

Intended for  
**Sysav**

Document type  
**Report**

Date  
**February 2022**

# **SYSAV CARBON CAPTURE STORAGE (CCS) CARBON CAPTURE TECHNOLOGY SCREENING**



# **SYSAV CARBON CAPTURE STORAGE (CCS) CARBON CAPTURE TECHNOLOGY SCREENING**

Project name **EFW SYSAV Feasibility Study CCS (SE)**  
Project no. **1100048750**  
Recipient **Sysav**  
Document type **Report**  
Version **2.0**  
Date **2022-02-22**  
Prepared by **EBBEH**  
Checked by **JSAND/CTR**  
Approved by **OP**  
Description **Carbon Capture Technology Screening**

Ramboll  
Hannemanns Allé 53  
DK-2300 Copenhagen S  
Denmark

T +45 5161 1000  
F +45 5161 1001  
<https://ramboll.com/energy>

## CONTENTS

<b>1.</b>	<b>Executive Summary</b>	<b>2</b>
<b>2.</b>	<b>Introduction</b>	<b>3</b>
2.1	Background for the CCS project	3
2.2	Purpose of this document	4
<b>3.</b>	<b>Available Carbon Capture Technologies</b>	<b>5</b>
3.1	Post-combustion	5
3.2	Pre-combustion	6
3.3	Oxy-fuel combustion	7
3.4	Chemical looping combustion	8
3.5	Summary of overall technology concepts	9
<b>4.</b>	<b>Post-Combustion CO<sub>2</sub> separation technologies</b>	<b>10</b>
4.1	Absorption	10
4.2	Adsorption	11
4.3	Membrane CO <sub>2</sub> separation	11
4.4	Cryogenic distillation	12
4.5	Summary of post-combustion CO <sub>2</sub> separation technologies	13
<b>5.</b>	<b>Absorption-based solvents and Technologies</b>	<b>14</b>
5.1	Amines	14
5.1.1	MEA	15
5.1.2	AMP-PZ	16
5.1.3	Rotating Packed Beds	16
5.2	Hot Potassium Carbonate	17
5.3	Cold Potassium Carbonate Enzyme	18
5.4	AMP-DMSO	19
5.5	Summary of Absorption-based solvents and Technologies	21
<b>6.</b>	<b>Technical and Commercial Readiness Assessment for Selected Technologies</b>	<b>22</b>
<b>7.</b>	<b>Selection Criteria</b>	<b>26</b>
<b>8.</b>	<b>Recommendations</b>	<b>29</b>

## 1. EXECUTIVE SUMMARY

Sysav is conducting a Carbon Capture and Storage (CCS) project (Utredningsprojekt CCS) to study the possibilities for realizing a cost-effective solution for CO<sub>2</sub> capture and transport and storage of the captured CO<sub>2</sub> for the Waste-to-Energy (WtE) plant at Sysav in Malmö, Sweden. The project covers all aspects of Carbon Capture (CC) at Sysav's site and transport and storage of CO<sub>2</sub>.

As part of phase 1 "Övergripande förstudie" a technology screening has been made to identify the two most promising and favorable CC technology for implementation at Sysav's WtE plant.

An overview of the available technologies for CO<sub>2</sub> capture is provided and the different technologies are divided based on their overall methodology such as post-combustion, pre-combustion, oxy-fuel combustion and chemical looping combustion.

Post-combustion CC technologies are found to be the most practical technology for retrofit installation of CO<sub>2</sub> capture at Sysav's WtE plant since this technology may be integrated in the flue gas path in the tail-end of the WtE facility and is selected as the overall methodology to proceed in the screening.

Post-combustion CC technologies cover absorption, adsorption, membrane CO<sub>2</sub>-separation and cryogenic distillation. Out of the available post-combustion CO<sub>2</sub> separation technologies, absorption-based CO<sub>2</sub> capture is by far the most mature technology. Due to the relatively low CO<sub>2</sub> concentration in the flue gas flow from conventional municipal solid waste combustions systems, coupled with the expected integration in the tail-end of the Sysav WtE facility means that absorption-based technologies are the most applicable and viable. Consequently, only absorption-type CO<sub>2</sub> separation technologies proceed in the screening.

Absorption-based post-combustion CC technologies cover amines, hot potassium carbonate, cold potassium carbonate enzyme and AMP-DMSO. The current and future technological readiness level (TRL) and the commercial readiness index (CRI) of the absorption technologies are assessed and the technologies are qualitatively evaluated and compared.

Based on the screening and evaluation of the relevant CO<sub>2</sub> capture technologies for implementation at Sysav, it is recommended to further investigate and study the following two technologies in the present pre-feasibility study (Övergripande förstudie):

**Base case technology:**

**Alternative technology:**

**Monoethanolamine (MEA)**

**Hot Potassium Carbonate (HPC)**

MEA is a known technology, scores high on both technological and commercial readiness levels and is principally ready for implementation today and thus serves as a conservative, safe technology choice. In addition, MEA is often the reference technology for CO<sub>2</sub> capture and it will be valuable for Sysav to study this technology further allowing better comparison with competing technologies.

HPC is a less commercially mature technology than MEA, is unproven at relevant scale, however, receives a reasonable score in terms of both technological and commercial readiness levels. It is interesting to investigate due to its very low external heat demand which would have a low impact on Sysav's energy system.

## 2. INTRODUCTION

### 2.1 Background for the CCS project

Sysav is conducting a Carbon Capture and Storage (CCS) project (Utredningsprojekt CCS) to study the possibilities for realizing a cost-effective solution for CO<sub>2</sub> capture and transport and storage of the captured CO<sub>2</sub> for the Waste-to-Energy (WtE) plant at Sysav in Malmö, Sweden. The project covers all aspects of Carbon Capture (CC) at Sysav's site and transport and storage of CO<sub>2</sub>.

The total project is planned to be carried out through the following project phases:

- Phase 1: Övergripande förstudie
- Phase 2: Fördjupad förstudie
- Phase 3: Utformning av ett eventuellt genomförandeprojekt

This report relates to phase 1 "Övergripande förstudie", which is a pre-feasibility study.

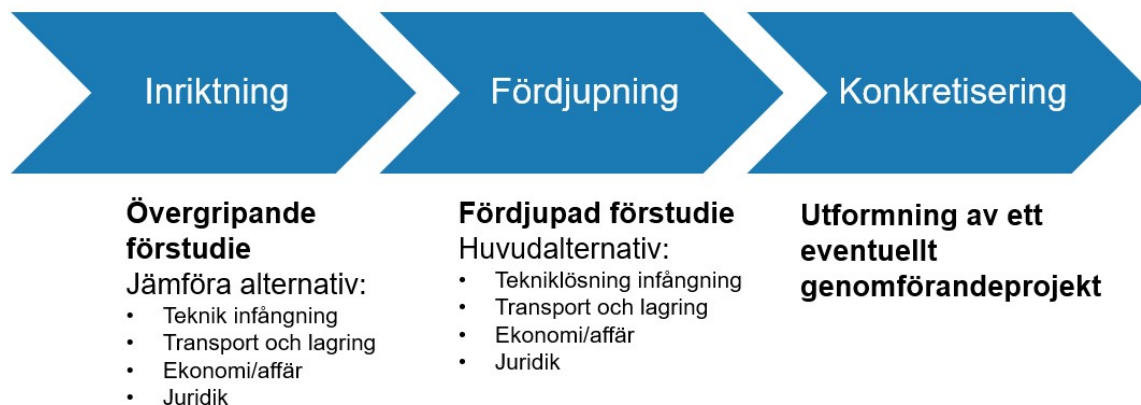


Figure 1 - Sysav implementation model for "Utredningsprojekt CCS"

The purpose of this pre-feasibility study is to:

- Develop the design basis
- Identify the most favourable CC technology for Sysav through a technology screening.
- Develop a basic concept/solution for CO<sub>2</sub> capture, liquefaction and storage from a technical and economical perspective.
- Analysis of possibilities for transport and store/use captured CO<sub>2</sub> safely and at the cost as low as possible.
- Set out the legal conditions for capture of CO<sub>2</sub> at Sysav
- Identify a reasonable economic model for carrying out the investment and subsequent operation of the Carbon Capture facility and analyse options for providing a reasonable financial risk while delivering according to the ambitions of Sysav.

The pre-feasibility study covers two scenarios dependant on the realization of a future boiler line P5.

- 1) A main scenario based on the existing boiler lines P3 and P4.
- 2) An alternative scenario based on the existing boiler lines P3, P4 and a new established boiler line, P5.

## 2.2 Purpose of this document

The purpose of this document is to provide an overview of the available technologies for CO<sub>2</sub> capture and a screening of available CC technologies. The screening includes an assessment of the technical and commercial readiness level of a selected number of relevant technologies for the implementation of CO<sub>2</sub> capture at Sysav.

The screening of the different CO<sub>2</sub> capture technologies divides the available technologies based on their overall methodology. The technologies are further subdivided in categories to provide a thorough overview of technical solutions relevant for a future CC plant integrated at Sysav's WtE site. Finally, for a selection of the most applicable technical solutions, an assessment of the current and projected future technical and commercial readiness is included to assist in the evaluation and selection of relevant CO<sub>2</sub> capture technologies.

Based on the projected technological and commercial readiness levels and the overall evaluation of the relevant technologies two technologies are selected for further study in the present pre-feasibility study.

### 3. AVAILABLE CARBON CAPTURE TECHNOLOGIES

This section provides an overview of the available CO<sub>2</sub> capture technologies for the CC integration at Sysav.

Carbon Capture technologies relevant for power generation facilities are classically divided into four separate sub-categories covering post-combustion capture, pre-combustion capture, oxy-fuel combustion and chemical looping combustion. Table 1 below provides a brief summary of the advantages and disadvantages of each carbon capture technology.

**Table 1 - Advantages and disadvantages of the different CO<sub>2</sub> capture technologies.**

Capture process	Application area	Advantages	Disadvantages
<b>Post-combustion</b>	Wide application area	More mature than alternative technologies. Simple retrofitting on existing plants.	Relatively low CO <sub>2</sub> concentration in flue gas affects the capture efficiency and energy requirements for sorbent regeneration.
<b>Pre-combustion</b>	Gasification plants	High CO <sub>2</sub> concentration in flue gas increases capture efficiency. Technology fully developed and commercially deployed in some industrial sectors. Can be retrofitted to existing gasification plants.	High parasitic power requirement for sorbent regeneration. Inadequate technological maturity with only few gasification plants currently operated.
<b>Oxy-fuel combustion</b>	Wide application area	Very high CO <sub>2</sub> concentration enhances capture efficiency. Mature air separation technologies are available. Greatly reduced volume for flue gas treatment allows for a smaller boiler and other systems.	High energy penalty with integrated air separation. Current availability of O <sub>2</sub> is low and production is costly. Potential corrosion problems for high-O <sub>2</sub> systems.
<b>Chemical Looping Combustion</b>	Wide application area	CO <sub>2</sub> is the main combustion product which remains unmixed with N <sub>2</sub> , thus avoiding energy intensive air separation.	Process is still under development and inadequate large scale operation experience.

The different general methodologies for CO<sub>2</sub> capture are described further in depth in the following sub-sections.

#### 3.1 Post-combustion

As the name suggests, post combustion capture removes the CO<sub>2</sub> from the flue gases after combustion has taken place. CO<sub>2</sub> can be removed from the remaining flue gases with different CO<sub>2</sub> separation technologies e.g, absorption, adsorption or membranica separation technologies. It is the preferred option for retrofitting existing power plants with carbon capture, since it may, with little modification to the existing plant, be fitted to the tail-end of a power and/or heat



generation facilities. Post-combustion CO<sub>2</sub> capture technology has been proven for facilities with CO<sub>2</sub> recovery rates upwards of 800 tons per day. The major drawback of post-combustion CO<sub>2</sub> capture is a large parasitic load when integrated in power generation facilities as the relatively low concentration of CO<sub>2</sub> in conventional combustion flue gases means a larger energy penalty for post-combustion CO<sub>2</sub> capture than for pre-combustion capture.

Figure 2 illustrates the principal setup of post-combustion carbon capture.

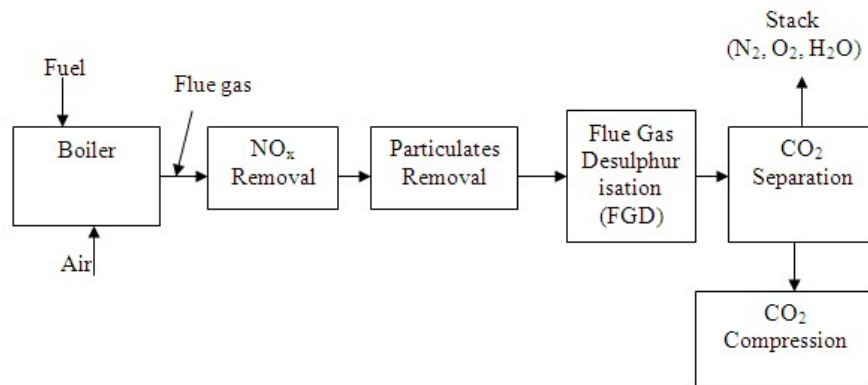
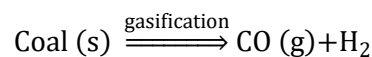


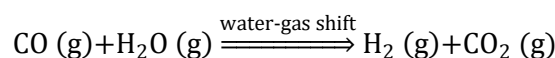
Figure 2 - Post-combustion CO<sub>2</sub> capture. (From: IntechOpen)

### 3.2 Pre-combustion

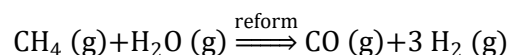
In pre-combustion carbon capture technology, the fuel (typically coal or natural gas) is pretreated before combustion. For coal-derived fuels, the pretreatment consists of a gasification process conducted in a low oxygen environment in a gasifier that produces a syngas consisting primarily of carbon monoxide (CO) and hydrogen (H<sub>2</sub>) as described in the equation below:



The syngas then undergoes a water gas shift reaction with steam to form additional H<sub>2</sub> while CO is converted to CO<sub>2</sub> as detailed in the equation below:



For natural gas fuels containing mostly methane (CH<sub>4</sub>), instead of gasification the fuel undergoes a steam reforming process to separate CH<sub>4</sub> into H<sub>2</sub> and CO, as described in the equation below. Following the reforming, the resulting syngas may undergo a water gas shift reaction, as detailed in the equation above to increase the H<sub>2</sub> concentration of the gas.



Following the gasification or reforming and water gas shift reaction, a gaseous mixture with a relatively high concentration of CO<sub>2</sub> above 20 % is ready for the separation process. Precombustion utilizes the same separation techniques as post-combustion capture, the possibilities for which will be described in section 4. A schematic illustration showing the operating principle of pre-combustion capture may be seen in the following figure.



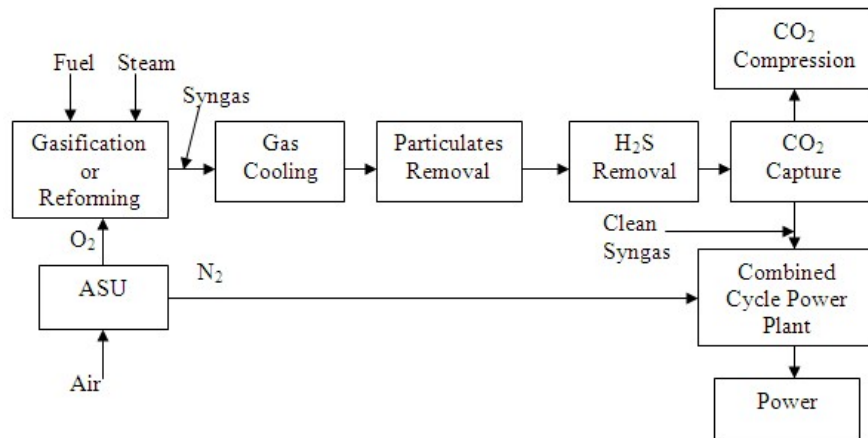


Figure 3 - Pre-combustion CO<sub>2</sub> capture. (From: IntechOpen)

The implementation of pre-combustion CO<sub>2</sub> capture at Sysav for boiler lines 3 and 4 constitutes a major modification of the installed process equipment, and essentially requires a complete rebuild of the boilers and flue gas paths. Additionally, gasification of waste is a complex issue due to the inhomogeneous nature of MSW. Waste gasification facilities are in operation globally, namely in Japan; however, these facilities are characterized by a relatively poor availability and frequent maintenance stops. For these reason, pre-combustion CO<sub>2</sub> capture is not relevant for the CO<sub>2</sub> capture implementation at Sysav and will thus not be discussed further.

### 3.3 Oxy-fuel combustion

In oxy-fuel combustion, rather than combusting the fuel with air, pure oxygen is used. This significantly reduces the amount of nitrogen (N<sub>2</sub>) present in the flue gases from the combustion process, thus, easing the separation process of CO<sub>2</sub>, as the CO<sub>2</sub>-concentration is much higher. Additionally, using pure oxygen for the combustion substantially reduces the amount of thermal NO<sub>x</sub> present in the flue gases. The major constituents in the flue gasses from oxy-fuel combustion are CO<sub>2</sub>, water vapor, particulate matter and SO<sub>2</sub>.

Particulate matter and SO<sub>2</sub> may be removed with conventional flue gas treatment systems, such as electrostatic precipitators and desulphurization systems. The water vapor may additionally in large part be removed by means of traditional flue gas condensation techniques. The resulting cleaned flue gas a very high concentration of CO<sub>2</sub> between 80-98 % depending on the fuel used, and may thus be directly compressed and prepared for storage or transportation. While oxy-fuel is theoretically possible, it requires large amounts of oxygen, which may be sourced from energy intensive air separation units, leading to a significant energy penalty for the facility.

Figure 4 illustrates the Oxy-fuel combustion process.

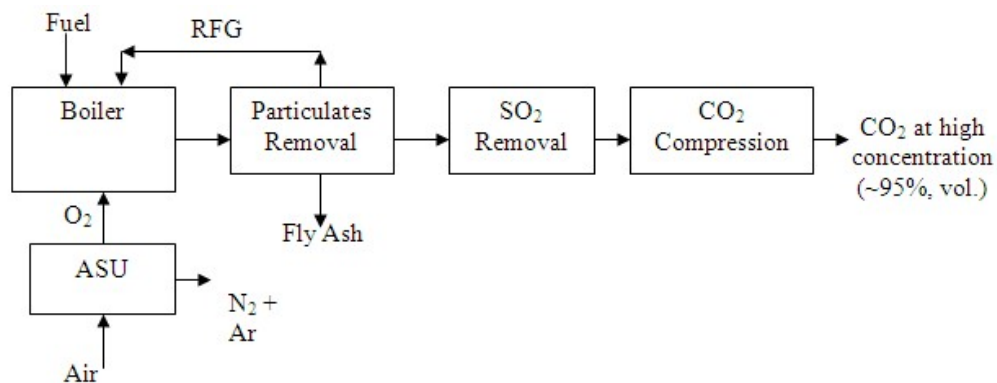
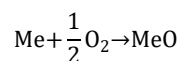


Figure 4 - Oxy-fuel combustion process (From: IntechOpen)

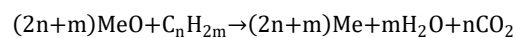
For future energy scenarios with prevalent PtX implementation, oxy-fuel combustion may present an interesting solution to make use of waste oxygen produced by electrolyzer plants, that in turn could potentially utilize the captured CO<sub>2</sub> in the production of green fuels. However, at present where high purity oxygen gas is still a valuable product, the implementation of oxy-fuel combustion at Sysav, without concurrent construction of large-scale electrolyzer facilities in the vicinity, will likely be prohibitively expensive. For this reason, oxy-fuel combustion is not discussed further.

### 3.4 Chemical looping combustion

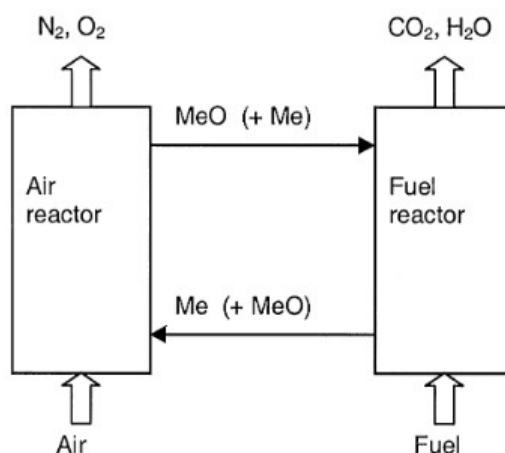
In Chemical Looping Combustion (CLC), a metal oxide is utilized as an oxygen carrier instead of using pure oxygen for combustion as in the case of oxy-fuel combustion. A schematic diagram of the CLC process may be seen in Figure 5 below. In the air reactor, a pure metal carrier is oxidized by ambient air after which the oxidized metal is moved to the fuel reactor. In the air reactor the chemical process occurs as shown in the equation below:



During the combustion process, the metal oxide is reduced to pure metal in the fuel reactor, where the fuel is oxidized to CO<sub>2</sub> and water vapor, as is shown in the equation below:



The water vapor from the combustion process may be easily removed with condensation units, leaving pure CO<sub>2</sub> that may be subsequently compressed and/or liquefied for sequestration or utilization. A wide variety of low-cost metal oxides may be utilized for this process including Fe<sub>2</sub>O<sub>3</sub>, NiO, CuO and Mn<sub>2</sub>O<sub>3</sub>. The principal major advantage of chemical looping separation is that the technology does not consume energy for CO<sub>2</sub> separation.



**Figure 5 - Chemical-looping combustion. MeO/Me denote recirculated oxygen carrier solid material. (From: Handbook of Climate Change Mitigation)**

While CLC is an interesting option for future new-builds of WtE facilities with integral CO<sub>2</sub> capture, the integration of CLC at Sysav constitutes a major departure from the presently installed process equipment requiring a complete replacement of boiler and furnaces and significant modifications to the flue gas path of boiler lines 3 and 4. For this reason, CLC is not discussed further.

### 3.5 Summary of overall technology concepts

In summary, of the technologies described in this section, by far the most practical for retrofit installation of CO<sub>2</sub> capture is post-combustion capture, since this technology may be integrated in the flue gas path in the tail-end of the WtE facility. As the Sysav project constitutes a CO<sub>2</sub> capture retrofit, only technologies relevant to post-combustion CO<sub>2</sub> capture is discussed in the following sections. For post-combustion CO<sub>2</sub> capture, multiple different CO<sub>2</sub> separation technologies exist. These are described in the following section.

## 4. POST-COMBUSTION CO<sub>2</sub> SEPARATION TECHNOLOGIES

This section briefly describes the four main CO<sub>2</sub> separation technologies that may be appropriately utilized in post-combustion carbon capture to remove CO<sub>2</sub> from flue gas flows: absorption, adsorption, membranes and cryogenic distillation. A summary table of the individual CO<sub>2</sub> separation technologies may be seen in the table below:

**Table 2 – Summary table of CO<sub>2</sub> separation technologies**

Separation process	Advantage	Disadvantage
<b>Absorption</b>	High absorption efficiency (>90 %). Sorbents can be regenerated with heating and/or depressurization. Most mature of the CO <sub>2</sub> separation technologies.	Absorption efficiency heavily dependent on CO <sub>2</sub> concentration. Large amounts of heat energy required for sorbent regeneration.
<b>Adsorption</b>	Adsorption process is reversible, and the sorbent can be recycled. Possible to attain high adsorption efficiencies (>85 %).	Adsorption process requires high temperatures, which necessitates high-grade energy use. Desorption of sorbent requires large amounts of energy.
<b>Membranes</b>	Process has been adopted for separation of other gases. Very low inherent energy consumption.	Operational problems include low fluxes and fouling. Large capital expenses. Low CO <sub>2</sub> permeate purity. Separation efficiency lower than alternatives (~80 %).
<b>Cryogenic distillation</b>	Mature technology. Adopted for many years in industry for CO <sub>2</sub> recovery. Extremely high separation efficiencies achievable (>95 %).	Only viable for very high CO <sub>2</sub> concentrations (>90 %). Process requires very low temperatures and is very energy intensive.

The different CO<sub>2</sub> separation technologies is described in further depth in the following.

### 4.1 Absorption

In absorption-based CO<sub>2</sub> separation technologies, a liquid sorbent is used to separate the CO<sub>2</sub> from the flue gas. by absorbing the CO<sub>2</sub>. The sorbent may then be regenerated through a stripping or desorption process by heat addition and or depressurization. Absorption-based CO<sub>2</sub> separation is a mature technology that has been used for decades in the oil and gas industries. Very high CO<sub>2</sub> capture rates above 90 % may be achieved. The biggest drawback of chemical absorption CO<sub>2</sub> capture is that the process requires large amounts of heat energy for solvent regeneration. Common sorbents include monoethanolamine (MEA), diethanolamine (DEA) and potassium carbonate. There is significant ongoing development in new solvents that have an inherently lower energy demand as well as process optimizations that reduce the external energy requirement for the process.

## 4.2 Adsorption

Adsorption-based CO<sub>2</sub> separation uses a solid sorbent to bind the CO<sub>2</sub> in the flue gas on the surfaces of the sorbent. Thus, large specific surface area, high selectivity and high regeneration ability are the main criteria for sorbent selection. Sorbent for adsorption-based CO<sub>2</sub> capture may be generally divided in two distinct categories: Physical adsorbents and chemical adsorbents. Typical physical adsorbents include molecular sieves, activated carbon, zeolites, calcium oxides, hydrotalcites and lithium zirconate. Chemical adsorbents include materials possessing very high specific surface areas that have been impregnated or grafted with amines to improve the CO<sub>2</sub> adsorption and selectivity. The CO<sub>2</sub> adsorbed on the surface of the sorbent may be recovered by swinging the pressure or temperature of the system containing the CO<sub>2</sub> saturated sorbent. CO<sub>2</sub> is preferentially absorbed on the surface of the solid sorbent at high pressure or low temperature and desorbed at low pressure or high temperature. This is known as Temperature-Swing Adsorption (TSA) and Pressure-Swing Adsorption (PSA), respectively.

The energy requirements for sorbent regeneration are comparable to absorption-based technologies. Physical adsorbents, while cheap and abundant, are challenged by having a relatively low gas selectivity and relatively low capture rate ( $\approx 80\%$ ) compared to absorption-based CO<sub>2</sub> capture. The low selectivity means that the recovered CO<sub>2</sub> is not of very high purity and physical adsorption technology is thus not applicable for processes requiring high CO<sub>2</sub> purity. These shortcomings are somewhat mitigated by chemical adsorption technology; however, these sorbents are significantly more expensive and have not yet been commercially matured.

## 4.3 Membrane CO<sub>2</sub> separation

Physical membranes can be utilized to separate the CO<sub>2</sub> from the remaining flue gases by exploiting the different molecule sizes of the gas constituents. The membranes are typically constructed from a composite polymer in which a thin selective layer is bonded to a thicker, non-selective layer providing mechanical strength to the membrane. Membrane-based gas separation technologies have been previously employed to separate O<sub>2</sub> from N<sub>2</sub> and to separate CO<sub>2</sub> from natural gas. Membrane-based CO<sub>2</sub> capture may theoretically achieve separation efficiencies between 82 to 88 % with ongoing research to further improve the separation efficiency. The efficiencies displayed by membrane separation technology is thus generally below that achievable through the use of absorption and adsorption technologies. The primary benefit of using membrane technology for CO<sub>2</sub> capture is the inherently low energy consumption of the technology. A schematic showing a membrane module for CO<sub>2</sub> removal from flue gases may be seen in Figure 6 below:

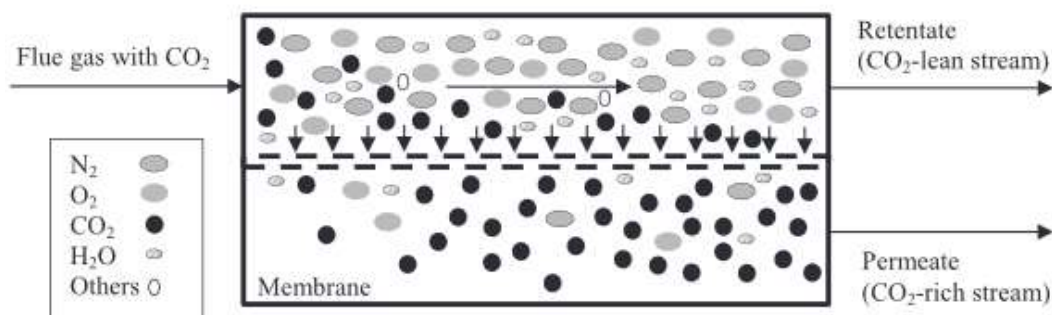


Figure 6 – Schematic diagram showing the principle of CO<sub>2</sub> separation with membrane technology

Due to a limited membrane selectivity with regards to the flue gas constituents, it is also not possible to achieve high purity CO<sub>2</sub> in the permeate stream, which makes the technology unsuitable for applications where high-purity CO<sub>2</sub> is required.

The performance of membrane systems is heavily dependent upon the flue gas conditions including the concentration of CO<sub>2</sub> and the overall pressure exerted by the flue gases. Additionally, membrane performance is detrimentally impacted by fouling from impurities and particulate matter present in the flue gas and low mass fluxes through the membranes require very large membrane modules for full-scale applications. Membrane CO<sub>2</sub> separation has been demonstrated as a promising technology in lab environments for relatively slow-moving gas streams at elevated pressures. It should be noted though, that flue gas flows are generally relatively fast moving, which greatly limits the residence-time of the flue gas in a given membrane section. Issues relating to the low fluxes generally attainable by current membrane technology is further exacerbated by the high flue gas velocities found in energy generation facilities, thus requiring extremely large membrane surface areas to facilitate the required capture rate, with high capital expenses. For these reasons, membrane separation technology is not applicable for carbon capture from conventional WtE facilities and will not be addressed further.

#### 4.4 Cryogenic distillation

Gas separation through cryogenic distillation is very similar to conventional distillation processes where gas components are separated based on differences in their respective boiling points. CO<sub>2</sub> at ambient and slightly elevated pressures (up to 5.2 atm) does not have a liquid phase, and instead will change state directly from a gas to a solid in a process known as de-sublimation. For cryogenic distillation CO<sub>2</sub> capture, the entire flue gas flow is moderately compressed and cooled to the sublimation temperature of CO<sub>2</sub> (-100 °C to -135 °C) where CO<sub>2</sub> solidifies and then may be removed from the remaining flue gases. The temperature greatly influences the CO<sub>2</sub> capture rate, with 99 % capture being possible at -135 °C, while only 90 % capture is possible at -120 °C. A schematic showing the major components of the cryogenic distillation process may be seen in Figure 7 below:

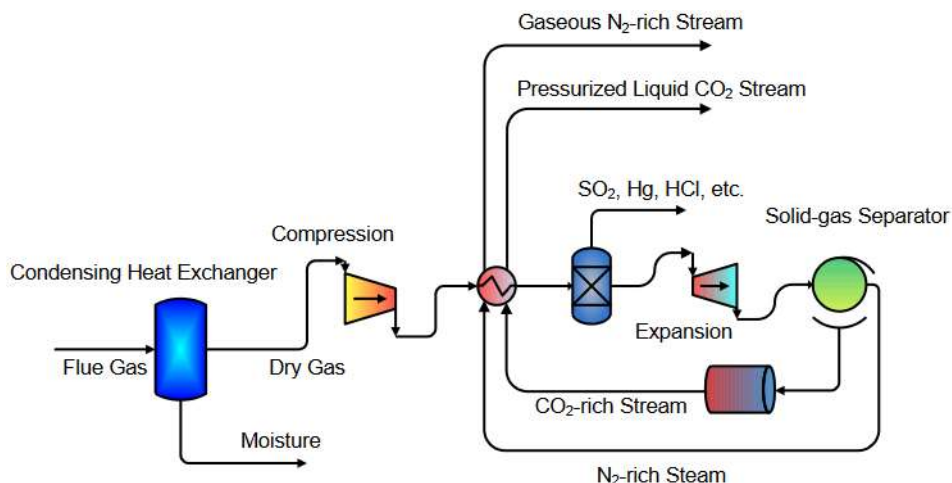


Figure 7 – Schematic diagram showing the operating principle of cryogenic distillation

The efficiency of cryogenic distillation CO<sub>2</sub> capture systems is closely related to the concentration of CO<sub>2</sub> in the flue gas. This is because the entire flue gas flow needs to be compressed and cooled to very low temperatures. For this reason, cryogenic distillation is only practically viable for

combustion processes yielding extremely high concentrations of CO<sub>2</sub> above 90 %. For this reason, cryogenic distillation is not relevant for implementation at conventionally fired waste to energy facilities where the CO<sub>2</sub> concentration is in the order of 10% and will not be discussed further.

#### **4.5 Summary of post-combustion CO<sub>2</sub> separation technologies**

Out of the discussed post-combustion CO<sub>2</sub> separation technologies, absorption-based CO<sub>2</sub> capture is by far the most mature technology. Due to the relatively low CO<sub>2</sub> concentration in the flue gas flow from conventional MSW combustions systems, coupled with the expected integration in the tail-end of the Sysav WtE facility means that absorption-based technologies are the most applicable and viable. Consequently, only absorption-type CO<sub>2</sub> separation technologies is considered relevant for Sysav's WtE facility. Absorption-based technologies are discussed in the following section.



## 5. ABSORPTION-BASED SOLVENTS AND TECHNOLOGIES

This section includes a detailed description of an inexhaustive selection of solvents, some of which are presently available and mature, while others are more developmental in nature. A summary of the different absorption-based solvents and technologies may be seen in Table 3 below:

**Table 3 – Summary table of absorption-based solvents and technologies.**

Solvent	Advantage	Disadvantage
<b>MEA</b>	Most mature technology. Applied commercially in fossil-fuel industry for decades.	Very high energy demand for solvent regeneration (3-4 MJ/kgCO <sub>2</sub> ). Thermal degradation of solvent. Degradation products potentially carcinogenic. Ammonia emissions from absorber require mitigation technologies. Highly corrosive solvent.
<b>PZ-AMP</b>	Lower energy demand for solvent regeneration (2.97 MJ/kgCO <sub>2</sub> ). More stable and less corrosive than MEA.	Less mature than MEA. Untested in full scale.
<b>HPC</b>	Can potentially be run with very low external heat delivery.	Requires pressurization of entire flue gas flow which requires significant power consumption.
<b>CPC Enzymatic</b>	Provides the benefits of HPC without the need for flue gas compression. Can use low-grade heating.	Less mature than both MEA and HPC. Only works at low temperatures.
<b>Rotating Packed Beds</b>	Amine-based technology. Significantly smaller components (75 % reduction claimed). Claimed slightly lower heat demand than fixed packed bed columns.	Not tested in full-scale. Significantly more complex solution and higher parasitic loads than fixed packed bed columns.
<b>AMP-DMSO</b>	Potentially very low energy demand (1.2 MJ/kgCO <sub>2</sub> ). Can use low-grade heating.	Still a lab-based technology. Not yet demonstrated in relevant scale.

The different absorption-based solvents and technologies is described in further depth in the following.

### 5.1 Amines

Of the CO<sub>2</sub> separation technologies described above, absorption-type CO<sub>2</sub> capture with amine-based solvents is currently the most technologically mature and cost-effective solution. Amine CO<sub>2</sub> capture technologies have been used for more than 60 years to remove CO<sub>2</sub> from natural gas in a process known as natural gas sweetening. However, integration of amine-based CO<sub>2</sub> capture in the flue gas streams from power generation facilities is substantially different than CO<sub>2</sub> capture from natural gas. This is due primarily to the much lower partial pressure of CO<sub>2</sub>

and relatively high temperature of the flue gas. Regardless, absorption-based CO<sub>2</sub> capture with amine solvents is by far the most studied for point energy generation point sources such as WtE facilities with atmospheric flue gas containing approximately 5-15 % CO<sub>2</sub>.

The process works by scrubbing the flue gas with a solvent that absorb the CO<sub>2</sub> from the flue gas. The absorption process typically occurs in a packed bed tower denoted as the absorber column. Amine-based CO<sub>2</sub> capture utilize the difference in solubility of CO<sub>2</sub> in the solvent at different temperatures, with the solubility being inversely proportional with temperature. Thus, CO<sub>2</sub> is absorbed by the solvent at relatively low temperature in the absorber column after which the now CO<sub>2</sub>-loaded solvent is directed to a separate column where it is heated against steam in a counter current packed bed tower denoted as the stripper column. The heating causes the absorbed CO<sub>2</sub> to be released or desorbed from the solvent. After the CO<sub>2</sub> is released it is typically compressed and/or liquefied for transportation.

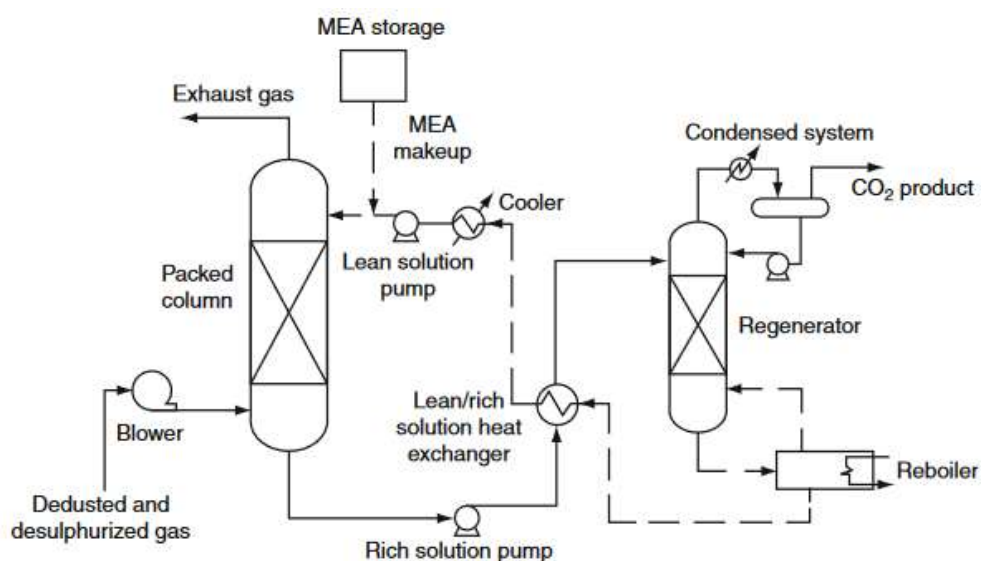


Figure 8 – Stylized schematic of Amine-based CO<sub>2</sub> capture system.

The biggest disadvantage of amine-based CO<sub>2</sub> capture is the high amount of energy required for the solvent regeneration or CO<sub>2</sub> desorption. Of the amines applied for CO<sub>2</sub> capture, monoethanolamine (MEA) is by far the most well studied and is often considered as the benchmark for amine scrubbing.

Additionally, many amines are challenged by thermal and oxidative solvent degradation. These degradation products can be harmful to both humans and the environment. Emissions of nitroamines, one of the primary degradation products from amine CO<sub>2</sub> capture systems, is also potentially carcinogenic. Thus, special emission mitigation systems must be implemented for amine-based CO<sub>2</sub> capture systems.

### 5.1.1 MEA

A traditional amine-based CO<sub>2</sub> capture system has specific reboiler duty between 3.0-4.0 MJ/kgCO<sub>2</sub>. For amine CO<sub>2</sub> capture, the solvent regeneration energy is typically sourced from the power plants' steam cycle, which has a significant penalty on the overall energy production and efficiency of the facility. For MEA-based solvents this penalty can incur an upwards of 30 % efficiency drop. The high required energy for solvent regeneration remains the biggest technical challenge with MEA-based CO<sub>2</sub> capture.

It should be noted that multiple different solutions have been developed to reduce the external heat energy requirement of MEA-based CO<sub>2</sub> capture systems. Examples of this include Lean Vapor Compression (LVC), steam ejectors and Mechanical Vapor Recompression (MVR), which all upgrade heat energy for internal recycling. Additionally, the recoverable heating from MEA based systems is at a temperature suitable to produce district heating either directly or through the use of heat pump systems.

CO<sub>2</sub> capture using MEA solvents have been demonstrated at full-scale in a WtE facility in Duiven in the Netherlands, where CO<sub>2</sub> is captured during the summer period and supplied to nearby greenhouses to enhance plant growth through elevated CO<sub>2</sub> levels. The Duiven CO<sub>2</sub> capture facility has been in operation since 2020.

### **5.1.2 AMP-PZ**

An alternative solvent to using MEA is 2-Amino-2-methyl-1-propanol/piperazine commonly denoted as AMP-PZ, which is known to have a significantly lower specific energy demand than for MEA. It has also been shown that AMP-PZ is significantly more stable against oxidative degeneration and less corrosive than MEA. Experimental investigations have shown that the specific solvent consumption for AMP-PZ is 0.45 kg/tCO<sub>2</sub> compared to approximately 1.5 kg/tCO<sub>2</sub> for MEA. For these reasons, AMP-PZ has been suggested as a new benchmark to replace MEA.

It should be noted though, that AMP-PZ is significantly less mature as a solvent than MEA having been tested only in pilot-scale facilities.

### **5.1.3 Rotating Packed Beds**

To optimize the capture process with regards to the volume taken up by the packed bed absorber and stripper columns, it is possible to utilize Rotating Packed Beds (RPBs). The fundamental concept involves replacing the large conventional vertical packed bed columns typically applied in CO<sub>2</sub> capture systems with significantly smaller units. These units consist of disks of packing material that rotate at high speeds (600-1000 rpm) to generate high gravity centrifugal forces. The solvent flows from the inner edge of the rotating disk radially towards the outer edge with the incoming countercurrent flue gas contacting the solvent. The super gravity generated in the RPBs provide high liquid shear and improved CO<sub>2</sub> mass transfer efficiency.

The principal benefit of using RPBs is that highly concentrated solvents can be used in smaller units to absorb similar quantities of gas that would normally require tall contacting columns and high solvent circulation rates. This leads to higher CO<sub>2</sub> loadings and consequently lower specific energy requirements (approx. 13 %).

Additional benefits include reduced sizing requirements for heat exchangers, pumps and coolers by up to 50 %, lower residence time in both absorber and stripper mean less oxidative and thermal degradation, that in turn reduces solvent consumption by up to 77 %. A schematic illustration of the working principle of RPBs may be seen in Figure 9 below:

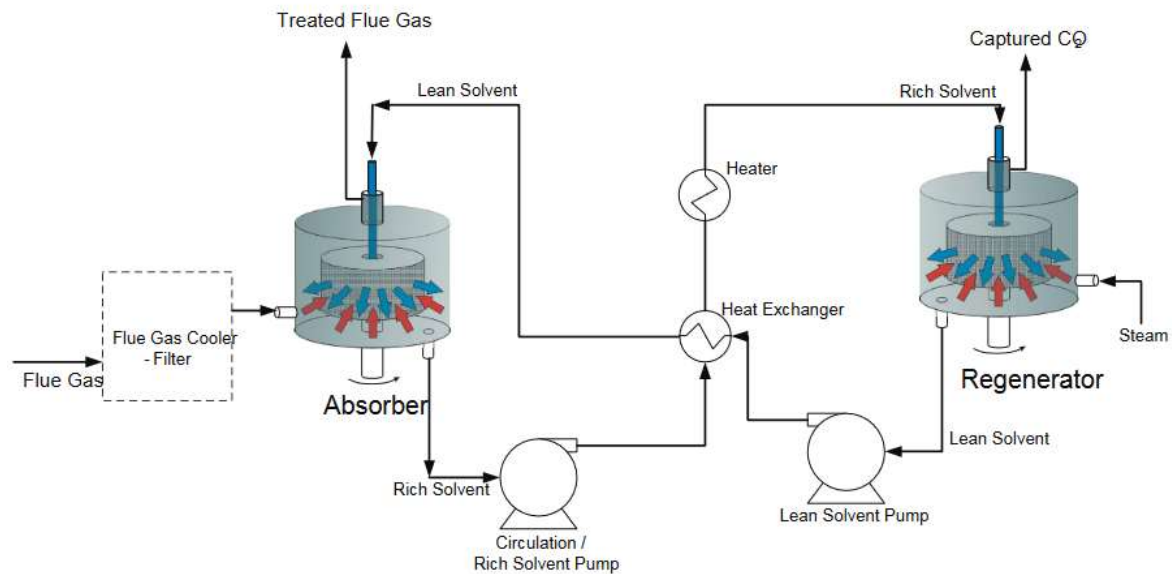


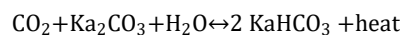
Figure 9 – Schematic diagram of RPB technology (From: NETL ROTA-CAP)

It should be noted though, that there are some significant disadvantages to the usage of RPBs. For example, the rotation of the packed beds constitutes a significant additional complexity compared to conventional static columns. Consequently, the RPBs will likely have far higher maintenance costs. Additionally, the parasitic power consumption of the CO<sub>2</sub> capture module will be significantly higher than for static columns due to the electric power required for the rotating columns. While RPBs for CO<sub>2</sub> capture have been tested in lab and pilot-scale, the technology has not been demonstrated in full-scale.

## 5.2 Hot Potassium Carbonate

The Hot Potassium Carbonate (HPC) process is very similar to the amine-based technologies, with the solvent being an aqueous solution of potassium carbonate rather than amines. The HPC process additionally employs a far greater degree of Pressure-Swing Absorption (PSA) than amine-based technologies that are typically based on Temperature-Swing Absorption (TSA).

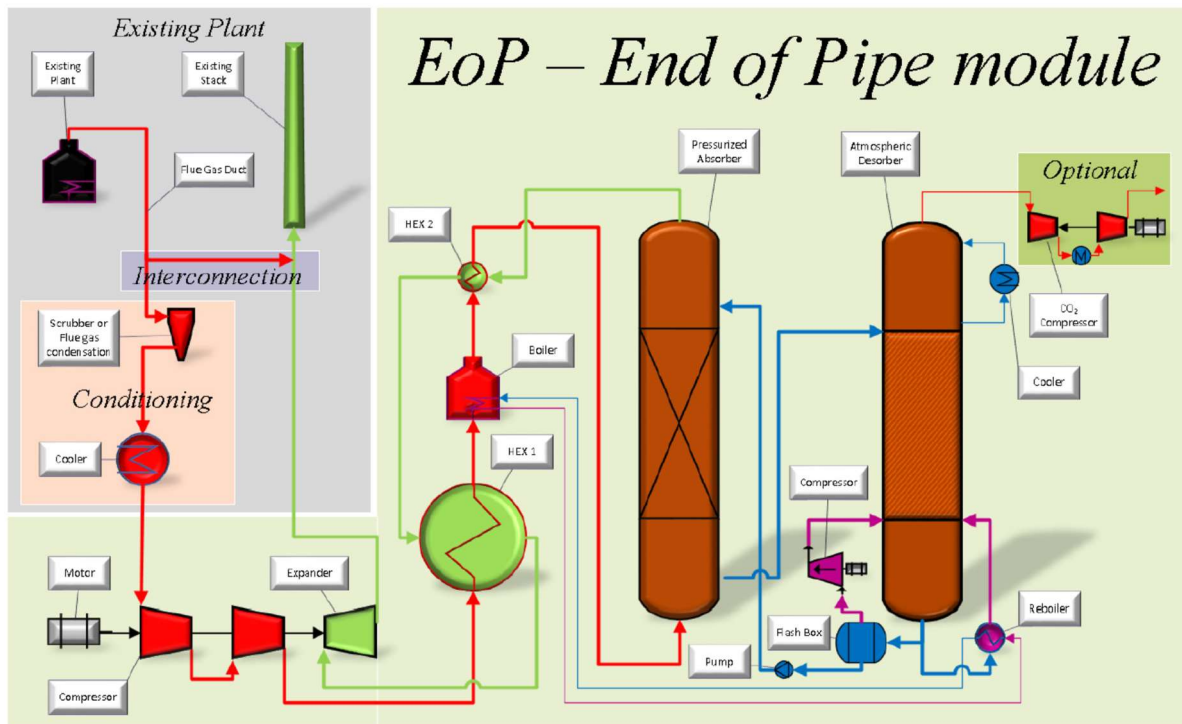
The process in the absorber column proceeds as aqueous potassium carbonate reacts with CO<sub>2</sub> and forms potassium bicarbonate as shown below:



The HPC process has been applied in more than 1000 facilities globally. It should be noted though that the HPC technology has been primarily applied to capture CO<sub>2</sub> at elevated pressures e.g., in the chemical industry, where the potassium carbonate absorbs the CO<sub>2</sub> from high pressure gas mixtures after which the CO<sub>2</sub> is released at lower pressures. The pressurized HPC process has been selected by Stockholm Exergi as the method of choice for CO<sub>2</sub> capture from their upcoming bio-char combustion facility.

In the pressurized HPC process the entire flue gas flow must be pressurized until the partial gas pressure of CO<sub>2</sub> is approximately 1 bar. For a typical flue gas stemming from WtE facilities the concentration of CO<sub>2</sub> is approximately 12-13 %, which means that the entire flue gas must be compressed to a pressure between 7 to 9 bar. The high compression power required to facilitate

this pressure increase is one of the primary drawbacks of the HPC technology. The advantage, however, is that the process largely does not require external heat energy. A schematic showing the working principle of CAPSOLs pressurized HPC process may be seen in Figure 10 below:



**Figure 10 – Stylized diagram showing the working principle of CAPSOLs pressurized HPC process.**

As the figure above shows the heating requirement for the gas stripping process in the right column is driven by waste heat from the compression process and a Lean Vapor Compression (LVC) system that utilizes low-grade heat from the lean solvent flow to generate steam for the gas stripping process. LVC systems are also frequently applied in amine-based solvents. Additionally, most of the generated waste heat from the compression of the flue gas is used for preheating the “clean” CO<sub>2</sub>-free outlet flue gas, ensuring that part of the input power requirement for the flue gas pressurization is recuperated.

Finally, potassium carbonates are cheap and environmentally benign chemicals that form salt and thus do not react with other compounds in the flue gas or degrade from oxidization or heating as for amines.

### 5.3 Cold Potassium Carbonate Enzyme

One interesting recent development to CO<sub>2</sub> capture with Potassium Carbonate is the use of enzymes such as carbonic anhydrase to increase the reaction kinetics of the process, allowing it to operate at significantly lower temperatures and pressures. For this reason, this technology is often denoted as the Cold Potassium Carbonate (CPC) process. The addition of carbonic anhydrase has been shown to increase CO<sub>2</sub> absorption by between 6-20 times making the reaction kinetics comparable to those exhibited by amine-based solvents such as MEA, DEA and PZ.

The principal advantage of the CPC process is the non-hazardous qualities of the solvent constituents, being only water, potassium carbonate and carbonic anhydrase. Carbonic anhydrase is a naturally occurring enzyme that can be found in many living organisms where its role is to speed up various chemical reactions.

The specific energy consumption is comparable to conventional amine-based solvents. One benefit though, is that the heat may be delivered at a much lower temperature than conventional amine systems (70 °C vs 125 °C) which enables the use of lower quality heat energy for CO<sub>2</sub> desorption. This is possible principally due to the process utilizing a greater degree of PSA than amine systems with the stripper column operated in a vacuum (0.28 bara). The requirement for operating the stripper in a vacuum necessitates the implementation of a booster compressor at the stripper outlet to maintain the pressure.

An additional disadvantage is that the enzyme is very sensitive to temperature changes, and the activity of carbonic anhydrase decreases with increasing temperatures. This means that the flue gas at the absorber inlet must be relatively cold for the solvent to perform well.

A pilot CO<sub>2</sub> capture facility based on the CPC process has been built in Saint-Felicien in Canada. It is however unclear whether the technology has been sufficiently demonstrated through operation of the pilot plant.

#### **5.4 AMP-DMSO**

The AMP-DMSO is a new emerging solvent developed by Chemical Engineering Faculty of Lund University, Sweden. The solvent utilizes an amine, AMP (2-Amino-2-methyl-1-propanol), to absorb CO<sub>2</sub> from the flue gases. However, where other amine technologies utilize an aqueous solution, the Lund University uses an organic solvent, DMSO (Dimethyl sulfoxide). Upon the carbamate formation after the amine has absorbed CO<sub>2</sub>, due to a very low solubility in DMSO, the carbamate precipitates out of the solution as a white salt that may be relatively simply separated from the non-reacted solvent. The principal benefit to this is that only the loaded solvent has to be generated, and thus only a small percentage of the solvent needs to be heated to strip off the absorbed CO<sub>2</sub>.

The smaller loaded solvent flow to the stripper means that the specific energy demand for solvent regeneration is considerably smaller than for conventional solvents at around 1.2 MJ/kgCO<sub>2</sub>. The separation of the loaded solvent requires a hydro-cyclone or centrifuge which separates the liquid and solid phases of the solvent after the absorber. The unreacted entirely liquid solvent is returned to the absorber, while the precipitated salt is directed to a CO<sub>2</sub> stripper as a slurry. Since the solution is non-aqueous, it is necessary to heat the loaded solvent indirectly with steam to strip off the absorbed CO<sub>2</sub>. This is done in a falling film heat exchanger where the loaded solvent is heated to 90 C to strip off the CO<sub>2</sub>. A diagram of the AMP-DMSO process may be seen in the figure below.



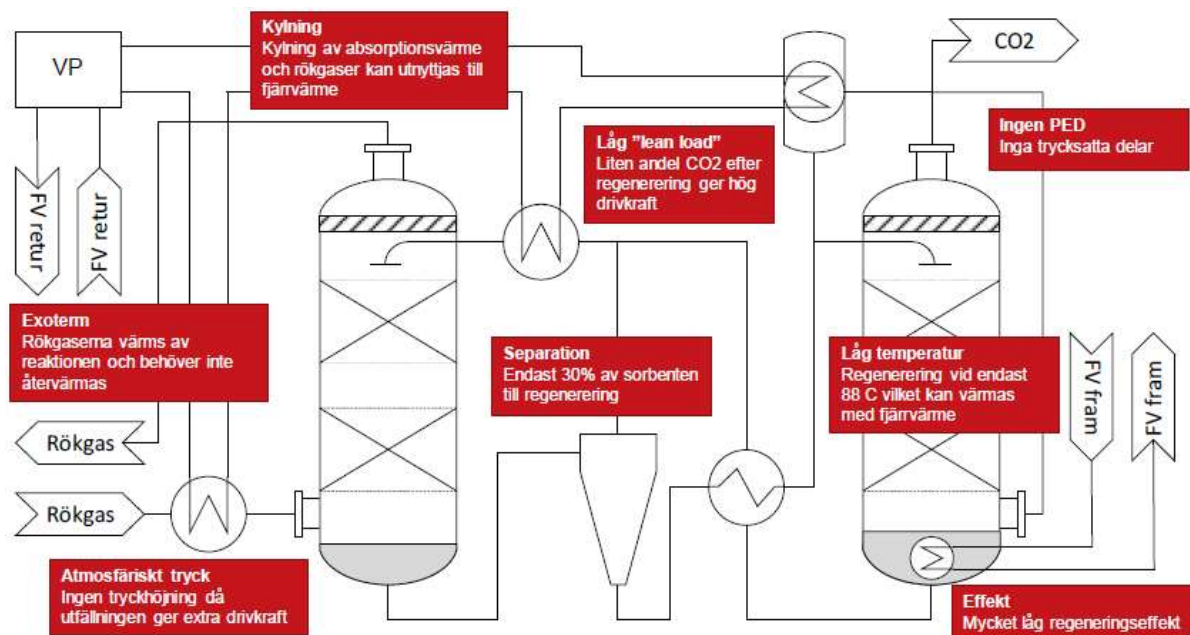


Figure 11 – Schematic of the AMP-DMSO technology. (From Midrock)

As it may be seen from the figure, the stripper has been shown as a conventional packed bed column but will as mentioned be constructed as a falling film heat exchanger. One of the key advantages to this is that the stripper can be made significantly smaller and cheaper than for conventional systems. Additionally, shown in the figure is the hydro-cyclone that separates reacted and unreacted solvent between the absorber and stripper column.

The technology has some very clear advantages compared to conventional solvents, namely the very low specific energy demand and the potential to use lower-value heat for solvent regeneration. Additionally, the entire process operates at atmospheric pressure. There are, however, also some considerable disadvantages. For one the precipitation of the solvent requires low temperatures (25 °C) in the flue gas at the absorber inlet. For many applications ensuring this low temperature will require active cooling of the entire flue gas flow with refrigeration systems. Finally, since the absorption process is very exothermic, ensuring that the temperature in the absorber allows for precipitation of carbamate requires multiple stages of intercooling.

Additionally, the power consumption of the hydro-cyclone has not been quantified, but it seems highly probable, that the parasitic loads of the AMP-DMSO technology is higher than conventional solvents. Thus, it is not currently established whether the lower specific heat delivery for CO<sub>2</sub> desorption is offset by a significantly higher parasitic power consumption.

DMSO is classified as a non-toxic solvent with lethal median dose higher than ethanol. However, because DMSO is a skin-penetrating solvent dissolved toxic compounds can enter the body upon contact with the solvent. Additionally, DMSO can decompose at temperatures above 189 °C which can in some cases case an explosion. Thus, special care must be implemented for DMSO-based systems, and while the decomposition temperature is unlikely to be exceeded in normal operation, DMSO explosivity is a hazard in case of fires.

Finally, it must be mentioned that the technology is very immature compared to the alternative solvents discussed in this section. It is still a lab-based technology, and while the basic operating



principles have been demonstrated in smaller experimental setups, the technology remains untested at relevant scales and a number of important questions remain unanswered.

## **5.5 Summary of Absorption-based solvents and Technologies**

To summarize, there are a number of existing and emerging solvent solutions that are interesting for implementation at Sysav. These six solvents (MEA, AMP-PZ, HPC, CPC Enzymatic, RPBs and, AMP-DMSO) is assessed with regards to their respective current and projected technical and commercial readiness in the next section.

## 6. TECHNICAL AND COMMERCIAL READINESS ASSESSMENT FOR SELECTED TECHNOLOGIES

Given that the timeline for the CO<sub>2</sub> capture integration at Sysav is for operation to begin in 2030, the final design and selection of solvent and technology should be made with ample time for basic and detailed design, tendering, construction and commissioning. As a result, the deadline for final selection should be made at the latest in 2027. To quantify which of the solvents and technologies listed in the previous section that can be made ready for implementation at Sysav by 2027 an evaluation of technical commercial readiness is included in this section.

A standardised evaluation method is the Technical and Commercial Readiness evaluation. Technical readiness evaluation has been performed in many industries and for many decades and the common scale is the Technology Readiness Level (TRL) scale developed by NASA in the 1970s. The scale ranges from research stage to ready for deployment stage but does not have an operational experience requirement and does not involve market conditions or response like the German VDI3460 standard.

The Commercial Readiness Index (CRI) introduces also operational experience and market conditions. The CRI evaluation is based on a methodology introduced by, among others, the Australian Renewable Energy Agency (ARENA) "Commercial readiness index for renewable energy sectors" (2014). CRI is used to describe the challenges of commercialising renewable energy production technologies and differs from the Technology Readiness Level. Thus, reaching the maximum Technical Readiness Level (TRL) 9 does not necessarily mean that a technology is commercially attractive.

A description of the different TRL levels as defined by ARENA may be seen in Table 4 below.

**Table 4 - Technology Readiness Levels as defined by ARENA. (From Australian Renewable Energy Agency)**

Level	Summary
1	<b>Basic principles observed and reported:</b> Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
2	<b>Technology concept and/or application formulated:</b> Applied research. Theory and scientific principles are focused on a specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
3	<b>Analytical and experimental critical function and/or characteristic proof of concept:</b> Proof of concept validation. Active research and development is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
4	<b>Component/subsystem validation in laboratory environment:</b> Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
5	<b>System/subsystem/component validation in relevant environment:</b> Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
6	<b>System/subsystem model or prototyping demonstration in a relevant end-to-end environment:</b> Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

Level	Summary
7	<b>System prototyping demonstration in an operational environment:</b> System prototyping demonstration in operational environment. System is at or near scale of the operational system with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
8	<b>Actual system completed and qualified through test and demonstration in an operational environment:</b> End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.
9	<b>Actual system proven through successful operations:</b> Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

A description of the ARENA definitions of the different levels of commercial maturity may be seen in Table 5 below.

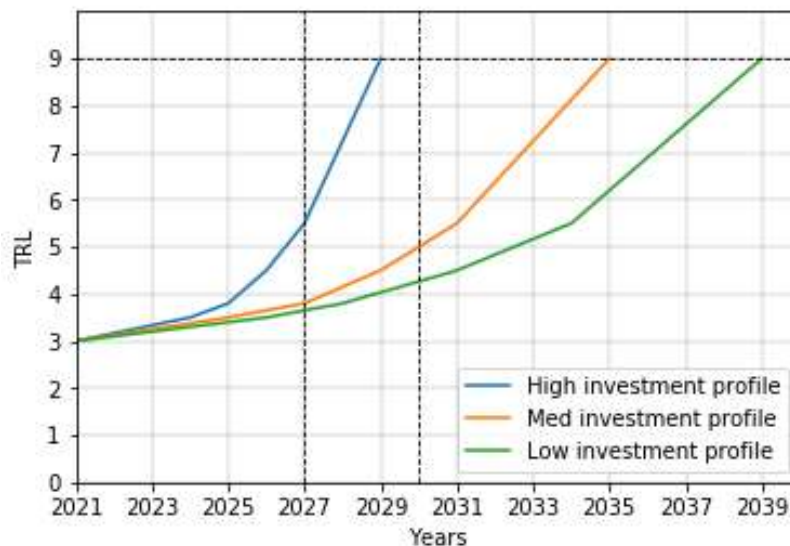
**Table 5 - Commercial Readiness Indices as defined by ARENA. (From Australian Renewable Energy Agency)**

Level	Summary
6	<b>"Bankable" grade asset class</b> driven by the same criteria as other mature energy technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other market forces driving uptake.
5	<b>Market competition driving widespread deployment</b> in context of long-term policy settings. Competition emerging across all areas of supply chain with commodisation of key components and financial products occurring.
4	<b>Multiple commercial applications</b> becoming evident locally though still subsidised. Verifiable data on technical and financial performance the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.
3	<b>Commercial scale up</b> occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publically discoverable data driving emerging interest from finance and regulatory sectors.
2	<b>Commercial trial:</b> Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
1	<b>Hypothetical commercial proposition:</b> Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.

The different technologies and solvents listed in Table 3 (MEA, AMP-PZ, HPC, CPC Enzymatic, RPBs and, AMP-DMSO) have been assessed based on available information and paired with the definitions of TRL and CRI as defined in Table 4 and Table 5.

Based on the currently assessed TRL and CRI level, the given solvent or technology may mature and develop differently according to how much capital is invested in the development process.

This is shown graphically in Figure 12 below for a generic solvent technology, where low, medium, and high investment profiles are shown.



**Figure 12 – Projected development for the TRL level for emerging successful technologies for different levels of investments**

In Figure 12 a dashed horizontal line has been included to show when the solvent technology matures to be fully ready for implementation at TRL 9. Additionally, two vertical dashed lines show the deadline for technology selection in 2027 and the planned commissioning date in 2030. This methodology has been applied to the solvents and technologies listed in Table 3 to assess the potential range of TRL and CRI levels probable by 2027 as a consequence of potential development and investment profiles.

Table 6 shows the evaluated current (2021) TRL’s and CRI’s and the future projected (2027) TRL’s and CRI’s for the most relevant technologies for Sysav’s WtE plant.

**Table 6 – Current and projected TRL and CRI levels.**

Solvent	TRL - 2021	TRL - 2027	CRI - 2021	CRI - 2027
<b>MEA</b>	9	9	5	6
<b>PZ-AMP</b>	7	8-9	2	3-5
<b>HPC</b>	7	8-9	3	4-5
<b>CPC Enzymatic</b>	7	8-9	2	3-5
<b>Rotating Packed Beds</b>	6	7-9	2	3-5
<b>AMP-DMSO</b>	3	4-6	1	2-3

As it may be seen from Table 6, the projected technology and commercial readiness levels vary significantly depending primarily upon the assessed current levels. The motivations behind the projected technical and commercial readiness levels are detailed in the following.

For MEA, there are already large-scale CO<sub>2</sub> capture facilities in operation. The technology is fully developed, and the technical hurdles and benefits are very well understood. As a result, the TRL level is 9 for both the current assessment and the 2027 projections. The CRI level is currently assessed to be 5 since multiple companies are presently able to deliver CO<sub>2</sub> capture systems based on MEA technology. For the 2027 projections of CRI for MEA, the level is 6 thus representing a bankable asset. The motivation behind this assessment is that the regulatory frameworks to make MEA systems bankable is projected to be implemented by year 2027.

For PZ-AMP, HPC, CPC Enzymatic, and RPBs, the technologies have been tested and demonstrated in pilot-scale facilities. For this reason, the solvents and technologies are assigned current TRLs of 6 or 7 and CRIs of 2 to 3. By 2027, the TRLs are projected to have increased to between 7 and 9 depending on the level of investment into developmental efforts. Similarly, the CRIs are projected to increase to between 3 and 5.

AMP-DSMO is still a lab-based technology that has not been tested in proper scale outside of a lab environment. For this reason, it is assigned a TRL of 3 and a CRI of 1 at the current level of development. For the 2027 projections, a TRL level between 4-6 is achievable with CRI levels between 2-3.

## 7. SELECTION CRITERIA

To evaluate and compare the different solvents and technologies, a scoring table based on the relevant parameters has been developed, which is presented in Table 7. The scoring table represents the qualitative selection criteria. The relevant parameters are HSE, CAPEX, energy demand and operations and maintenance costs. For the four parameters, a value of 1 reflects a low performance, 2 reflects a medium performance, and 3 reflects a high performance.

**Table 7 – Comparative scoring table for investigated solvents and technologies.**

Solvent	HSE	CAPEX	Energy demand	Operations & maintenance
<b>MEA</b>	*	**	*	**
<b>PZ-AMP</b>	**	**	**	**
<b>HPC</b>	***	*	*	*
<b>CPC Enzymatic</b>	***	*	*	*
<b>Rotating Packed Beds</b>	*	***	**	*
<b>AMP-DMSO</b>	*	**	***	**

MEA has by far the highest level of technical and commercial maturity of the detailed technologies and with known, well-understood behaviors related to the parameters in Table 7, MEA is a conservative choice for CO<sub>2</sub> capture at Sysav. Aqueous MEA solvent is highly corrosive, and some degradation products are toxic and carcinogenic. Thus, MEA requires special measures such as a water scrubbing section implemented at the outlet of the absorber. For this reason, MEA is assigned an HSE scoring of 1, however, solutions are possible to mitigate the HSE challenges. With regards to the capital expenses (CAPEX) and operations and maintenance costs, MEA is relatively well-understood and is often used as reference point for comparison with other technologies. For this reason, MEA is assigned a score of two in both the CAPEX and operations and maintenance costs. With regards to the energy demand for different CO<sub>2</sub> capture technologies, MEA has a relatively high energy demand and is also generally considered the reference for comparison. For this reason, MEA is assigned a score of 1 in the energy demand category.

AMP-PZ is projected to achieve a reasonably high TRL and CRI by 2027 and may be deployable for the CO<sub>2</sub> capture integration at Sysav. In terms of HSE, AMP-PZ performs better than MEA due to the less corrosive solvent and better stability to oxidative and thermal degradation – leading to less degradation products. For these reasons, AMP-PZ is assigned a HSE score of 2. With regards to CAPEX a system operating with AMP-PZ is fundamentally the same as a system using MEA solvent, and for this reason the CAPEX and operations and maintenance costs are very similar, therefore AMP-PZ is assigned a score of 2 in both categories.

HPC is projected to attain a reasonably high level of TRL and CRI by 2027 and may be deployable for the CO<sub>2</sub> capture at Sysav. In terms of HSE performance, HPC has a significantly better conditions than MEA due to the non—hazardous solvent with no degradation products. For this reason, HPC is assigned a score of 3 in the HSE category. With regards to CAPEX, the HPC technology is projected to require significant capital investment due to the requirement for pressurization of the entire flue gas flow. For this reason, HPC is assigned a score of 1 in the CAPEX category. In terms of energy demand, the HPC process consumes very little heat energy, but requires a significant amount of high-value electricity to operate. For this reason, the HPC technology is assigned a score of 1. The operations and maintenance costs are closely related to the overall complexities of the capture system and due to the required flue gas compression systems, the HPC technology is assigned a score of 1 in the operations and maintenance costs.

The enzymatic CPC process is projected to attain a reasonably high level of TRL and CRI by 2027 and may be deployable for the CO<sub>2</sub> capture integration at Sysav. In terms of HSE, enzymatic CPC has better conditions than MEA due to the non—hazardous solvent with no degradation products. For this reason, enzymatic CPC is assigned a score of 3 in the HSE category. With regards to CAPEX, the enzymatic CPC technology is projected to require significant capital investment due to the requirement for booster compressors to maintain the vacuum in the stripper column. The energy demand of the enzymatic CPC process is comparable to conventional MEA systems and scores the same as MEA in this category. In terms of operations and maintenance costs, the enzymatic CPC process utilizes a very cheap base solvent, but the enzyme accelerants are likely to be relatively expensive. Similarly, the solution is more complex than the basic MEA process, necessitating more maintenance. For these reasons, the enzymatic CPC process is assigned a score of 1 in the operations and maintenance category.

The Rotating Packed Bed (RPB) process is projected to attain a reasonably high level of TRL and CRI by 2027 and may be deployable for the CO<sub>2</sub> capture integration at Sysav. In terms of HSE, the RPB technology is based on amine-type solvents with HSE scoring equivalent to MEA and AMP-PZ solvents. The promised claim-to-fame for RPB technology is a significantly reduced CAPEX costs. Whether this is actually attainable with spinning packed beds has not yet been demonstrated. However, taking the claimed CAPEX reductions for RPBs at face value, the CAPEX could potentially be significantly lower than comparable packed fixed bed technologies. For this reason, a score of 3 is assigned to the RPB technology in the CAPEX category. The energy demand for RPBs is claimed to be slightly lower for a given solvent than for packed fixed bed columns. For this reason, RPBs are assigned a score of 2 in the energy demand category. The operations and maintenance costs are closely related to the overall complexities of the capture system and due to the required systems to ensure a fast rotation of the packed beds, the RPB technology is assigned a score of 1 in the operations and maintenance costs.

The AMP-DMSO process is projected to attain a relatively low level of TRL and CRI by 2027 and is very unlikely to be deployable for the CO<sub>2</sub> capture integration at Sysav within the conditioned timeframe. In terms of HSE, AMP-DMSO have similar issues related to solvent degradation emissions as MEA and AMP-PZ. However, the inclusion of DMSO does present additional issues relating to the skin-penetrating nature of the solvent and the risk of explosions at high temperatures. For these reasons, AMP-DMSO is assigned a score of 1 in the HSE category. In terms of CAPEX, AMP-DMSO is very similar to MEA-based systems. Because of the separation of loaded solvent from the lean stream, the stripping side equipment can be made significantly smaller than for conventional systems. This is however, offset by the extra required equipment for the hydro-cyclone and multiple stages of absorber intercooling. For these reasons, the AMP-DMSO solvent is assigned a score of 2 in the CAPEX category. In terms of energy demand, the promise of a very low energy requirement makes the AMP-DMSO technology very interesting for future



implementations of CO<sub>2</sub> capture. Whereas the implementation of conventional MEA-based CO<sub>2</sub> capture systems generally incurs a penalty in the energy delivery of approximately 30 % of the power plant, the AMP-DMSO implementation can potentially be implemented with a much lower penalty in the produced energy. This means that the overall distributed costs per ton of CO<sub>2</sub> captured may potentially be significantly lower than for competing systems. For the operations and maintenance costs of AMP-DMSO, the technology is very similar to the MEA-based system, with the principal unknown parameter being the consumption of DMSO and the associated costs for the solvent. There is likely to be more maintenance related to the hydro-cyclone, but the maintenance costs for the stripping side are likely to be lower than for MEA systems. For these reasons, a score of 2 for the operations and maintenance costs are assigned.

Based on the projected TRL and CRI levels in 2027 shown in Table 6 and the overall evaluation of the scoring of the individual solvents and technologies shown in Table 7, two solvent technologies are to be selected for further study in the current project by Sysav. The recommended technologies for further study are presented in section 8 "Recommendations".

## 8. RECOMMENDATIONS

Based on the screening and evaluation of the relevant CO<sub>2</sub> capture technologies for implementation at Sysav, it is recommended to further investigate and study the following two technologies in the present pre-feasibility study (Övergripande förstudie):

**Base case technology:**

**Monoethanolamine (MEA)**

**Alternative technology:**

**Hot Potassium Carbonate (HPC)**

The motivation for selecting these two technologies is explained in the following.

MEA is a known technology, scores high on both technological and commercial readiness levels and is principally ready for implementation today and thus serves as a conservative, safe technology choice. In addition, MEA is often the reference technology for CO<sub>2</sub> capture and it will be valuable for Sysav to study this technology further allowing better comparison with competing technologies.

HPC is a less commercially mature technology than MEA, is unproven at relevant scale, however, receives a reasonable score in terms of both technological and commercial readiness levels. It is interesting to investigate due to its very low external heat demand which would have a low impact on Sysav's energy system.

The two solvents utilize a fundamentally different technology for solvent regeneration, and it is thus interesting to further study the implementation, performance and the economics of operating an HPC-based capture system compared to a more conventional MEA-based system.

The HPC technology has also been selected for implementation or as study case by several other Swedish WtE facilities potentially allowing for Sysav to benefit from the operational experience from other operators of this technology. Similarly, it may be possible to leverage the large-scale benefits from a consortium of WtE plants operating HPC systems to cost-effectively purchase solvents and other consumables.