some important insight on the behaviour of the capture system when exposed to variations in two key influencing factors. While combining the two influencing factors which is close to how the actual plant data is from a bio-CHP plant it is observed in Case 3 that when the flue gas flow rate and CO2 vol% increase the capture rate of the system decreases, which was expected based on the observations made previously for cases 1 and 2.

In this case the capture rate of the system becomes 62% which is very low when the performance of the capture systems is considered.

Fluctuation of reboiler heat.

From the case study 4 performed some clear indicators of impacts such as the amount of CO2 captured can help understand the impacts of the fluctuation of reboiler heat on the system. As it was observed in the figure 35 the amount of captured carbon is the least when no controllers are equipped in the system and the amount of captured CO2 being 366 ton which is very low in the context of CO2 capture systems.

6.2 Control strategy implementation

Based on the case study on the various key influencing factors on the system without any control strategies in place it can be observed that the dynamic operation and performance of the CO2 capture system is vastly affected by variations in the influencing factors. Hence, in order to ensure smooth functioning of the CO2 capture system and stable performance it is important to implement the right control strategies. In order to do these two cases were simulated with controllers with one having a fine-tuned controller and the other with general controller settings. The key performance indicators such as the captured CO2 and the energy penalty for both the control strategies are compared. The following table shows the comparison.

<table>
<thead>
<tr>
<th>CASE</th>
<th>CASE 1</th>
<th>CASE 2</th>
<th>CASE 3</th>
<th>CASE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTROL STRATEGY</td>
<td>GENERAL SETTING</td>
<td>WITH FINE TUNING</td>
<td>DEFAULT TUNING</td>
<td>WITH FINE TUNING</td>
</tr>
<tr>
<td>CO2 CAPTURED(ton)</td>
<td>386.3</td>
<td>389.3</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>ENERGY PENALTY</td>
<td>10.4</td>
<td>10.7</td>
<td>11.1</td>
<td>11.6</td>
</tr>
</tbody>
</table>

The comparison above shows the total captured CO2 and the energy penalty over a simulation of 7 hours and from the comparison it is established that the implementation of a fine-tuned control system resulted in better capture rates and the total captured CO2. From the above
table it is clear that the amount of CO$_2$ captured is higher in the case of the controller which undergoes fine tuning in all the studied cases with case 2 where it is approximately the same. This is a clear indicator of better captured CO$_2$ performance in the case of the control strategy implemented where the controllers undergo fine tuning. The capture rate of the plant also showcases consistency and stability, and it is maintained closer to the designated set point for the system.

From figures 19, 21, 24, 26, 29, 31 and 34 it is apparent that implementation of proper tuning parameters in the control system provides for higher stability and finer control of the CO$_2$ capture system. This is justified by comparing the maximum deviation and the settling times of both the controllers implemented.

In the figures 19, 21, 24, 26, 29, 31 and 34 which illustrated the change in the PV before it attains steady state it can clearly be observed that the tuned controller offers for more steady control by showcasing shorter deviation from the set point, whereas the controller with general settings has higher maximum deviation when compared to the controller with was fine tuned. The settling time in this case also makes it more evident to how fine-tuned controllers provide more accurate control by achieving stability faster than the controller with general settings. Figure 29 is a clearer illustration of how tuning is essential as the controller with general settings shows high deviation from the set point and doesn’t attain stability within the provided time of study.

The energy penalty per unit captured CO$_2$ also gives us insight on the performance of the capture system where the fine-tuned controller has better energy utilization compared to the controller with general settings. It also can be seen that the controller maintains the set point temperature throughout with little to no deviation whereas the controller without tuning fails to attain stability.

While analysing and comparing the reboiler duty in figures 18, 23, 28 and 32 it is also shown that better control allows for much better energy utilization and reduction in the reboiler duty whereas the controller with general settings consumes more energy due to the lack of accuracy which is caused due to the general settings. While comparing the capture rate of the system, the controller with fine tuning shows slightly better CO$_2$ capture rates compared to the controller with general settings. The energy penalty per unit captured CO$_2$ as discussed is an important indicator of efficient energy utilisation the table 13 showcases the amount of CO$_2$ captured over the period of the simulation, similarly table 13 illustrates the energy penalty for both the controller with general settings and the controller with fine tuning.

Hence it can be concluded that fine-tuned controllers are more accurate at controlling the CO$_2$ capture system when compared to controllers without any tuning.

It should also be noted that the energy penalty per unit captured CO$_2$ for all the 4 cases in this study is relatively higher while compared to the expected values and values obtained from the literature study. It can be speculated that this is due to the absence of a centralized cross heat exchanger and absence of other key components which make up for the CO$_2$ capture system. The modelling process was simplified throughout the study considering the intensity of the input parameters and reduce the workload of calculations.
6.3 System controller design influence on CO$_2$ capture performance

As discussed earlier, adoption of effective control strategies is key to enable proper functioning and performance of the CO$_2$ capture plant. The comparison between the performance of the system, and the total captured CO$_2$ shows us the importance of implementing a definite dynamic control design results for better stability of the capture rate in the CO$_2$ capture system.

The system performance of the system in the absence of a control strategy is compared to the system equipped with controllers fine-tuned for the system requirements. The compared results are given below,

**Case 1:** Compared to the system without controller, the amount of captured CO$_2$ increases by 4.5 ton, and reboiler duty increases by 300.6 GJ, and energy penalty by 0.6 MJ/kg with the finely tuned controller, in which the relevant difference are 1.1%, 7.7% and 5.9% respectively.

**Case 2:** Compared to the system without controller, the amount of captured CO$_2$ decreases by 1 ton, and reboiler duty decreases by 22 GJ, and energy penalty increases by 0.5 MJ/kg with the finely tuned controller, in which the relevant difference are -0.2%, -0.5% and 4.5% respectively.

**Case 3:** Compared to the system without controller, the amount of captured CO$_2$ increases by 2 ton, and reboiler duty increases by 285 GJ, and energy penalty by 0.7 MJ/kg with the finely tuned controller, in which the relevant difference are 0.5%, 7.3% and 7% respectively.

**Case 4:** Compared to the system without controller, the amount of captured CO$_2$ increases by 62 ton and energy penalty decreases by 2 MJ/kg with the finely tuned controller, in which the relevant difference are 16.7% and -15% respectively.
7 CONCLUSIONS

The case studies performed on the system with the fluctuations in the influencing factors gives us conclusive results on how the key influencing factors such as the flue gas flow rate and CO\textsubscript{2} vol% and reboiler heat vastly affect the performance of the CO\textsubscript{2} capture system. It is also evident that the performance of the CO\textsubscript{2} capture system is directly affected by these influencing factors and even minute differences can result in changes in the key performance indicators. Hence control strategies are essential for the flexible operation of the system and to handle disturbances. This can be determined by the following results when the flue gas flow rate and CO\textsubscript{2} vol% both increases by 30% where compared to the system without controller, the amount of captured CO\textsubscript{2} increases by 2 ton, and reboiler duty increases by 285 GJ, and energy penalty by 0.7 MJ/kg with the finely tuned controller which a difference of 0.5%, 7.3% and 7% respectively. And when the reboiler, duty is increased compared to the system without controller, the amount of captured CO\textsubscript{2} increases by 62 ton, and reboiler duty remains the same, and energy penalty decreases by 2MJ/kg with the finely tuned controller which is a difference of 16.7%, 0% and -15% respectively.

The implementation of controllers which are specifically tuned to handle disturbances of the system are proven to be more accurate at controller functioning and stability. With notable higher captured CO\textsubscript{2} percentage increases in all the cases discussed where the amount captured CO\textsubscript{2} increases by 1 ton when the flue gas flow rate and CO\textsubscript{2} vol% both increase in a ramp up variation. It is also an important conclusion that the tuned control parameters showcase no deviation in the manipulated variable and maintain stability throughout the simulation.

In conclusion the system control design increases the efficiency of the CO\textsubscript{2} capture plant both by conserving energy spent for the solvent regeneration and the total amount of captured CO\textsubscript{2}. 
8 SUGGESTIONS FOR FURTHER WORK

The simulation time of 7 hour-timescale is determined considering the workload of calculations. It may be interesting to compare the approaches over a longer period. There is a potential to investigate the effects in future work. and data can be chosen for longer time, not only for 7 hours. For the data treatment and case study the heat input is assumed and not obtained due to the unavailability of data from the bio-CHP plant in this work and can be implemented to understand impact the actual reboiler heat input would have on the capture rate of the system.

The energy penalty achieved throughout the course of the study remained higher compared to that of pilot plant, which could be resulted from the not well-designed lean-rich heat exchanger. This would require for more detailed component design and rate based dynamic modelling of the CO₂ capture system.

The dynamic modelling is validated against steady state validation, but not the dynamic validation which needs to be improved as Aspen plus also provides for rate-based modelling of the components used in this study but Aspen plus dynamics only simulates models which are in equilibrium hence validation of data is difficult. This also can be a reason for the higher energy penalty observed through the simulations conducted in this study.

The controller performances can further be investigated to improve the controllability of the system and determine better control strategies.
REFERENCES


Carbon capture, use and storage is needed urgently to meet carbon neutrality targets, according to UNECE report | UNECE. (n.d.). Retrieved February 7, 2023, from https://unece.org/circular-economy/press/carbon-capture-use-and-storage-needed-urgently-meet-carbon-neutrality


