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Appendix I to WP4 report – 30 November 2023

Appendix I - Definition of scenarios for an EU-wide shared CO2 infrastructure

DEMO UP CARMA

WP4: Subtask 2.3 – Definition of scenarios for an EU-wide shared CO2 infrastructure.

1 Introduction

1.1 Background & Objectives

The Swiss Federal Council has stressed the deployment of carbon capture, transport, and storage (CCTS) as a key component of Switzerland's strategy to reach net zero by 2050. The estimated difficult-to-avoid emissions remaining by 2050 amount to 12 Mt CO_2, up to 7 Mt CO_2 of which will need to be avoided by utilising domestic carbon capture through CCTS and carbon removal (CDR) projects [1]. These strategies primarily rely on transport and subterranean storage (T&S) infrastructure to durably store the captured CO_2. However, due to the time needed to conduct domestic subsurface exploration and the risk of unfit geological formations, Swiss storage capacity is not expected to be operational for at least 15-20 years, if at all [2]. In the meantime – and even in the years to come – Switzerland will need to export substantial amounts of CO_2 emissions to foreign storage sites that have already established technical certainty regarding storage capacity.

In Europe, efforts are underway to establish a continent-wide CO_2 T&S network, which holds the potential to be shared or integrated with a Swiss CO_2 transport network, granting Swiss industries access to durable storage sites. The Swiss Federal Office of Energy (SFOE) intends to initially transport CO_2 by truck and rail [3]. However, without pipelines, transport capacity from Switzerland would remain limited. Therefore, Switzerland plans to establish a dedicated CO_2 pipeline infrastructure within its borders, contingent on connecting with emerging European infrastructure. Enabling this connection is a complicated endeavour, as it involves not only coordination and development within Switzerland but also broader coordination with other countries and industry players.

The main objective of this subtask is to identify and analyse potential cross-border T&S project plans across Europe that could enable Swiss industries to access permanent storage sites. Most of the project plans in Europe are nascent and mainly in the planning stages, with uncertainties concerning financing, governance, and other organisational and regulatory aspects yet to be considered and resolved. These aspects are critical in realising project plans. The focus in this task, however, is on analysing current infrastructure plans and how they contribute to developing a cross-border European CO_2 T&S network. Analysing these plans within a Swiss context serves as a crucial starting point to initiate concrete action on establishing a robust Swiss connection within the emerging network.

1.2 Procedures & Methodology

The development of a European cross-border CO_2 T&S infrastructure is in its early stages, and most of it presently remains non-operational. A broad overview of the overall landscape of the development of a European CO_2 network is provided in **Section 2**, with special attention to targets and policies at the EU level. A set of criteria has been established to comprehensively identify cross-border CO2 transport and storage plans relevant to Switzerland's network. Analysed project plans must (i) involve storage and/or transport components, (ii) be publicly disclosed, (iii) be located within Europe, (iv) intend to have durable storage as an endpoint, and (v) have an announced capacity of at least 2 million tonnes per annum (Mtpa). The rationale behind establishing these criteria is elaborated on below.

After the identification of the relevant projects, detailed descriptions of the T&S project plans that align with the criteria above are provided in **Section 3.** Here, a comprehensive overview of emerging developments across Europe is critical given the operational complexity that such a transnational network presents. This section applies a directional distinction based on potential delivery points of the proposed Swiss CO_2 pipeline network towards the North on the one hand and the South on the other.

With the identification and analysis of all relevant projects that may be a part of developing Swiss access to permanent storage, **Section 4** focuses on presenting potential future scenarios for the T&S route from Switzerland to storage areas. Lastly, we discuss further uncertainties and potential future implications of different development scenarios, an essential context to provide due to the nascent yet fast-moving European CO_2 network developments.

For the analysis we look at CCS projects and plans under the following criteria:

- **(i)** **Plans involve CO_2 terminal, transport, and/or storage components.** Plans for only capture facilities are not within the scope of this task.
- **(ii)** **Plans have been publicly disclosed.** Plans that have not been publicly disclosed are disregarded, e.g., due to uncertainty surrounding their potential and progress.
- **(iii)** **Plans are located in Europe.** From Switzerland, CO_2 transport and storage outside Europe is deemed economically and logistically infeasible.
- **(iv)** **Plans have CO_2 permanent storage as their endpoint.** CCUS projects are excluded in this analysis. These projects are not central to the European CO_2 network.
- **(v)** **Plans have announced a capacity of at least 2 million tonnes per annum (Mtpa).** The focus is on projects that exhibit intentions to be a part of a wider transport and storage network. Therefore, all collocated capture and storage projects (i.e., full-chain projects) are excluded.

The study draws upon open databases maintained by the International Energy Agency (IEA) [4] and Clean Air Task Force (CATF) [5], both of which list openly communicated CCTS projects across Europe. To ensure a comprehensive overview, both databases are merged and compared, considering their differences in scope and detail. Projects not listed in these databases are not considered. However, essential project details missing for this analysis had to be collected from various other relevant sources.

There are certain limitations to this analysis. Since it relies on project plans and outlooks, there is a possibility that plans undergo changes. Project plans may scale up or down, accelerate or slow down, or even be cancelled. Furthermore, new projects are likely to emerge and be developed in the near future. Additional projects will be critical to the success of the European T&S network, given that the current capacities of confirmed projects still fall short of meeting the rapidly growing demand for CCTS across Europe [6].

2 Development of a European CO2 Transport & Storage Network

To understand how a future European CO_2 T&S network might look like, a holistic approach is necessary. That entails listing the key characteristics and requirements of such a network whilst also exploring the broader European network development landscape. Therefore, before delving into specific T&S project details, we provide a general overview of the regional developments that surround the projects in question.

2.1 Characteristics & Requirements

The CCTS value chain captures CO_2 from point emitters, at which point, emissions can be transported using different modes of transportation to underground offshore and onshore storage sites for durable storage. Today, this infrastructure is limited in scale, but there is a growing recognition within the European Union (EU) of the importance of expanding the use of CCTS to meet climate goals. This emphasis on CCTS expansion is highlighted in the recently proposed Net Zero Industry Act, which underscores the necessity of a coordinated effort to effectively broaden CCTS adoption. The EU envisions a shared cross-border CO_2 network with a single-market approach, offering clear advantages to economies of scale [6].

Owing to the diverse technical, regulatory, and socioeconomic factors that can vary across different countries and regions, emitters and countries may encounter distinct opportunities and challenges when it comes to transporting and securely storing their CO_2 emissions. Here, the implementation of a shared cross-border CO_2 network ensures an effective means for emitters and CCTS developers to address these regional disparities and navigate them successfully. These barriers are particularly relevant in the context of onshore infrastructure developments, where issues over land ownership and social acceptance may emerge [7].

2.1.1 Transportation Infrastructure

Large-volume CO_2 transportation is only practical and economically feasible by ship or pipeline transport. The transport of CO_2 via rail, road, and barges is still viable for smaller amounts of CO_2 but will not be feasible for large-scale CCTS deployment [8]. Consequently, countries aiming to capture substantial CO_2 amounts must consider CO_2 pipelines as the long-term mode of onshore transport.

Onshore pipeline infrastructure is ideal for industry clusters as it provides high-capacity CO_2 transport and can be connected to existing industry infrastructure. For remote emitters, pipeline infrastructure is not financially sensible, given the investment costs attached. Here, multimodal transport will remain important throughout the expansion of the network as remote emitters will utilise non-pipeline transport methods to reach CO_2 collection hubs or export terminals.

For offshore transport, both pipelines and shipping options are expected to be utilised in a future European CO_2 network. Pipelines and shipping offer different benefits and come with different challenges. For example, pipeline transport will become increasingly cost-effective with increasing flow rates, while ship transportation can offer economies of scale with transport distances [9]. In general, ship transportation is more suitable for transporting smaller quantities over long distances, while pipeline transport is better suited for larger quantities and shorter distances. Shipping can be ideal during the pilot and ramp-up stages of the CCTS value chain but can face critical challenges in terms of buffer storage infrastructure at export terminal locations.

Importantly, opportunities exist to utilize existing infrastructure for the development of the cross-border CO_2 network. Here, repurposing existing oil and gas transport infrastructure can offer various benefits, particularly in reducing costs and environmental impacts of new infrastructure projects. Nevertheless, such activities still require extensive planning, testing, and retrofitting to ensure safe and reliable use. In addition, competition for the use of these pipelines can be expected from the hydrogen sector. Some hydrogen projects have also proposed pipeline retrofits to develop a European import and export hydrogen network [10]. However, through effective cooperation, overlapping infrastructure needs between hydrogen and CO2 T&S projects can also be integrated into shared plans that produce co-benefits for both parties.

2.1.2 Storage Sites

Both onshore and offshore storage sites are expected to be part of the European CO_2 network. However, not all countries possess equal capabilities to store CO_2 within their respective territories. Assessments of European CO_2 storage potential exhibit significant theoretical potential, but nonhomogeneous between areas [11]. In simple terms, geological storage formations can be split into two categories: storage reservoirs within saline aquifers and hydrocarbon fields that can exist both within and outside of saline aquifers. The assessments have shown that the North Sea area is home to the largest European sedimentary basins, with storage regions in Southern Europe being more geographically scattered [11].

This assessment provides a look into theoretical CO_2 storage potential given that scientifically certain judgements require more extensive exploration and analysis. Importantly, the effective utilisation of it is beset by a range of technical, financial, regulatory, and social challenges, collectively impeding the realisation of CO_2 storage site developments in Europe.

The largely uncharted and poorly understood subsurface geology in many areas contributes to the uncertainty surrounding storage capacity. Furthermore, the exploration and development of storage sites entail time-consuming and expensive permit processes under high risks and uncertainties, which discourage investments in storage projects [6]. On the regulatory front, some European countries, such as Germany and Austria, have imposed outright bans on onshore storage development, further complicating the pursuit of CO_2 storage solutions within their borders [12].

As of now, the first storage development targets are anticipated to focus on offshore storage sites, particularly in depleted oil and gas fields. These storage sites naturally serve as underground traps for CO_2. Moreover, the valuable insights gained from the extraction industry regarding subsurface geology make these sites typically better characterised and understood. In Europe, these areas are primarily situated in Northern Europe, particularly in the North Sea.

2.2 European-Level Developments

The EU's Projects of Common Interest (PCIs) for the European cross-border CO_2 network will play an important role in advancing key infrastructure developments. On a bi-annual basis since 2017, the EU has drawn a list of cross-border CO_2 transport and storage PCI projects under the Trans-European Networks for Energy (TEN-E) regulation. The infrastructure developed through these projects must be shared between at least two countries to incentivise transnational network development. By being on the PCI list, these projects benefit from various advantages, including accelerated planning and permit granting, improved regulatory conditions, funding, and more [13]. Collectively, the list is thus highly indicative of how the European CO_2 network will initially develop.

The list from 2017 included four CO_2 network projects [14], five in 2019 [15], and six projects in the currently enforced list from 2021 [16]. Projects from these three lists differ in scope and maturity level. Some projects have kept their status on the list, while others have been added, discontinued, or lost their status. All these projects are based in Northern Europe; more specifically, all projects plan for transportation and storage infrastructure leading to the North Sea.

The list of PCI candidates for the 2023 list was publicised for consultation in December 2022 and included 18 CO_2 network projects [17], an increase of over twofold from the eight candidates in 2021. Some of this year's candidate projects will likely not be on the final list, but a final decision is expected in November 2023. This new candidate list stands as proof of the significant advancements that have transpired since 2017, both in scale and broader scope. It is the first list to encompass ventures in Southern Europe, providing initial indications of a more expansive future European network. Moreover, the list is the first to offer projects the status of a Project of Mutual Interest (PMI), which are projects involving non-EU countries within the development of the European CO_2 network.

The 2023 list is also the first to include geological storage projects, i.e., network projects that are specifically storage-focused. This mirrors the need to advance storage development in Europe, which has clearly been highlighted in the EU's NZIA. It clearly states that as carbon capture investments become increasingly economically viable, the lack of operational storage sites will present the single largest bottleneck for these investments to materialise [6].

In response to this challenge, the Act sets a Union-level objective to be achieved by 2030 for an annual injection capacity into storage sites of 50 Mtpa CO_2. A key measure to implement this goal involves a requirement for better information on geological data relating to oil and gas production sites. This would further advance developments in the North Sea, which has evidently emerged as the natural starting point for the initial phases of European CO_2 storage infrastructure. The region is strategically positioned based on Northern European emitter locations and the wealth of existing knowledge on subsurface geology from the extraction industry. However, this does not imply the exclusion of other storage regions from playing a significant role in the subsequent stages of network development once effectiveness in operation is proven.

2.3 Regional Transport & Storage Developments

Following the criteria set in Section 1.2, we zoom in on individual countries, examining their storage site developments and transportation infrastructure separately. Subsequently, details on specific project specifications are provided in Section 3.

2.3.1 Storage Developments

The North Sea has emerged as the central hub for storage developments in Europe. Out of the seven countries bordering the North Sea, four have plans to develop storage areas under their North Sea jurisdiction: Norway, Denmark, the Netherlands, and the UK. These countries are well positioned to utilise these advantages to offer storage capacity for European countries with lower domestic storage potential.

Detailed studies regarding geological storage fields in recent years [18] position **Norway** as a frontrunner in storage site developments. The Norwegian storage projects, Sleipner and Snøhvit, stand out as the only operational offshore CO_2 storage areas at present and have gained extensive research attention in the field of subterranean CO_2 storage [19]. These pioneering demonstrations have been in operation since the late 90s and 2000s and have since served as formative examples. The two projects do not aspire to connect to a wider network but have set the stage for further network developments. Currently, eight defined offshore areas are planned for cross-border CCTS development in the country [5]. Many cross-border T&S projects plan to transport CO_2 to these storage areas, both via pipelines and ships.

In **Denmark**, both offshore and onshore storage projects are currently in development: two offshore storage sites and two onshore storage sites. All projects aspire to eventually connect to the wider European network [4] [17] via terminals on the shores of continental Europe. Just off the coast of **The Netherlands**, two offshore storage sites are under development. Transport to those storage areas will be from terminals in the Netherlands. Much of the planned storage infrastructure in the **United Kingdom** is developed with the potential to receive CO_2 from mainland Europe. Under the country's jurisdiction, five storage areas are currently planned [5].

The North Sea is bordered by three other countries: **Germany**, **Belgium**, and **France**, which, as of now, have no publicly disclosed plans for offshore storage that would contribute to the cross-border CO_2 network. There is, however, ongoing development of an onshore depleted gas storage facility in Southern France, designed primarily to handle domestic CO_2 emissions while also receiving CO_2 from Northern Spain.

The investigation of CO_2 storage sites, whether onshore or offshore, beyond the North Sea region, is at an even earlier stage of development. One notable exception is **Iceland**, which has explored and demonstrated onshore storage of CO_2 in basalt rock formations. Currently, there are plans to transport

CO_2 by ship to Iceland from mainland Europe [20]. Other countries and seas in Europe, while theoretically promising for storage, currently lack established project plans. There have been some initial moves, marked by a handful of small and isolated full-chain projects, in countries like Bulgaria, Hungary and Croatia [4]. Recently, however, more ambitious offshore storage initiatives have emerged along the coastlines of **Italy** and **Greece**. Both proposed storage areas have the potential to receive international emissions and be a part of the future European CO_2 network [17].

Uncertainty still surrounds the specific locations where storage areas will be established in the future, and many options have yet to be explored. Like **Switzerland**, other Central European countries have not publicly disclosed storage site development plans, which could be included a European T&S network. However, the landscape is fast-changing as indicated by the growing number of smaller-scale projects, and regulatory changes in countries like Poland, which took steps to lift its ban on onshore storage development [21].

2.3.2 Transportation Developments

Most of the current CO_2 transport plans in Europe revolve around connecting emitters to coastal export terminals and/or connecting terminals to storage [4] [5]. The largest planned onshore network connects emitters in **Germany**, **the Netherlands**, and **Belgium** via pipelines with different export and import terminals bordering the North Sea. Shipping routes between the countries add further flexibility and capacities to this network. For example, export terminals in Northern and Western **France** are connected to this network by smaller onshore pipelines and shipping routes. This vast network is characterised by complex synergies between multiple projects and developers. Another smaller planned transport network connects **Poland**, **Lithuania**, and **Latvia** to a coastal export terminal in Northern Poland. This Polish-Baltic network plans to utilise multiple modes of transport during the initial stages of network development [17].

In **the United Kingdom**, several pipeline systems connecting emitters to coastal terminals are planned. Although there are no aspirations to extend the pipeline to other countries, terminals will allow for CO_2 imports. Another onshore pipeline stretching from a coastal import terminal in Western **France** through Southern France and Northern **Spain** will connect regional emitters to the onshore storage site in Southern France. Similarly, the terminal in Western France enables CO_2 imports.

Regarding terminal-to-storage transportation, the landscape is more fluid as pipelines will be heavily complemented by transhipment plans, essentially developing a hybrid transport offshore network. From **the Netherlands**, **Germany**, and **Belgium**, high-capacity pipelines are planned to transport CO_2 to the continental shelves of **the Netherlands**, **The United Kingdom**, **Denmark**, and **Norway** for offshore storage. In addition to this planned infrastructure, a handful of projects will provide dedicated transport between terminals on the North Sea shore and storage sites or import terminals acting as temporary storage before redirecting the CO_2 for permanent storage. In addition, transport between export terminals will be possible, facilitating the management of shifts in stocks and flows of CO_2 through the European network.

3 Descriptions of Planned T&S Projects & Swiss Involvement Potential

In 2021, a conceptual study on a possible Swiss CO_2 pipeline network determined that a national pipeline system could have around 10 Mtpa in transport capacity [22]. This underscores the utility of a pipeline, as these capacities exceed the practical limits achievable by truck or rail. Preliminary feasibility assessments indicate that there is potential financial viability for two primary trunklines connecting Switzerland's major emitters with two final delivery points, enabling potential future connections to networks in neighbouring countries. An outline of the 1000 km pipeline network is shown in Figure 1.

One delivery point is defined towards the north in Basel, near the border intersection of France and Germany. The other delivery point is in Collombey, the Swiss Southwest, near the Italian province of Aosta and the French province of Rhone Alpes.

Although additional studies are still needed, and various challenges regarding the implementation process are yet to be resolved, this analysis is the foundation for this report. In the following two subsections, we apply a directional distinction between a North orientation on the one hand (Basel) and a South orientation (Collombey) on the other. By adopting this approach, potential challenges and opportunities can be assessed in relation to the projects that Swiss CO_2 infrastructure will be part of.

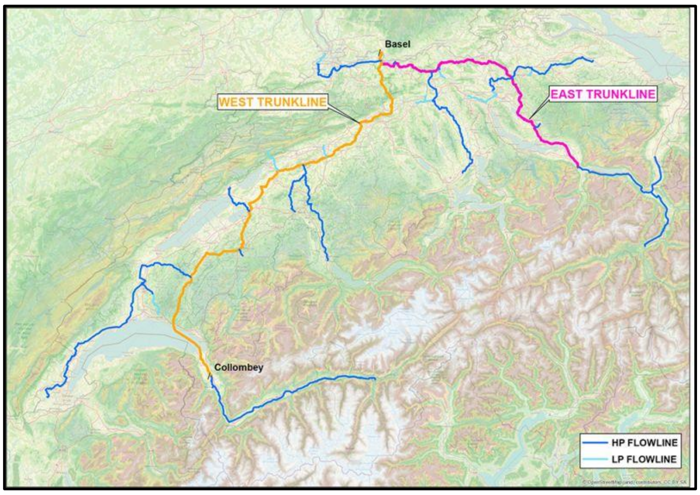

Figure 1: The proposed CO2 pipeline network in Switzerland [22]

In the following subsections, we list and assess all CCTS projects based on the project criteria outlined in Section 1.2. Most of the projects are either 2023 PCI candidates or closely linked to the candidate projects. Sixteen out of the eighteen PCI candidates for the 2023 list meet the specified criteria. Given the often early-development status of the projects, the capacity plans, timelines, and relations with other projects were often unclear, with information points scattered across various sources, increasing the complexity of data aggregation. On the basis of the research conducted, the following sections provide a new level of oversight of the entire planned network and clarity regarding the projects and their interrelations.

All projects under the utilised criteria that provide a timeline indicate that they are scheduled to commence operations in 2030 or earlier. However, it is common for these projects to be planned in multiple operational phases, extending through the 2030s and beyond. Additionally, many project plans remain somewhat ambiguous, still exploring different transportation and storage alternatives.

To facilitate the comprehensive overview of the projects, we define different project clusters, as seen on Figure 2. These clusters have been divided depending on their geographic location and level of interrelation with one another. We define the first cluster (North I) as the planned pipeline infrastructure in Germany, the Netherlands and Belgium, which forms a continuous pipeline and export terminal network bordering the North Sea. The second cluster (North II) refers to the same region, adding projects that either directly synergise with the pipeline network or offer other modes of transport and flexibility, also extending the network to neighbouring countries. The third cluster (North III) consists of North Sea transhipment and storage projects. The fourth (North IV) and fifth (North V) project clusters are projects based in the UK and Baltic region, respectively. The sixth and last project cluster (South) refers to projects south of Switzerland. Details on the projects are summarised in Appendix A.

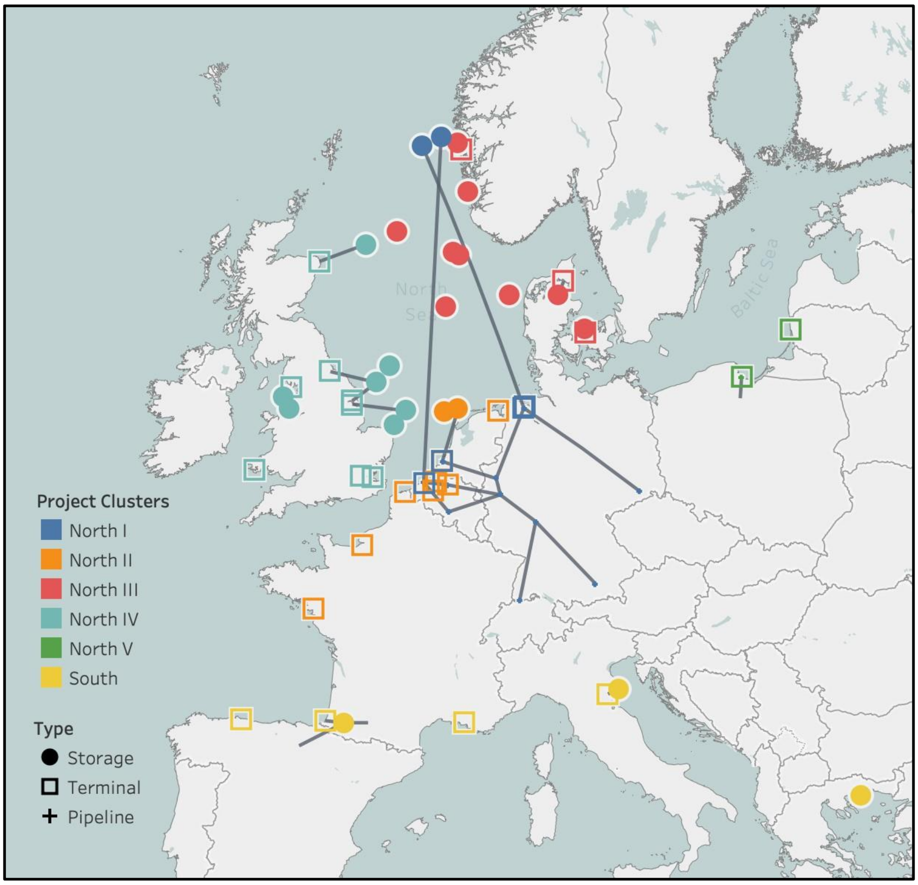

Figure 2: CCTS Project plans in Europe. Projects are split into six project clusters. Shipping routes, connecting export terminals to storage sites, are not shown, and pipeline pathways are simplified. Two storage sites in Iceland and Norway are not shown on this map.

3.1 Projects in Northern Europe

3.1.1 Project Cluster North I: Germany, The Netherlands, and Belgium

Germany represents the heart of planned onshore transport infrastructure in Europe. Here, Open Grid Europe (OGE), the coordinator of the **German Carbon Transport Grid (GCTG)** project, has submitted plans to develop around 1,500 km of pipeline infrastructure with 25.8 Mtpa capacity to expand German CO_2 transport potential in addition to opening access to neighbouring countries. Phase I will develop 700 km of pipeline infrastructure, connecting both industrial clusters in West and South Germany, in addition to Switzerland [17]. Phase II would extend the pipeline network to connect France, Austria, Poland, and the Czech Republic to the German grid [23]. A series of projects are directly linked to the GCTG, namely: EU2NSEA, Delta Rhine Corridor, Fluxys Belgium pipeline, WH2V, and CO2nnect Now.

EU2NSEA, led by Equinor, aims to implement a series of infrastructure plans intended to expand the capacity of the entire European network. First, it will develop five CO_2 collection networks in Belgium, Denmark, France, Germany, Netherlands, and Switzerland. These hubs will then be connected through the GCTG, transhipment or rail to two export terminals in Zeebrugge (Belgium) and Wilhelmshaven (Germany) [24]. These terminals will serve as the point of departure from which CO_2 will travel through a new 900 km offshore pipeline grid, primarily built through project **NOR-GE**, to storage sites in the North Sea, named Luna and Smeaheia (Norway), with the ability to expand to other nearby storage areas in the future. This pipeline network will be developed by Equinor in collaboration with Fluxys and Wintershall Dea, with an average capacity of 34 Mtpa [25].

In addition to the pipeline infrastructure developed through the GCTG and EU2NSEA, the **Delta Rhine Corridor** project will add additional infrastructure to this network by connecting Rotterdam with West

German cities [26]. Chemelot, an industrial area in the Netherlands, will also be connected, and the possibility of extending the network to include Antwerp also remains. This project expects to transport 14.9 Mtpa through its main pipeline by 2027, with more than 50% of transport capacity being sourced from Germany. Also adding additional infrastructure to the same network is the **Fluxys CO_2 Belgium Network.** This pipeline network plans to expand Belgian onshore pipeline infrastructure further inland to accommodate CO_2 sources from France, Luxembourg, Germany, and beyond [27].

Finally, Wilhelmshaven is home to two projects directly linked to the network described above. First, **WH2V**, operated by TES and part of the GCTG, will serve as an export terminal with an expected capacity of 10 Mtpa starting in 2029. For this project, Switzerland has been named within the PCI as a direct provider of CO_2 to the terminal for storage in the North Sea [17]. Second, Wintershall Dea is exploring the potential development of another hub in Wilhelmshaven called **CO2nnect Now**. This hub would provide similar capabilities, beginning with transhipment and eventually providing offshore pipeline transport as well [28]. CO2nnect Now is expected to begin operations in 2028 with a transport capacity of 10 Mtpa [28].

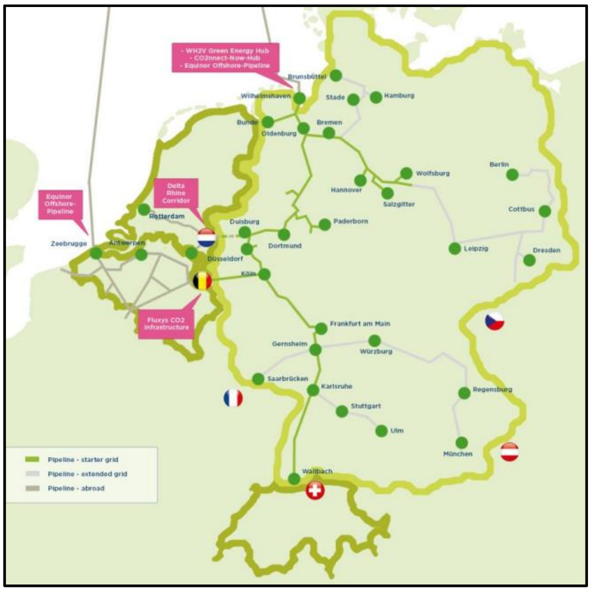

Figure 3 The German Carbon Transport Grid and pipeline extensions [23]

> ➔ The pipeline infrastructure planned through these projects will be fundamental to connect the Swiss CO2 network with North Sea storage options through coastal export terminals along the North Sea coast of continental Europe.

3.1.2 Project Cluster North II: The Netherlands, Belgium, and France

Along the North Sea coast of continental Europe, **CO2TransPorts** aims to create an 'open access' CO_2 transportation and storage network. In terms of transport, this project will connect the Port of Rotterdam, the North Sea Port Partnership (Vlissingen, Terneuzen, Ghent), Antwerp, and potentially the Belgian hinterland [17]. Regarding storage, CO2TransPorts is coordinating the development of onshore and offshore pipelines, in addition to shipping lanes that will connect export terminals in Rotterdam to storage in the Dutch continental shelf and beyond, with the aim of providing 10 Mtpa by 2030. Although CO2TransPorts is indirectly connected to a network of projects, two plans are directly under its supervision, namely Porthos and Aramis.

Porthos is comprised of an onshore local collection pipeline, a compressor station in the Port of Rotterdam and an offshore pipeline connecting the compressor station with the P18 gas fields located

22 km from the Dutch shore [29]. The local collection pipeline extends from the compressor station 30 km inland to facilitate connections to incoming CO_2 sources from nearby emitter clusters and abroad. Parallel to the development of this Rotterdam infrastructure, Phase I of the CO2TransPorts project also includes the development of local CO_2 collection pipelines in Antwerp. Porthos and both collection pipelines are expected to be operational by 2026 [17].

During Phase II (2027+), Rotterdam and Antwerp collection pipelines will be connected, and further onshore pipelines will link industrial clusters in the south of Belgium to the Antwerp infrastructure. Simultaneously, the **Aramis** project will begin initial development. It aims to establish additional offshore pipeline infrastructure that will add 5-22 Mtpa in storage capacity, progressively increasing over time. As the Aramis project develops, additional compression and buffer storage facilities will be developed in the hinterland of Rotterdam to prepare incoming CO_2 streams for offshore pipeline transport [17]. In addition to the mentioned infrastructure being developed by CO2TransPorts, other projects will play a critical role within this transboundary network, particularly planned onshore pipeline connections and transhipment routes with various Belgian cities.

CO2Next, an export terminal in Rotterdam, will be developed with the following capacities: train, truck and onshore pipeline import capabilities, temporary CO_2 storage, and vessel loading for export [30]. This terminal will operate in partnership with the Aramis project as its main export terminal. Other projects, such as the **L10** storage project, will also be utilising the Aramis pipeline to transport CO_2 to L10 offshore facilities for geological storage in the Dutch Continental Shelf. As neighbouring transport projects develop around the turn of the decade, CO2Next will transform into a regional hub for import and export based on CO_2 transport flows.

For example, **Carbon Connect Delta**, a project planned to transport 6.5 Mtpa by 2030, will provide cross-border shipping services, mainly for the North Sea Port Partnership (Vlissingen, Terneuzen, Ghent). These shipping plans explicitly include both Porthos and Aramis as partners within the eventual CO_2 transport ecosystem. On a larger scale, **Northern Lights** will provide shipping transport options across the entire North Sea for storage in the Norwegian Continental Shelf. Here, the Port of Rotterdam, alongside neighbouring export terminals, will form part of this transport network.

Noordkaap will provide additional transport options, particularly to industrial clusters lacking access to offshore pipeline infrastructure. In Phase I (2028+), this project will transport 12 Mtpa from the industrial cluster in Eemshaven/Delfzijl for storage in the Dutch and Norwegian Continental Shelf. Phase II (2030+) will expand operations to include industrial clusters in Antwerp, North Sea Port, Wilhelmshaven, Dunkirk, Le Havre, and the Stockholm/Gotland region. Transport during this Phase will likely include a combination of direct transport to storage sites, shipment to temporary storage sites, and offloading at terminals for subsequent offshore pipeline transport. Notably, Noordkaap vessels will have the capability for ambient Direct Offshore Injection (DOI), effectively circumventing the need for offshore pipeline transport as part of the transhipment storage process [17].

In Belgium, the **Ghent Carbon Hub** could provide an additional 6 Mtpa in shipping transport capacity [27]. This project is part of the larger Fluxys CO_2 Belgium Network [31]. Export terminals in Antwerp, Ghent, and Zeebrugge will then transport the CO_2, either by onshore pipeline to Rotterdam or offshore transport, for geological storage [31].

The **Nautilus** project, which will mainly operate on the French coast, aims to develop additional collection and transport hubs for regional industrial clusters. Nautilus is divided into three subsidiary projects, namely ECO2Normandy (Le Havre, France), D'Artagnan (Dunkirk, France), and C Zero (Duisburg, Germany). As part of the Northern Lights project, **ECO2Normandy** will connect regional capture facilities to a CO_2 shipping terminal in Le Havre for transport to geological storage in the North Sea. **D'Artagnan** will provide similar regional services by developing a shipping export terminal in the Dunkirk harbour with the future potential for an offshore pipeline connecting to North Sea storage facilities. **C Zero** is a collection hub for industrial clusters around Duisburg. In partnership with CO_2Next, C Zero will transport CO_2 by truck, train, and barge to Rotterdam for export to storage in the North Sea. In later phases of development, C Zero expects to also utilise the regional pipeline network to transport CO_2 to both Rotterdam and Wilhelmshaven.

Finally, there is another announced transport and terminal project planned to be developed in the Port of Nantes Saint-Nazaire, named **GO CO2**. This project plans to develop onshore pipelines from industrial clusters in the Western part of France to the Montoir-de-Bretagne LNG terminal in Nantes Saint-Nazaire for liquification and transhipment to offshore storage in Norway or Denmark [32].

- ➔ The terminal and transport infrastructure planned the Netherlands will be a central artery within the European network, due to: (i) the dense interconnections with Belgian infrastructure and (ii) extensive export capabilities planned in the Port of Rotterdam.
- ➔ Swiss emissions will be able to travel through a variety of export terminals, where transhipment and pipeline options create flexibility for the transport-to-storage phase.

3.1.3 Project Cluster North III: Norway, Denmark, and Iceland

In addition to the projects outlined above, the following transport-focused plans represent future cornerstones of the CO_2 T&S network. Already under construction and starting in 2024, **Northern Lights** will provide transhipment to seven countries (Netherlands, Germany, Belgium, France, UK, Sweden, and Norway), specifically to sixteen private emitters within these countries. The project will connect export terminals within each country to the Northern Lights receiving terminal Øygarden in Norway. From there, a 108 km offshore pipeline will transport the CO_2 to a Norwegian storage site, the Aurora Formation. This pipeline will be designed to allow for future tie-in options with other nearby pipelines or wells. Furthermore, an additional phase is already under consideration to expand storage capacity past the current 5.2 Mtpa planned for 2026.

In Denmark, the **NORNE** project will develop a range of infrastructure, culminating in the onshore storage of liquefied CO_2 at the Gassum Formation in Jutland. Two separate receiving, compression and temporary storage terminals will be built in Port Aalborg (Project Fykrat) and Port Kalundborg (Project Trelleborg), with onshore pipelines connecting to the storage site in Jutland. The project aims to store 2.3 Mtpa by 2026 and 18.7 Mtpa by 2030. It is currently expected to cover storage needs for Denmark, Sweden, Belgium, and the UK but is theoretically available to any country exporting LCO_2 by ship [17].

Another Danish project, **Bifrost**, will provide transport and offshore storage capacity to key emitter clusters in Denmark, Germany, Sweden, and Poland. In Phase I (2029), ships will transport CO_2 from export terminals in the mentioned countries either directly to the Harald platform (offshore storage) or to an onshore terminal equipped with buffer storage facilities for eventual storage through a dedicated offshore pipeline. Phase II (2030) will expand the storage capacity of the system, adding 10 Mtpa by developing pipelines to connect industrial clusters in Denmark and Germany to additional storage sites offshore Denmark [17].

Currently finalising its pilot project, **Greensand** is aiming to develop offshore storage capacity near the Bifrost storage area. Following the completion of its demonstration project, Phase II (2025) will expand capacity to 1.5 Mtpa and Phase III (2030) to 8 Mtpa [33]. Regarding the expansion of storage capacity for the entire European network, there are various projects that have recently acquired licensing approvals for infrastructure development, including **Poseidon**, **Trudvang**, **Polaris**, and **Errai** in Norway and the **Coda Terminal** project in Iceland [4] [5].

Finally, like Noordkaap, **Stella Maris** aims to further expand CO_2 storage access to countries or clusters unable to utilise the developing European offshore pipeline network by providing specialised transhipment capabilities and two export terminals located in the Western UK and Rotterdam [34]. Currently, the following countries have been identified as potential partners: the Netherlands (Rotterdam), Norway, the UK, and Poland. Unlike Northern Lights, Stella Maris vessels will directly inject CO_2 into storage sites through floating stations connected to saline aquifers. This approach intends to increase efficiency, cost-effectiveness, and scalability [35].

➔ Through transhipment and pipeline infrastructure, North Sea coastal terminals will connect to these planned storage options in Norway, Denmark, and Iceland.

3.1.4 Project Cluster North IV: The UK

A total of seven CO2 T&S systems have been announced and identified under the UK's territories: one in Scotland, four in East England, and two in West England and Wales.

In Scotland, the **Acorn CCS** will provide transport and storage as part of a larger supply chain named "The Scottish Cluster". The project reuses legacy onshore and offshore oil and gas pipelines in Scotland and the Scottish North Sea, with a terminal in St. Fergus. The project's developers foresee importing captured CO_2 from regions by ship to the storage site. By 2030, the project aims to store 5-10 Mtpa, with planned expansion to cumulatively store 500 Mt by 2050 [36].

"The East Coast Cluster" includes a mix of diverse low-carbon projects in the Humber-Teeside region and two offshore storage areas. The **Northern Endurance Partnership (NEP)** consists of the construction of a new offshore pipeline from two terminals (Teeside and Humber) and a storage capacity of 10 Mtpa by 2030, with further expansion plans beyond this timeframe [37]. Another nearby project, **Viking CCS**, involves the construction of a new onshore pipeline and the use of an existing offshore pipeline from Humber for storage in a depleted gas field. The Viking CCS storage capacity is reported as 10 Mtpa by 2030 and 15 Mtpa by 2035. There are also plans to bring in emissions from elsewhere in the UK and overseas to the Humber terminal [38].

Also operating on the UK's East Coast is the **Bacton Thames Net Zero** project. The project involves a pipeline and shipping transport infrastructure between the Bacton and Thames areas with storage at an offshore gas field, Hewett. Starting in 2027, the reported capacity is 10 Mtpa by 2030 and 15 Mtpa by 2035. There is potential to import captured CO_2 from European countries to the Hewett storage site and use the interconnecting pipelines between Bacton and Zeebrugge to store CO_2 but also transport locally-produced Hydrogen [39]. **Medway CCS Hub,** another project on the East Coast, has less advanced capacity plans, reportedly planning to store 2 Mtpa over 25 years. The plan is to transport CO_2 from emitters near London via tankers to offshore storage [40].

Several low-carbon projects are planned in the South Wales and Liverpool region on the UK's West coast, with two main CO_2 T&S projects. **Liverpool Bay CCS** involves onshore and offshore pipeline infrastructure from the Liverpool region to an offshore storage site. Beginning in stages from 2025, the storage capacity is expected to be 4.5 Mtpa, growing to 10 Mtpa in 2030 [41]. **Morecambe Net Zero Cluster** is a recently announced project, essentially a storage cluster, with its developer, Storegga, planning to turn depleted gas fields in Morecambe Bay into CO_2 storage sites, with a terminal in Barrow. It will be designed to accept CO_2 through shipping, rail, and pipeline. Initially, the cluster will accommodate 5 Mtpa, although details regarding commencement and international project synergies are not yet communicated [42].

➔ As an alternative to storage projects in Norway, Denmark, and Iceland, these UK projects may provide additional storage options for export terminals along the North Sea coast of continental Europe.

3.1.5 Project Cluster North V: Poland and the Baltics

CCS Baltic Consortium has plans to develop a CCS value chain in the Baltic region, with Latvia and Lithuania as involved countries. Collaborating with the EU2SNEA and ECO2CEE project, this Consortium is developing a cross-border CO_2 infrastructure in Lithuania and Latvia, which will also be accessible by entities in other neighbouring countries. A new multimodal liquid CO_2 (LCO_2) export and import terminal will be built in Klaipėda, Lithuania, as part of the project. Ships will be used for transporting LCO_2 to offshore storage sites in collaboration with other projects [17].

ECO2CEE involves a terminal in Gdansk, Poland, with onshore and offshore transport infrastructure connected to the Klaipėda terminal in Lithuania. From these terminals, CO_2 can be shipped to storage sites in the North Sea, through collaboration with storage projects there, and potentially in the Baltic Sea in the future. Pipeline construction in the vicinity of Gdansk is planned, with rail, truck, inland waterways or pipeline for the Poland hinterland and Lithuania as transport-to-terminal options [17].

> ➔ These projects provide Poland and neighbouring countries with access to North Sea terminals. However, there are currently no plans to develop connections to the wider European CO2 pipeline network.

3.2 Projects in Southern Europe

Two T&S projects are currently planned in the Mediterranean Sea with another project in the Pyrenees. Although this region lags Northern European network development, the relative geographical proximity for Switzerland must be kept in mind. Here, given the pace at which T&S projects are arising across the continent, the potential viability of a Southern-directed CO_2 network cannot be excluded in the long-term.

3.2.1 Project Cluster South: Italy, Greece, France, and Spain

The **Callisto Mediterranean CO2 network** aims to initiate the establishment of a CCTS chain in Southern Europe. The project features two key CO_2 hubs in the Mediterranean: one in Marseille, France, and the other in Ravenna, Italy. Construction of all facilities is expected by 2029, with capacity plans split into two phases: 3.6 Mtpa in Phase I (2027-2032) to 6.4 Mtpa in Phase II (2033-2050). At the Marseille Hub, CO_2 is transported via ship to the Ravenna Hub. In addition, the hub at Ravenna also receives CO_2 via pipelines from nearby emitters. The **Ravenna CCS** project, participating in this network project, includes the transportation of CO_2 via pipeline to an offshore storage site in the Adriatic Sea [17]. **Prinos CO_2 storage** is another Mediterranean-based project. It features a storage hub located in Western Greece, which may receive captured CO_2 from nearby emitters in addition to other neighbouring regions and countries via shipping [17]. The project plans to start operations in 2025 with an initial capacity of 1 Mtpa, growing to 2 Mtpa by the end of 2027, with potential expansions thereafter.

The **Pycasso** project plans to connect France and Northern Spain through onshore and shipping infrastructure with onshore depleted natural gas reservoir storage in Southwestern France in Lacq in two project phases. The infrastructure will involve the construction of a purpose-built terminal in Bayonne receiving CO_2 by ship from Gijon, Spain and potentially other places in France, and new pipelines enabling a west-east (Phase I) and a south-north connection (Phase II). In Phase I (2030-2034), a pipeline is built from Bayonne stretching east to the Lacq storage area, extending further east with 2.5 Mtpa transport capacity. In Phase II (2035+), industries in Northern Spain (San Sebastian, Outer Bilbao) and in areas north of Lacq to the Lacq storage area are connected via pipeline, adding an additional 3.4 Mtpa transport capacity [17].

> ➔ The storage and pipeline developments south from Switzerland are currently smaller in scale. Additional infrastructure development in France and or Italy would be needed to connect the Swiss CO2 pipeline network to these projects.

4 Expansion Scenarios for the Swiss CO_2 Network

Building on the conclusions in Section 3, the near-term strategic T&S infrastructure focus is North of Switzerland. Switzerland is actively participating as an ‘involved third country’ in PCI projects situated in the North, all of which have the common goal of transporting CO_2 through Germany to the North Sea. The storage developments in this region exhibit a certain degree of assurance given the number of projects, providing resilience in case of setbacks, alterations, or capacity downsizing in one or more projects.

Projects south of Switzerland are characterised by lower confirmed storage capacity and uncertainty regarding pipeline expansion possibilities. For Switzerland, the southern direction requires substantial additional pipeline infrastructure. Any potential setbacks in the southern projects would have considerable consequences due to the limited availability of viable transport and storage alternatives.

The subsequent subsections are dedicated to exploring scenarios of connecting the Swiss pipeline network through Basel in the north direction. Firstly, pathways from Switzerland to coastal terminals bordering the North Sea are explored in Section 4.1. Then, pathways from these terminals to storage facilities are explored in Section 4.2.

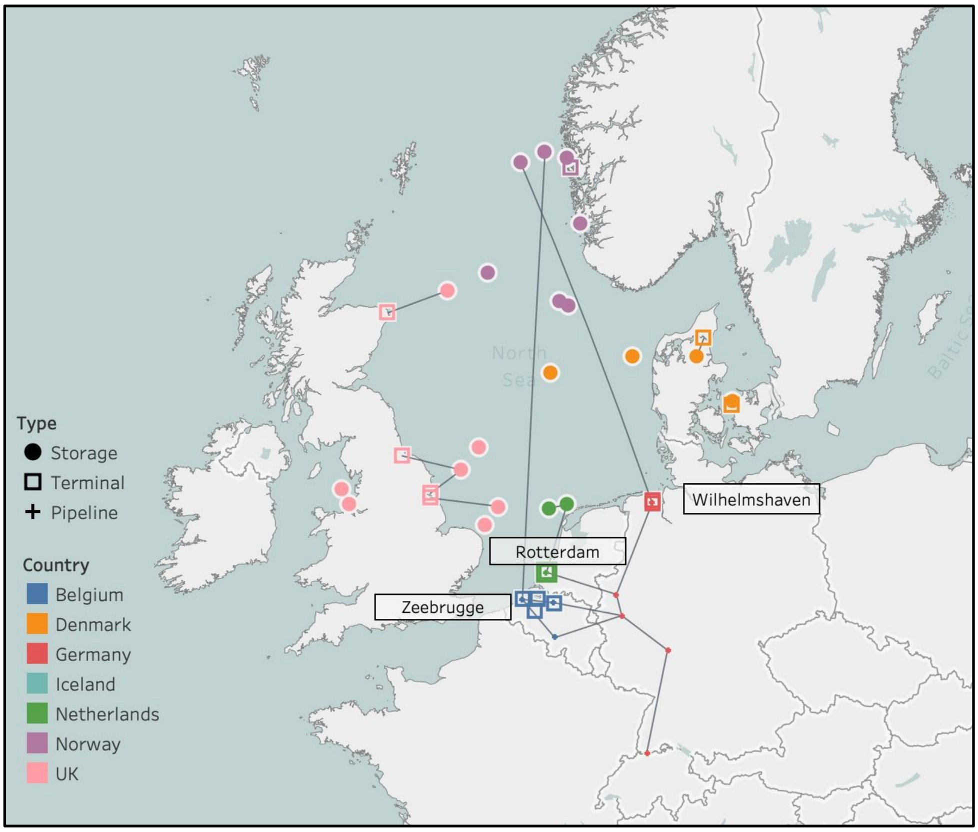

Figure 4 The scenarios base on the Swiss CO2 pipeline network connecting north towards three main export terminals. From there, CO2 may be transported towards storage sites via pipeline or via multiple possible shipping routes, not shown on this map. Two storage sites in Iceland and Norway are not shown on this map.

4.1 Swiss CO_2 Network – Coastal Terminals

Based on the abovementioned CO_2 network projects, three potential scenarios stand out through which Swiss emissions can be transported to export terminals along the North Sea coast. These scenarios outline the countries and planned projects that would be part of each transport pathway. Importantly, each scenario utilises the German Carbon Transport Grid (GCTC) pipeline infrastructure to reach Northern Europe before splitting into three alternative options.

4.1.1 Wilhelmshaven, Germany

To reach the export terminals in Wilhelmshaven, the dedicated Swiss pipeline may be connected from Basel to the GCTG pipeline network. The GCTG network extends from Wallbach in the south of Germany through Frankfurt, Cologne, and Dortmund to the coastal city of Wilhelmshaven. Here, the CO_2 will either be delivered to the WH2V or CO2nnectNow terminal. Both terminals will have a capacity of 10 Mtpa, with WH2V expected to start operations in 2029 and CO2nnectNow in 2028. In addition, Switzerland has already been explicitly named as a future CO_2 provider within the WH2V project.

4.1.2 Rotterdam, Netherlands

The pathway for the Swiss network to reach Rotterdam terminals starts out identically to the first scenario through Basel and the GCTG. Here, the GCTG transports the CO_2 through its pipeline until Cologne. From Cologne, the Delta Rhine Corridor project can transport the CO_2 through Venlo to Rotterdam by pipeline. The Delta Rhine Corridor will either deliver the Swiss CO_2 directly to terminals at the Port of Rotterdam or at collection hubs in the Rotterdam hinterland, given that the pipeline has various delivery points across Rotterdam. Considering the latter, the pipeline infrastructure developed by Porthos, a part of the CO_2TransPorts project, can deliver the CO_2 to coastal terminals as it connects the Port of Rotterdam to CO_2 collection areas inland through onshore pipelines. At the coast, CO_2 can be deposited at either the CO_2Next or Porthos terminal for eventual storage.

4.1.3 Zeebrugge, Belgium

To reach Zeebrugge, Swiss emissions initially travel the same path as the first scenarios through Basel and Cologne. However, in Cologne, the CO_2 is redirected to the city of Liége in Belgium. Liége is one of multiple potential CO_2 collection hubs in Belgium, interlinked through a national pipeline network developed by Fluxys. Here, it is important to highlight that the way Cologne and Liége will be connected has not yet explicitly been established through any of the projects covered in this report. However, Fluxys and Wintershall Dea are actively investigating pathways to connect the German and Belgian planned pipeline networks [24]. Although a Cologne-Liége pipeline would be logical, it is possible that alternate infrastructure would connect the two pipeline networks. Finally, once the Swiss CO_2 has reached the Belgian network, it will travel to the Zeebrugge terminal, where it can be exported for eventual permanent storage.

Multiple alternatives exist within this scenario. Instead of being delivered to Zeebrugge, the CO_2 can travel North through the Belgian network to Rotterdam. This would be possible due to the planned infrastructure connecting these neighbouring countries, namely by CO_2TransPorts, Ghent Carbon Hub, or Carbon Connect Delta. CO_2TransPorts will eventually connect Ghent and Antwerp with Rotterdam through an onshore pipeline. Ghent Carbon Hub and Carbon Connect Delta will provide additional transhipment options from Ghent, Terneuzen, and Vlissingen for potential transport to Rotterdam terminals, CO_2Next or CO_2TransPorts.

4.2 Coastal Terminals – Geological Storage

North Sea, offshore transport plans are set to connect all coastal countries through an intertwined network of projects, facilitating the storage of CO_2 across the region. Major pipelines planned through EU2NSEA (~34 Mtpa), Aramis (22 Mtpa), and Bifrost (~10 Mtpa) have the potential to become central players within the European network, given their transport capacities. In addition to pipeline infrastructure, projects such as Northern Lights, NoordKaap, and Nautilus are at the forefront of a developing transhipment network that will be crucial in achieving the storage objectives of the European CO_2 transport network. Critically, transhipment projects will play an important role in addressing CO_2 overflows at export terminals or shortages at storage sites that could be injecting more CO_2. Here, the rigidity of the pipeline network will be counterbalanced through a fluid and expansive transhipment network connecting terminals to storage sites and terminals to other terminals.

Many other transport and storage projects, for example, in the UK (Acorn CCS, Bacton Thames Net Zero, Northern Endurance Partnership), Denmark (NORNE, Greensand), Norway (Poseidon, Trudvang, Polaris, Errai, Stella Maris) and Iceland (Coda Terminal) have the potential to add additional storage capacities for the European T&S network. It can be expected that the storage sites in these projects will receive CO_2 from one or more export terminals bordering the North Sea.

4.2.1 Wilhelmshaven, Germany

From Northern Germany, the planned NOR-GE pipeline plans to provide an average of 34 Mtpa transport capacity, deploying emissions in the Norwegian Continental Shelf, specifically at the Luna and Smeaheia storage sites. This pipeline would likely be the main pathway through which Swiss emissions can be taken to permanent storage sites. In addition, the NoordKaap project explicitly includes Wilhelmshaven as one of the coastal cities that it will service through its planned transhipment options. Notably, Noordkaap vessels will have the capability for ambient Direct Offshore Injection (DOI), effectively circumventing the need for offshore pipeline transport as part of the transhipment storage process. Finally, terminals in Wilhelmshaven may also be able to utilise Bifrost transhipment infrastructure to store emissions at the Harald Platform off the coast of Denmark.

4.2.2 Rotterdam, Netherlands

Rotterdam represents the epicentre of the planned European CO_2 transport network. Therefore, it presents the largest number of options for offshore transport. First, the Aramis pipeline is expected to provide 22 Mtpa in transport capacity, taking CO_2 to be stored off the shore of the Netherlands. In addition, Porthos, another project under the CO_2TransPorts portfolio, will provide similar transport and storage options with a fraction of the capacity. The CO_2Next terminal, operating in close partnership with Aramis, will also act as an open-access import/export terminal for many other projects, including L10, another offshore storage site potentially accessible for Swiss emissions on the Dutch Continental Shelf. Finally, regarding transhipment, CO_2Next may be able to take advantage of the Northern Lights network to transport emissions to other storage sites inaccessible to the currently planned offshore pipeline infrastructure.

4.2.3 Zeebrugge, Belgium

From Zeebrugge, multiple offshore transport options exist. First, besides Wilhelmshaven, Zeebrugge is the only other terminal connected to the EU2NSEA offshore pipeline. In collaboration with Equinor, Fluxys will develop the infrastructure to transport CO_2 for permanent storage at the Luna and Smeaheia storage sites off the shore of Norway. Importantly, this massive pipeline infrastructure will have the capability to add additional storage sites to its core pipeline in the future, allowing for the possibility to extend its total storage potential. Second, like the projects above, Zeebrugge, a Fluxys-developed terminal with transhipment docking capabilities, will provide CO_2 to projects such as Northern Lights for storage at locations not connected to the EU2NSEA pipeline.

4.3 Network Uncertainties & Future Prospects

These scenarios listed above are based on publicly disclosed project plans, which are backed by reputable public and private actors, instilling a degree of confidence. Nonetheless, it is crucial to acknowledge that the European project landscape is characterised by rapid evolution and uncertainty.

While these aspects are not extensively explored in this report, they are of great importance for the realisation of these network plans.

The nascent stage at which the planned network currently finds itself will inherently be accompanied by external pressures that may destabilise current plans. Many of the projects are still pending final approval whilst being confronted with a multitude of technical, financial, and social challenges that remain to be dealt with by industry players and governments alike. Storage capacities are still being investigated and confirmed, with projects inherently at risk of going over budget and past the projected timeline. Moreover, public opinion on CCTS is not reliably supportive, particularly for those regions that will be most directly impacted by planned infrastructure developments. It is foreseeable that numerous projects will have to adapt their plans and strategies to address these multifaceted challenges. The interdependencies of projects, especially relevant for the cross-border onshore pipeline infrastructure developments in Germany, the Netherlands, and Belgium, make assessing risks difficult. Nevertheless, in this scenario, intermediate and hybrid transport solutions can serve as bridges until an established network fully links the Swiss CO_2 pipeline network with storage sites.

Various other operational aspects are also important to address when translating plans into reality. This includes the task of incorporating, managing, and allocating responsibilities between public and private actors in a shared network. Not only will CO_2 flows have to be effectively allocated, but competition may arise from, e.g., hydrogen projects.

Regarding the selection of specific storage areas, uncertainty remains, with many options yet to be explored. Constantly evolving developments are evident, exemplified by the recent emergence of projects beyond Northern Europe. Therefore, when assessing prospective CO_2 T&S pathways from Switzerland, it is imperative to integrate the most recent projects and their plans into the evaluation process. The upcoming final PCI list, which will be announced in November 2023, will provide clearer indications of the projects prioritised by the EU in shaping the cross-border CO_2 T&S network.

Numerous catalysts can further influence and accelerate network developments, both on regional and national levels. For example, in its Net Zero Industry Act (NZIA), the EU emphasises additional storage exploration with the objective to reach injection capacity in CO_2 storage of 50 Mt CO_2 by 2030. A key measure the EU will implement, is to require better information on geological data relating to oil and gas production sites. Finally, national CCTS action plans are likely to further incentivise and accelerate network developments.

5 References

[1] The Swiss Federal Council, “Carbon capture and storage (CCS) and negative emission technologies (NETs) - How they can gradually contribute to the long-term climate target,” 2022. [Online]. Available: https://www.bafu.admin.ch/dam/bafu/en/dokumente/klima/fachinfo-daten/br-bericht-zu-ccs-und-net.pdf.download.pdf/. [Accessed 15 September 2023].

[2] Swiss Federal Council, “CO2-Abscheidung und Speicherung (CCS) und Negativemissionstechnologien (NET),” Bern, 2022.

[3] Swiss Federal Office of Energy (SFOE), “Energieperspektiven 2050+: Technischer Bericht,” Swiss Federal Council, Bern, 2022.

[4] International Energy Agency, “CCUS Projects Database,” March 2023. [Online]. Available: https://www.iea.org/data-and-statistics/data-product/ccus-projects-database. [Accessed 8 August 2023].

[5] Clean Air Task Force, “Europe Carbon Capture Activity and Project Table,” [Online]. Available: https://www.catf.us/ccstableeurope/.

[6] European Commission, “Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act),” 2023.

[7] D. P. Schrag, “Storage of Carbon Dioxide in Offshore Sediments,” *Science,* 2009.

[8] Global CCS Institute, “Fact Sheet: Transporting CO2,” 2018. [Online]. Available: https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Transporting-CO2-1.pdf. [Accessed 10 October 2023].

[9] Weihs, G. F., Kumar, K., & Wiley, D., “Understanding the Economic Feasibility of Ship Transport of CO2 within the CCS Chain,” *Energy Procedia,* vol. 63, pp. 2630-2637, 2013.

[10] International Energy Agency (IEA), “Hydrogen - Tracking Hydrogen,” 2023. [Online]. Available: https://www.iea.org/energy-system/low-emission-fuels/hydrogen#tracking. [Accessed 10 October 2023].

[11] Geological Survey of Denmark and Greenland (GEUS), “EU Geological CO2 storage summary,” 2021. [Online]. Available: https://cdn.catf.us/wp-content/uploads/2021/10/20183953/EU-CO2-storage-summary_GEUS-report-2021-34_Oct2021.pdf?_gl=1*pvdlsg*_gcl_au*MTEyMDky. [Accessed 8 August 2023].

[12] Clean Energy Taskforce, “European Strategy for Carbon Capture and Storage,” May 2022. [Online]. Available: https://cdn.catf.us/wp-content/uploads/2022/05/10050419/CATF_CCSEuropeStrategy_Report_final.pdf. [Accessed 10 October 2022].

[13] European Commission, “Energy - Projects of Common Interest,” [Online]. Available: https://energy.ec.europa.eu/topics/infrastructure/projects-common-interest_en. [Accessed 8 August 2023].

[14] European Commission, “Commission Delegated Regulation (EU) 2018/540 of 23 November 2017 amending Regulation (EU) No 347/2013 of the European Parliament and of the Council as regards the Union list of projects of common interest,” 2017. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R0540. [Accessed 8 August 2023].

[15] European Commission, “Commission Delegated Regulation (EU) 2020/389 of 31 October 2019 amending Regulation (EU) No 347/2013 of the European Parliament and of the Council as regards the Union list of projects of common interest,” 2019. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0389&qid=1692193232803. [Accessed 8 August 2023].

[16] European Commission, “Commission Delegated Regulation (EU) 2022/564 of 19 November 2021 amending Regulation (EU) No 347/2013 of the European Parliament and of the Council as regards the Union list of projects of common interest,” 2021. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0564&qid=1692193232803. [Accessed 8 August 2023].

[17] European Commission, “Description of the candidate projects in the thematic area of cross-border carbon dioxide transport and storage networks,” December 2022. [Online]. Available: https://zeroemissionsplatform.eu/wp-content/uploads/Detailed_information_regarding_the_candidate_projects_CO2_networks_Dec_2022_v2.pdf. [Accessed 8 August 2023].

[18] Norwegian Petroleum Directorate, “CO2 Atlas for the Norwegian Continental Shelf,” [Online]. Available: https://www.npd.no/en/whats-new/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/. [Accessed 8 August 2023].

[19] Institute for Energy Economics and Financial Analysis, “Norway's Sleipner and Snohvit CCS: Industry models or cautionary tales?,” [Online]. Available: https://ieefa.org/resources/norways-sleipner-and-snohvit-ccs-industry-models-or-cautionary-tales. [Accessed 8 August 2023].

[20] Carbfix, “Coda Terminal - A scalable onshore CO2 mineral storage hub in Iceland,” [Online]. Available: https://www.carbfix.com/codaterminal. [Accessed 10 September 2023].

[21] Clean Energy Task Force (CATF), “Where will Europe store its CO2,” July 2023. [Online]. Available: https://www.catf.us/2023/07/where-will-europe-store-its-co2/. [Accessed 10 October 2023].

[22] SAIPEM, “Pipeline System Hydraulic & Optimization Study Report,” 2021.

[23] OGE, “German Carbon Transport Grid,” Essen, 2023.

[24] Energy Connects, “Wintershall Dea and Fluxys jointly investigate options for transport of CO2,” 7 March 2023. [Online]. Available: https://www.energyconnects.com/news/renewables/2023/march/wintershall-dea-and-fluxys-jointly-investigate-options-for-transport-of-co2/. [Accessed 10 October 2023].

[25] Equinor, “CO2 Transport and Storage at Equinor”.

[26] Shell, OGE, BASF & Gasunie, “For more movement on energy and climate in Europe - H2 and CO2 transport through the Delta Rhine Corridor as a unique cross-border infrastructure project,” [Online]. Available: https://www.delta-rhine-corridor.com/en. [Accessed 8 August 2023].

[27] Fluxys, “Fluxys Belgium, North Sea Port and ArcelorMittal Belgium receive EU funding for Ghent Carbon Hub project, a key step towards decarbonizing Belgium,” [Online]. Available: https://www.fluxys.com/en/projects/ghent-carbon-hub. [Accessed 8 August 2023].

[28] Wintershall Dea, “Wintershall Dea and HES Wilhelmshaven Tank Terminal intend to jointly develop a CO2 Hub in Wilhelmshaven,” [Online]. Available: https://wintershalldea.com/en/newsroom/wintershall-dea-and-hes-wilhelmshaven-tank-terminal-intend-jointly-develop-co2-hub-wilhelmshaven. [Accessed 8 August 2023].

[29] Porthos CO2 transport & storage, “Project,” [Online]. Available: https://www.porthosco2.nl/en/project/. [Accessed 8 August 2023].

[30] CO2next, “Terminal,” [Online]. Available: https://co2next.nl/terminal/. [Accessed 8 August 2023].

[31] Fluxys, “CO2: Preparing to build the network,” [Online]. Available: https://www.fluxys.com/en/about-us/energy-transition/hydrogen-carbon-infrastructure/carbon_preparing-to-build-the-network. [Accessed 8 August 2023].

[32] X. Boussion, “Un projet pour capter le CO2 du Grand Ouest,” Ouest France, [Online]. Available: https://www.ouest-france.fr/economie/industries/photos-un-projet-pour-capter-le-co2-du-grand-ouest-84bba672-1f38-11ee-990b-509b31c26799. [Accessed 15 August 2023].

[33] Greensand, “What is Project Greensand,” [Online]. Available: http://www.projectgreensand.com. [Accessed 10 October 2023].

[34] Altera Infra, “What we do - Stella Maris CCS,” [Online]. Available: https://alterainfra.com/what-we-do/ccs. [Accessed 8 August 2023].

[35] Ellis Geo, “CCS: Norway thinks big!,” [Online]. Available: https://www.eliis-geo.com/ccs-norway-thinks-big-a.html. [Accessed 8 August 2023].

[36] Acorn, “Acorn CCS,” [Online]. Available: https://www.theacornproject.uk/projects. [Accessed 8 August 2023].

[37] East Coast Cluster, “Three East Coast Cluster projects selected on CCUS cluster sequencing Phase 2: project negotiations list,” [Online]. Available: https://eastcoastcluster.co.uk/press-release/three-east-coast-cluster-projects-selected-on-ccus-cluster-sequencing-phase-2-project-negotiations-list/. [Accessed 10 October 2023].

[38] Viking CCS, “Viking CCS - About,” [Online]. Available: https://www.vikingccs.co.uk/about. [Accessed 10 October 2023].

[39] Eni, “Bacton Thames NetZero - An initiative for the future,” [Online]. Available: https://www.eni.com/static/bactonthamesnetzero/. [Accessed 10 October 2023].

[40] Synergia Energy, “Medway Hub - Carbon Capture & Storage Project,” 2022. [Online]. Available: https://www.synergiaenergy.com/sites/synergia-energy-ltd/files/synergia-energy-ltd/operations/united-kingdom/medway-hub-ccs-r7-we.pdf. [Accessed 10 October 2023].

[41] Eni, “The HyNet North West project,” [Online]. Available: https://www.eni.com/en-IT/operations/united-kingdom-hynet-north-west.html. [Accessed 10 October 2023].

[42] Energy Live News, “Morecambe gas fields embrace carbon capture,” 19 May 2023. [Online]. Available: https://www.energylivenews.com/2023/05/19/morecambe-gas-fields-embrace-carbon-capture/. [Accessed 10 October 2023].

6 Appendix A

Table 1: List of publicly disclosed T&S network projects in Europe

Project Name	Category	Main Location	Operations Start	Capacity Plans	Development Lead	Section
German Carbon Transport Grid*	Transport	Germany	2028	Phase I: 700 km pipeline connecting N. Germany to S. Germany, including Switzerland // Phase II: grid expansion opening access to additional neighbouring countries // 25.8 Mtpa pipeline transport capacity	Open Grid Europe (OGE)	3.1.1
EU2NSEA*	T&S	North Sea	2029	NOR-GE pipeline + Zeebrugge section: transport capacity 20-40 Mtpa // 25 Mtpa storage capacity through Luna and Smeaheia // 612 Mt estimated to be stored over 21 years of operation	Equinor	3.1.1
Delta Rhine Corridor*	Transport	Netherlands	2027	14.9 Mtpa pipeline capacity through main pipeline	Shell New Energies NL	3.1.1
Fluxys CO2 Network	Transport	Belgium	2030	Unknown	Fluxys	3.1.1
WH2V*	Terminal	Germany	2029	10 Mtpa shipping transport capacity	Tree Energy Solutions (TES)	3.1.1
CO2nnect Now	Terminal	Germany	2028	10 Mtpa transport capacity starting with transhipment and eventually providing offshore pipeline transport as well	Wintershall Dea	3.1.1
CO2 TransPorts**	T&S	Netherlands	2025/2026	Phase I (2025/2026): 2.5 Mtpa through Porthos storage ***//*** Phase II (2027+): Additional 5 Mtpa transport and storage capacity through transnational pipeline transport and Aramis project // Phase III (2030+): unknown	Port of Rotterdam	3.1.2
Porthos	T&S	Netherlands	2026	2.5 Mtpa storage capacity over 15 years. Total estimated storage capacity 37 Mt CO2	Port of Rotterdam	3.1.2
Aramis**	T&S	Netherlands	2027	Phase I (2027): 5 Mtpa pipeline transport and storage // Phase II (unknown): 22 Mtpa transport and storage capacity with further capacity to expand	Aramis CCS C.V.	3.1.2
CO2 Next	Terminal	Netherlands	2026/2027	7 Mtpa throughput capacity	Gasunie & Vopak	3.1.2
L10 Project	T&S	North Sea	2026	5 Mtpa storage capacity through both shipping and pipelines // Total estimated storage capacity 120-150 Mt	Neptune Energy	3.1.2
Carbon Connect Delta	Transport	Netherlands & Belgium	2023	Phase I (2023): 1 Mtpa shipping transport capacity // Phase II (2030): 6.5 Mtpa shipping transport capacity	Smart Delta Resources (SDR)	3.1.2
NoordKaap*	T&S	North Sea	2028	Phase 1 (2028): 12 Mtpa shipping transport // Phase 2 (2030): expansion providing services to additional industrial hotspots across Europe, Mtpa unknown	Cape Omega AS	3.1.2
Ghent Carbon Hub	Terminal	Belgium	2027	6 Mtpa shipping transport capacity	Fluxys	3.1.2
Nautilus**	T&S	France & Germany	2027	Le Havre - 2028: 1.2 Mtpa, 2031: 2.4 Mtpa, 2036: 3 Mtpa // Dunkirk - 2027: 3 Mtpa, 2031: 4.4 Mtpa, expected expansion // Duisburg - Phase 1: 1.2 Mtpa, Phase 2: 2.4 Mtpa, Phase 3: >3 Mtpa	Air Liquide France Industrie	3.1.2
GO CO2	T&T	France	2030	Phase I (2030): 2.6 Mtpa shipping export capacity // By 2050, up to 4 Mtpa shipping export capacity // Collecting CO2 emissions from industrial plants in the Greater West of France	GRT & Elengy	3.1.2

**Project is on the PCI 2023 candidate list, **Project is on the PCI 2023 candidate list and previous PCI list*
T&S: Transport and storage, T&T: Transport and terminal

Project Name	Category	Main Location	Operations Start	Capacity Plans	Development Lead	Section
Northern Lights**	T&S	North Sea	2024	Phase 1 (2024): 1.5 Mtpa storage capacity // Phase 2 (2026): 5.2 Mtpa storage capacity // shipping capacity: unknown	Equinor, Total & Shell	3.1.3
NORNE*	Storage	Denmark	2026	Phase I (2026): 2.3 Mtpa storage capacity // Phase II (2030): 18.7 Mtpa storage capacity	Capio Denmark	3.1.3
Bifrost*	T&S	Denmark	2029/2030	Phase I (2029/30): 2-3 Mtpa transport and storage capacity // Phase II (2030/32): +10 Mtpa pipeline transport and storage capacity // GEUS2 estimated Danish subsoil storage capacity at 12-22 billion tons over 25 years	TotalEnergies SE	3.1.3
Greensand	T&S	Denmark	2021	Phase I (2021): pilot project // Phase II (2025): 1.5 Mtpa // Phase III (2030): 8 Mtpa	INEOS	3.1.3
Poseidon	Storage	Norway	Unknown	Storage capacity potential of 5 Mtpa or more	Aker BP, OMV	3.1.3
Trudvang	Storage	Norway	2029	Storage capacity of 9 Mtpa for 25-30 years	Sval, Storegga, Neptune Energy	3.1.3
Polaris	Storage	Norway	Unknown	Preliminary estimation of 100 Mt storage capacity	Horisont Energi, Equinor	3.1.3
Errai	Storage	Norway	Unknown	Initial capacity of 4-8 Mtpa, with additional capacity in later phases	Horisont Energi, Neptune	3.1.3
Coda Terminal	T&S	Iceland	2026	Phase I (2026-2028): 0.5 Mtpa // Phase II (2028-2030): 1 Mtpa // Phase III (2031+): 3 Mtpa	Carbfix	3.1.3
Stella Maris	T&S	North Sea	2027	10 Mtpa storage capacity // 7 Mtpa terminal capacity per unit	Altera	3.1.3
Acorn CCS	T&S	UK	mid 2020s	(By 2030): 5-10 Mtpa // Cumulative storage plans: 25.5 Mt by 2030, and 500 Mt by 2050	Scottish Cluster cons.	3.1.4
Medway CCS	T&S	UK	Unknown	Plans of 2 Mtpa over 25 years, with 173 Mt total storage capacity	Synergia	3.1.4
Bacton Thames Net Zero	T&S	UK	2027	Storage capacity of 10-20 Mtpa beginning in stages from 2027 // Cumulative storage capacity of 330 Mt	ENI	3.1.4
Northern Endurance Partnership	T&S	UK	2027-2030	By 2030: 10 Mtpa // Cumulative storage capacity of 450 Mt, other nearby sites increase the capacity	East Coast Cluster cons.	3.1.4
Viking CCS	T&S	UK	2030	(By 2030): 10 Mtpa // (By 2035): 15 Mtpa // 300 Mt of initial storage capacity	Harbour Energy	3.1.4
Liverpool Bay CCS	T&S	UK	2025	Phase I (from 2025): 4.5 Mtpa // Phase II (2030): 10 Mtpa	ENI / HyNet N-West Cons	3.1.4
Morecambe Net Zero Cluster	T&S	UK	Unknown	Initially, the cluster can accommodate over 5Mtpa // Cumulative capacity of up to 1 Gt	Spirit Energy	3.1.4
ECO2CEE**	T&T	Lithuania & Poland	2026/2027	Phase I (2027-2030): 2.5 Mtpa transport capacity // Phase II (2031-2032): 8.7 Mtpa transport capacity // Phase III (2033+) : up to 9 Mtpa transport capacity	Air Liquide Polska	3.1.5
CCS Baltic Consortium*	T&T	Latvia & Lithuania	2030	(2030): 4 Mtpa maximum handling capacity	Kalipedos Nafta AB	3.1.5
Pycasso*	T&S	France & Spain	2030	Phase I (2030-2034): Up to 2.5 Mtpa transport capacity "east-west" // Phase II (2035+): 3.4 Mtpa additional transport capacity "north-south"	Terega	3.2.1
Callisto*	T&S	Italy & France	2027-2029	Phase I (2027-2032): 3.6 Mtpa // Phase II (2033-2050): 6.4 Mtpa	Air Liquide	3.2.1
Prinos CO2 Storage*	T&S	Greece	2025	Phase I (end of 2025) 1 Mtpa // Phase II (end of 2027) 2Mtpa. // Overall cumulative capacity 100 Mt	Energean	3.2.1

**Project is on the PCI 2023 candidate list, **Project is on the PCI 2023 candidate list and previous PCI list*
T&S: Transport and storage, T&T: Transport and terminal

7 Appendix B

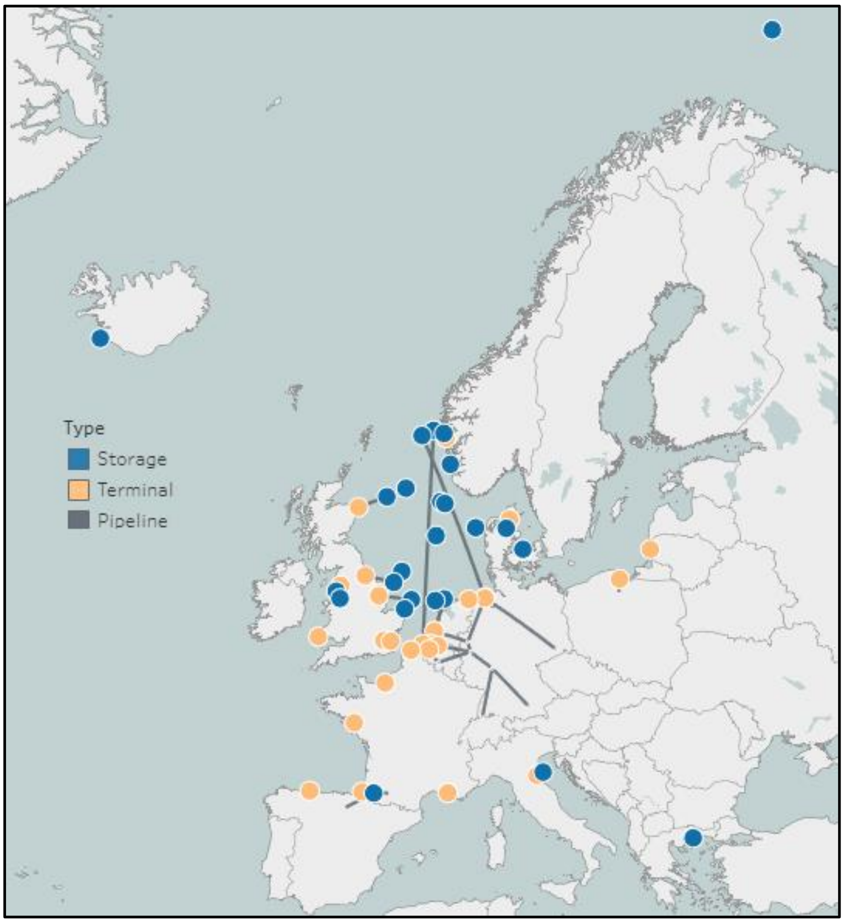

Figure 5 Map showing planned pipeline, terminal, and storage network infrastructure in Europe.

Schweizerische Eidgenossenschaft
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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Appendix II to WP4 report – 30 November 2023

Appendix II - Business models for waste-to-energy, cement, and chemical and pharma industries

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DEMO UP CARMA

WP4: Subtask 2.6 – Business models for waste-to-energy, cement, and chemical and pharma industries

1 Introduction

1.1 Background and objectives

With the adoption of the Climate Act in June 2023, Switzerland's net-zero target by 2050 was officially anchored in the federal law [1]. In principle, greenhouse gas (GHG) emissions in any industry must be reduced as far as possible, namely through technical measures or by promoting alternatives. Emissions from industrial processes that are difficult to avoid, such as from waste incineration or cement production, must be avoided through the implementation of carbon capture, transport, and storage (CCTS) and carbon capture, utilization, and storage (CCUS) technologies.

However, the implementation of CCTS and CCUS technologies in the cement, waste-to-energy, and chemical and pharma industries faces certain limitations and challenges. These are grounded in technical aspects but also arise from an evolving regulatory landscape and the absence of well-established business models that would render the adoption of these technologies economically feasible. In this context, this report analyses viable business models to support the implementation of CCTS and CCUS for the waste-to-energy, cement, and chemical and pharma industries in Switzerland. Differences and similarities between appropriate business models for these industries are identified.

1.2 Scope and methodology

For the analysis of viable business models, this report focuses on hard-to-decarbonize industries in Switzerland. These mainly include waste-to-energy, cement, as well as chemical and pharma, which are expected to have residual emissions of around 7 million tons of carbon dioxide (CO_2) per year as of 2050 that would need to be addressed through CCTS and CCUS (see Table 1) [2].

Table 1: Overview of the largest hard-to-decarbonize industries in Switzerland.

	Waste-to-energy	Cement	Chemical and pharma
Emitters with annual emissions of <100'000 tons of CO_2 as of 2021 [3]	20	6	4
Expected residual emissions in 2050 (whole industry) [4]	3.6 Mt CO_2	2.4 Mt CO_2	1.5 Mt CO_2
Origin of CO_2	~ 50% fossil ~ 50% biogenic	~ 90% fossil ~ 10% biogenic	~ 90% fossil ~ 10% biogenic
Ownership	Public	Private	Private

In general, business models can be defined as the structures for how an organization creates, delivers, and captures value [5]. The main components include the definition of a value proposition, the structure and management of the value chain, and a financial model aggregating the costs and revenues and distributing them across the involved actors [6]. In addition, the existing regulatory landscape shapes the options for designing a business model. And ultimately, certain policy measures can support the development of a sustainable business model.

In the context of CCTS and CCUS, the value proposition can be described as the positive climate impact through emissions reductions or removals. These are achieved through the durable storage of captured CO_2, which determines the last activity of the value chain, as described in the two pathways in section 3. The durable storage, in turn, is accompanied by the supposedly most important revenue stream – the sale of CO_2 credits. However, there are different options for the management and organization of the value chain and the distribution of responsibilities for the capture, transport, and storage activities. This, in turn, impacts the costs, risk, and complexity from the emitter's point of view.

In this report, the viability of business models for CCTS and CCUS is assessed along the following four key building blocks:

- First, the regulatory landscape determines in which markets, or with which instruments an emitter can generate revenue by implementing CCTS or CCUS. The different markets and instruments as well as their inclusion/exclusion of certain industries or pathways are assessed in section 2.
- Second, the design and choice of the specific CCTS or CCUS pathway, as these are characterized by different costs and risks. In this regard, the structures of the CCTS and CCUS value chains (i.e., the respective capture, transport, and storage activities for both pathways) are described in section 3.
- Third, the organization and management of the respective capture, transport, and storage activities (i.e., the integration vs. outsourcing of such activities from an emitter's perspective). Conclusively, different setups for the organization and management of the CCTS and CCUS value chains are discussed in section 4.
- Fourth, supporting revenue streams and financing that could further support the implementation of CCTS and CCUS and the viability of their business models are identified in section 5.

Lastly, the findings and the key open challenges that require future research are summarized. Due to the novelty of this topic and the scarcity of existing business models for the two decarbonization pathways specific to the Swiss context, this report does not provide concrete recommendations but rather an extensive overview of building blocks to consider when developing first-of-a-kind business models for CCTS and CCUS projects.

2 Regulatory landscape

The viability of CCTS and CCUS business models is fundamentally reliant on sustainable and sufficient revenues through the sale of CO_2 credits. The different options for emitters in Switzerland to generate revenue by selling CO_2 credits are regulated mainly by the CO_2 Act and the corresponding CO_2 Ordinance [7]. In general, the Swiss regulatory landscape distinguishes the following key policy instruments that aim at reducing GHG emissions and could therefore allow for the avoidance of taxation or the generation of revenues by CCTS and CCUS:

1. **The Swiss emissions trading system (ETS)** is the main national compliance market for the trading of GHG emission allowances.
2. National and international **compensation projects** are a second policy instrument for the sale of credits generated through national and international projects that reduce GHG emissions.
3. **The voluntary carbon market (VCM)** allows for the offsetting of GHG emissions beyond regulatory obligations by trading of CO_2 avoidance or removal credits.

2.1 The Swiss ETS

The Swiss ETS applies a 'cap-and-trade' principle, specifying the maximum amount of available emission allowances in the system ('cap'), which are reduced each year. Some of the emission allowances are allocated free of charge to companies while others are auctioned off. Each year, companies participating in the Swiss ETS must surrender the amount of allowances equivalent to the volume of their emissions. They can purchase allowances that they might need to cover their overall emission, but also sell any excess allowances that they might have accumulated. Since 2020, the Swiss ETS is linked to the EU ETS, allowing participants of the Swiss ETS to benefit from a larger market with more liquidity and flexibility [8]. In February 2023, the price of EU emission allowances exceeded EUR 100 per ton of CO_2 for the first time, while as of Q3 2023, prices fluctuate between EUR 85 and 95 per ton of CO_2 [9]. As for the expected price development until 2030, analysts and reports estimate prices between EUR 100 and EUR 130 per ton of CO_2 [10].

The current CO_2 Act does not take into consideration possible emissions reductions through CCTS or CCUS. As a result, companies currently participating in the Swiss ETS cannot account for emissions reductions and are unable to sell emission allowances from CCTS or CCUS. However, this limitation could change once the newly revised CO_2 Act is adopted in 2025. In September 2022, the Federal Council submitted a dispatch on the new revision of the CO_2 Act for the period 2025 to 2030, providing an explanation of the proposed amendments, to the Federal Assembly for approval. The newly revised CO_2 Act contains several proposals that are relevant to CCTS and CCUS in the context of the Swiss ETS. In the newly revised CO_2 Act, CCTS and CCUS of CO_2 from fossil origin is planned to be included in the Swiss ETS starting from 2025, in accordance with existing regulations in the EU ETS. In particular, the obligation to surrender emission allowances for captured and durably stored CO_2 from fossil origin will be eliminated and storage in underground sites in the European Economic Area will be creditable if it is in line with the European CCS Directive. Further, durable storage in long-lived products such as building materials is planned to become creditable, as envisaged by the European Commission in the revision of the EU ETS [11; 12]. At the same time, CCTS and CCUS of CO_2 from biogenic origin is only indirectly included in the Swiss ETS. Since biogenic CO_2 emissions are not accounted for, no allowances need to be surrendered for these emissions. Consequently, this also means that no reductions will be accounted for within the ETS from CCTS and CCUS of biogenic CO_2 [13]. The newly revised CO_2 Act does not foresee any changes regarding this approach.

The next revision of the CO_2 Act is planned for the time after 2030. For this revision cycle, the Federal Council aims to develop several options to regulate the necessary build-up of CCTS, CCUS, and carbon dioxide removal (CDR). More concrete options for a first legislative proposal, which will be open for public consultation by the end of 2025, are collected and developed by the end of 2024 [12].

Looking at industries in the scope of this report, emitters from both the cement as well as the chemical and pharma industries participate in the Swiss ETS [13]. In general, around 90% of emissions from cement, chemical, and pharma industries are of fossil origin and would therefore be included in the Swiss ETS. Emitters from the waste-to-energy industry are exempt from the Swiss ETS [13]. However, in accordance with the CO_2 Act, the federal government agreed on certain reduction targets for the industry [7]. In 2022, the Federal Department of the Environment, Transport, Energy and Communications (DETEC) concluded an agreement with the Swiss Association of Waste Treatment Plant Operators (VBSA) requiring at least one CO_2 capture plant to be operational by 2030 with a minimum nominal capacity of 100,000 tons per year, and to include subsequent geological or durable product storage [14]. In this regard, emitters from the waste-to-energy industry are currently not able to generate revenue from the sale of excess emission allowances in the Swiss ETS but would have to either seek registration of a compensation project (see section 2.2) or generate and sell credits on the VCM (see section 2.3). The newly revised CO_2 Act does not foresee the inclusion of the waste-to-energy industry into the Swiss ETS.

For a more detailed legal analysis of the inclusion of CCTS and CCUS in the Swiss ETS, see DemoUpCARMA WP5, Subtask 1.4 – *Analysis of potential strategies to acknowledge emissions reductions achieved through CCUS/CCTS implemented by industrial emitters participating in the Swiss Emissions Trading Scheme.*

2.2 Compensation projects

Further policy instruments to reduce GHG emissions that were established by the Swiss CO_2 Act are compensation projects in Switzerland and abroad [15]. The Federal Office for the Environment (FOEN) issues tradable certificates for verified reductions from national or international compensation projects that meet certain requirements [13]. This instrument was created mainly for the manufacturers and importers of fossil motor fuels, that are obliged to compensate for part of the GHG emissions caused by the consumption of these fuels by submitting attestations from compensation projects to the FOEN [7]. However, this instrument can also be used on a voluntary basis by other companies, provided that the respective GHG emissions are not already recorded in the Swiss ETS [13]. As of 2022, CCTS and CCUS of CO_2 from both fossil and biogenic origin are included in this instrument and qualify as a compensation project [11; 16].

Emitters from the cement as well as chemical and pharma industries are obliged to participate in the Swiss ETS. While their fossil CO_2 emissions are recorded in the Swiss ETS, this is not the case for their biogenic CO_2. As a result, in the case that these emitters implement CCTS or CCUS, their share of CO_2 from biogenic origin could qualify as a compensation project. Whether a specific CCTS or CCUS project qualifies as compensation project needs to be discussed with the FOEN administrative office for compensation on a case-by-case basis [17]. Emitters from the waste-to-energy industry that are exempt from the Swiss ETS can make use of these compensation projects and, in general, generate revenue streams from the sale of credits generated through CCTS and CCUS. Again, whether a specific CCTS or CCUS project qualifies as compensation project needs to be discussed with the FOEN administrative office for compensation on a case-by-case basis [17].

2.3 The Voluntary Carbon Market

The VCM allows for the offsetting of GHG emissions beyond regulatory obligations by trading CO_2 avoidance or removal credits [18]. The VCM is not regulated and is composed of many different actors and various carbon certification standards and methodologies that establish and clarify the value chain of carbon credits. Carbon certification standards are organisations defining, for example, requirements for project development or CO_2 credit issuance, and management of public registries. Methodologies are typically developed by an independent third party or the respective carbon certification standard itself. They establish the requirements for quantifying the GHG emission avoidance and/or removals from a specific activity [19]. As of today, the Verified Carbon Standard (VCS) is the world's leading carbon certification standard with its own registry system and numerous methodologies, accounting for approximately two-thirds of the overall VCM transaction volume [20].

Currently, methodologies for the generation of CO_2 credits from CCTS and CCUS (of both fossil and biogenic CO_2) are limited and vary in quality. This limitation is addressed in project DemoUpCARMA through the generation of publicly available modular methodologies for CCTS and CCUS activities (for details, see DemoUpCARMA WP5, Subtask 1, *Emissions accounting, reporting tools and climate finance mechanisms of negative emissions for national and transnational CCUS and CCTS solutions*). In a more international context, the CCS+ Initiative is developing comprehensive and integrated accounting methodologies for the generation of such CO_2 credits. Until 2024, the initiative aims to publish its methodologies under the VCS, therefore enabling its use across the market.

Currently, there is a lack of homogeneous and robust verification schemes, making it difficult for buyers to assess the quality of credits. Overall, the quality and price of credits as well as the demand for and supply of credits varies greatly depending on the respective project. On average, the price per CO_2 credit sold on the VCM is much lower compared to compliance markets such as the European or Swiss ETS, hovering around EUR 20 [21]. At the same time, credits generated from CCTS and CCUS projects could potentially achieve much higher prices due to their high level of durability of stored CO_2 and the relatively simpler verification methods.

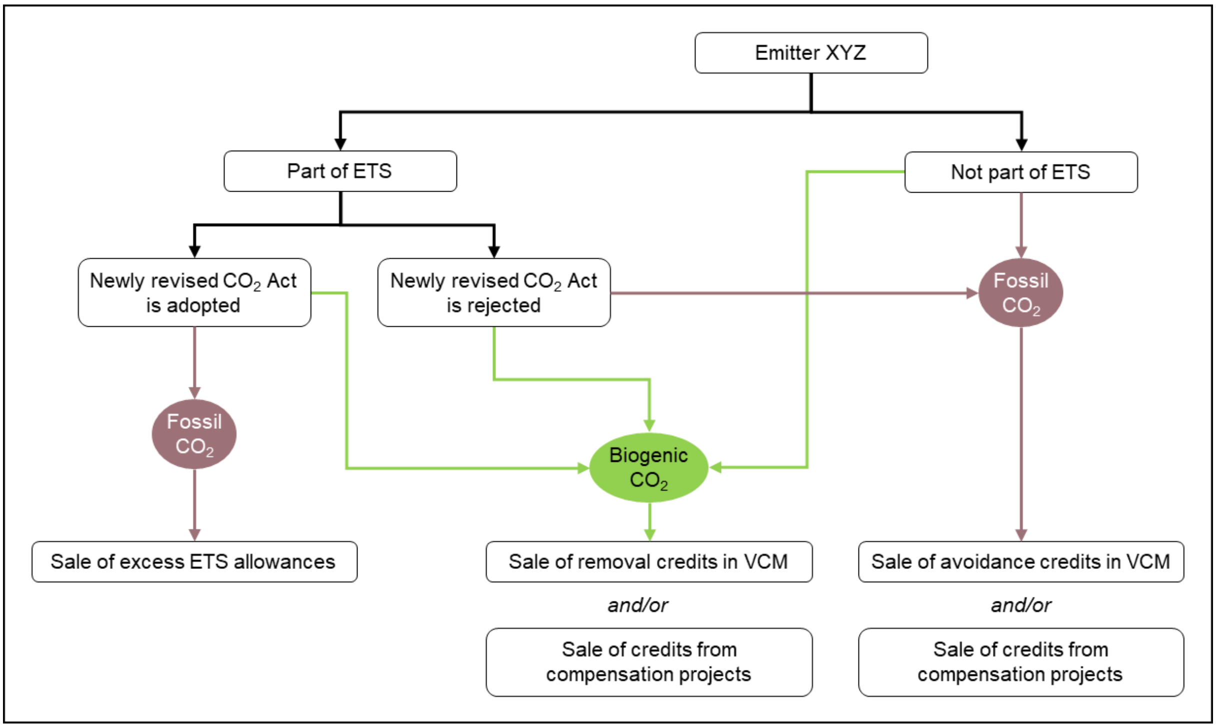
In general, CCTS and CCUS of CO_2 from fossil origins generates avoidance credits, while CCTS and CCUS of CO_2 from biogenic origin generates removal credits. This differentiation is important as the avoidance and removal markets are not completely the same: In general, removal credits may have a higher quality and therefore higher price compared to avoidance credits, due to the aforementioned verifiability and additionality concerns and the higher investment that is required for most removal projects [22].

Emitters from the cement as well as chemical and pharma industries are obliged to participate in the Swiss ETS. However, compared to their fossil CO_2 emissions, their biogenic CO_2 is not recorded in the Swiss ETS. Consequently, in case these emitters implement CCTS or CCUS, their share of CO_2 captured from biogenic origin could be certified and sold under the VCM. Emitters from the waste-to-energy industry that are exempt from the Swiss ETS can make use of the VCM for CCTS and CCUS of CO_2 from both fossil (accounting for ~50% of emissions) and biogenic (accounting for ~50% of emissions) origin.

2.4 Conclusions on the regulatory landscape

In summary, the regulatory landscape is fundamentally critical to the viability of CCTS and CCUS business models since it provides the framework for participation in certain policy instruments and thus determines the revenue streams an emitter can exploit. From the emitters' perspective, three aspects in particular are important: First, while the Swiss ETS includes emitters from the cement and chemical and pharma industries, it does not include the waste-to-energy industry. This prevents waste-to-energy companies from having the opportunity to generate revenue through the sale of excess emission reductions. Second, it is not yet clear whether CCTS and CCUS will be included in the Swiss ETS at all. This depends on whether the newly revised CO_2 Act will be adopted, allowing emitters in the ETS to sell their excess allowances that they have accumulated due to CCTS and CCUS. Third, for any emitter that will need to generate the large parts of its CCTS or CCUS revenue through the VCM (or compensation projects), it is critical to understand that the prices of the respective credits as well as the ability to sell the issued credits will highly depend on the perceived quality and demand on the market. For all three aspects, the distinction between biogenic and fossil CO_2 emissions further complicates the regulatory landscape and the applicability of business models for CCTS and CCUS.

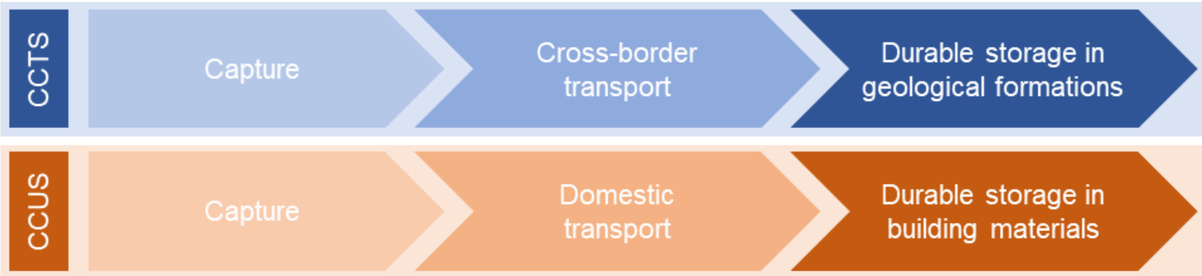
Figure 1: Simplified overview of the regulatory landscape for the waste-to-energy, cement, and chemical and pharma industries.



3 CCTS and CCUS pathways

In this section, the CCTS and CCUS pathways and their underlying value chain structures in the Swiss context are defined, including current limitations regarding transport and storage. The viability of CCTS and CCUS business models depends on the design and choice of the specific decarbonization pathway, as these are characterized by different costs and risks. The following definitions of the CCTS and CCUS pathways and their value chain activities are specific to the Swiss context, specifically the pilot and demonstration pathways of the DemoUpCARMA project (see also DemoUpCARMA WP2 – *Demonstration of CO_2 utilization and storage in concrete (domestic solution, CCUS)*, and DemoUpCARMA WP3 – *Demonstration of CO_2 transport and geological storage (abroad, CCTS)*) and the longer-term climate strategy regarding CCTS and CCUS [2] (see Figure 2). It should be noted that in principle other structures of CCTS and CCUS value chains are also conceivable and certain ones may become more important in the future (for example, in case sufficient capacities for underground storage become available in Switzerland).

Figure 2: CCTS and CCUS value chain structures for the Swiss context.



3.1 CCTS value chain structure

CCTS commonly refers to the chemical capture of CO_2 from an emission source and its subsequent transport and durable storage in geological formations, such as deep saline aquifers, depleted oil and gas fields, or reactive rock formations [23; 24]. For the examination of viable business models in this report, the defined CCTS value chain structure foresees cross-border transport with trucks, rail, ships, and barges for durable storage in a geological storage facility abroad. This is in line with both the pilot and demonstration pathway as set out in DemoUpCARMA WP3 and Switzerland's net-zero strategy.

As of today, Switzerland has no readily available durable storage capacity in geological formations and the potential is likely to remain very limited due to technical, economic, ecological, and social constraints. According to estimates from the SFOE, storage capacity will be ready for operation in 15-20 years at the earliest and only provided that subsurface exploration is successful. In accordance with this, significant amounts of CO_2 are expected to be exported to foreign storage facilities, also in the longer term. Swiss emitters will therefore rely heavily on CO_2 storage abroad [2; 25]. The first commercial storage facilities abroad with reserved capacity for foreign CO_2 are expected to start operations in 2025. Most of these are located in Northern Europe, particularly in the North Sea (for details, see DemoUpCARMA WP4, Subtask 2.3 – *Definition of scenarios for an EU-wide shared CO_2 infrastructure*).

To reach foreign storage facilities, cross-border transport of CO_2 is required. Currently however, no CO_2 pipelines are planned or developed in Switzerland to enable such transport. Looking at Switzerland's neighboring countries, in the optimal case, the most advanced pipeline project in Germany could become operational in 2028 with access to the Swiss border between 2035 and 2040 [26]. In accordance with this, only non-pipeline transport modes, such as trucks, rail, ships, and barges, are currently considered as possible options for cross-border transport in the context of CCTS. The Federal Office of Transport (FOT) estimates that the existing infrastructure could transport up to 1 million tons of CO_2 per year through such non-pipeline transport [12].

In general, costs per ton of CO_2 can differ fundamentally for specific projects, depending on the capture technology, the volume of CO_2, selected means of transport and exact location of the storage facility. As an example, recent cost-modelling for the CCTS value chain as outlined above show minimum costs of EUR 490 per tons of CO_2 in the short-term and EUR 420 per tons of CO_2 in the medium term. The modelling was specific to KVA Linth as the emitter and transport of CO_2 via trucks, ships, and barges to a storage facility in the North Sea. In the future, costs for CCTS might decrease due to new capture and transport technologies, the development of pipeline networks, learning curves and economies of scale, and the deployment of closer storage facilities [27].

3.2 CCUS value chain structure

In general, CCUS refers to the chemical capture of CO_2 from an emissions source and its subsequent transport, utilization, and storage in products, such as carbonated drinks, fuels, plastics and aggregates [23]. For the analysis of viable business models in this report, the defined CCUS value chain structure foresees durable storage in domestic building materials, in particular recycled concrete. This is in line with both the pilot and demonstration pathway as set out in DemoUpCARMA WP2 and Switzerland's net-zero strategy.

As of today, Switzerland has only small capacities for durable storage in building materials, although several companies are working on different processes of storing CO_2 in recycled concrete. The Swiss start-up neustark for example collaborates with several concrete facilities and has removed and stored over 500 tons of CO_2 in recycled concrete as of October 2023 [28]. In principle, a concrete facility in Switzerland can durably store between 300 and 2'000 tons of CO_2 in recycled concrete per year [29-31]. In 2025, the potential for storage in demolished concrete is expected to reach 0.6 million tons of CO_2 per year [32]. This is expected to increase to 2.5 million tons of CO_2 per year as of 2050 [33].

Considering the distribution of both concrete and larger point-source emission facilities in Switzerland, transport distances are relatively short – e.g., the average distance between biogas and concrete facilities in Switzerland is about 10 km [30]. Therefore, transport by trucks is considered as the only option for domestic transport of CO_2 in the context of CCUS.

In general, costs per ton of CO_2 can differ for specific projects, however, the range is much smaller compared to CCTS projects. Recent modelling of costs for the CCUS value chain as outlined above show minimum costs of EUR 240 per tons of CO_2. The modelling considered KVA Linth as the emitter and transport of CO_2 via trucks to a concrete facility nearby. In the future, costs for CCUS are likely to also decrease due to new capture technologies, learning curves and economies of scale [27].

3.3 Conclusion on CCTS and CCUS pathways

When comparing the CCTS and CCUS value chains as outlined above, two aspects become apparent. First, apart from the capture process, the structures of both value chains differ fundamentally in terms of activities, complexity, and costs. CCTS requires cross-border transport to foreign storage facilities, while CCUS is limited to transport and storage within Switzerland. This greatly simplifies complexity and decreases transport costs compared to CCTS by almost half [27]. As outlined before, within each pathway, the costs of implementing CCTS and CCUS can differ greatly depending on factors such as the type of industrial process being the source of the emissions, or the volumes of CO_2 to be captured, transported, and stored. The exact costs would therefore need to be calculated on a case-by-case basis.

Second, it is worth noting that both pathways show fundamental differences regarding storage potential, both in the short-term and as of 2050. First commercial storage facilities abroad with reserved capacity for foreign CO_2 relevant for the CCTS pathway are expected to start operations in 2025 and provide almost infinite theoretical long-term storage potential. At the same time, CCTS poses certain challenges in the short to medium term due to missing pipeline transport modes and uncertainties in securing third-party access to foreign storage capacities. On the other hand, the short- and long-term storage potential of the CCUS pathway is limited and will not be able to store the 7 million tons of CO_2 per year that are expected to be addressed through CCTS and CCUS in Switzerland as of 2050 [2].

Overall, an individual emitter is likely to opt for CCUS due to significantly lower costs and complexity. However, if the national perspective is taken and the available short- and long-term storage potentials of both pathways are considered, it becomes evident that only a few, rather small emitters will be able to pursue CCUS. In the longer term, however, most emitters, especially larger ones, will not be able to avoid establishing CCTS value chains.

Notably, the choice of the pathway is also driven by the regulatory landscape, specifically, whenever reduction or removal credits are generated and sold on the VCM. Since the VCM does not provide for a fixed price per credit, credits may not generate equally high prices for the two pathways discussed. For emitters that are part of the Swiss ETS however, both the current as well as the revised CO_2 Acts do not differentiate between the two pathways, which therefore would generate the same revenue (for the fossil portion of their emissions that are recorded in the Swiss ETS). As such, the designated marketplace for the credits generated through CCTS or CCUS can impact the financial viability of choosing one pathway or the other, particularly due to the volatility of credit prices on the VCM.

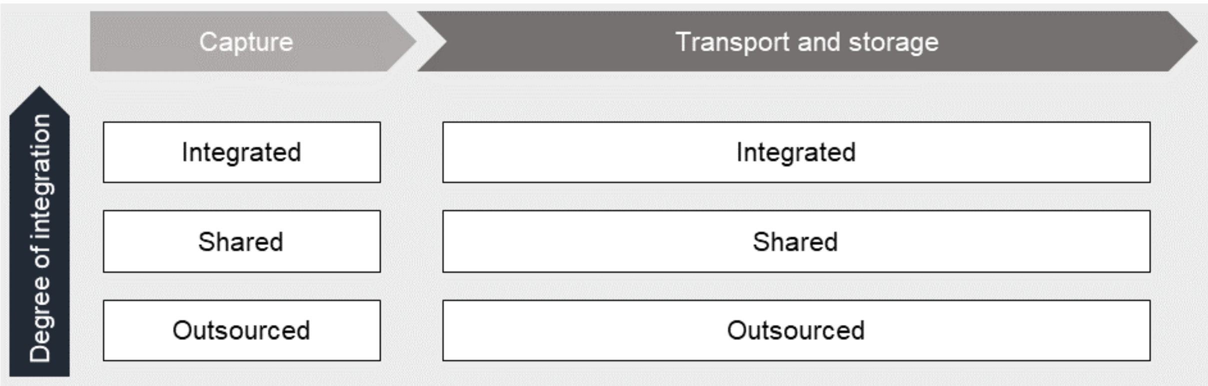
4 Management and organization of CCTS and CCUS value chains

In this section, different options are investigated of how an emitter can manage and organize the value chain structures described in section 3. The management of these value chains decides which activities the emitter owns and performs, and which are performed by other actors of the value chain. In a first step, this analysis is performed independently of the CCTS or CCUS value chains, but rather focuses on the degree of integration of the respective value chain activity. Second, two setups for the overall management and organization are explored and set into context for the two value chains.

4.1 Management and organization of the capture as well as the transport and storage activities

The analysis of CCTS and CCUS management and organization is structured along (i) the capture activity and (ii) the transport and storage activities – both independent of the CCTS or CCUS pathway. It considers different degrees of vertical integration into the emitters existing business processes (see Figure 2). This dichotomy of (i) capture and (ii) transport and storage is based on the inherent linkage between the capture activity and the emitter's industrial process, whereas transport and storage are more independent of the emitters current business process.

Figure 3: Setups of how an emitter can manage the capture and transport and storage activities.



Six options are compared based on their expected costs, potential revenue, and risk profile. Costs mainly include considerations around CAPEX and OPEX for the construction and operation of infrastructure or service fees paid to third parties carrying out value chain activities. In line with the general CCTS and CCUS pathways that are considered, potential revenues only include the sale of CO_2 credits (for an assessment of additional revenue streams that are independent of the value chain management, see section 5). Notably, for all six options, the total revenues generated remain the same – only their distribution to the parties of the value chain might differ.

Lastly, even though business model considerations in general mainly focus on costs and revenues, it is important to also carefully assess the associated risks. In particular in the context of CCTS and CCUS, there are a few hard-to-mitigate risks that could arise within the management of these value chains [34; 35]: Technical risks, such as technology uncertainty or impact on existing operations; Economic risks, such as uncertainty of costs and revenues; Political risks, such lack of policies or CO_2 credit price uncertainty; Cross-chain risks, such as uncertainty of infrastructure availability or coordination of involved parties.

4.1.1 Management and organization of capture activity

Integrated capture: The emitter fully integrates the CO_2 capture activity into existing business processes. In this case, the emitter typically owns and operates the CO_2 capture facility on its premises and bears the CAPEX and OPEX for the construction and operation thereof. At the same time, it can claim the full revenue from the sales of credits but also bears the full risks associated with the capture activity. An integration can be beneficial for the following reasons: capture facilities are typically built for a specific CCUS or CCTS value chain, on the emitter's premises, and tailored to the conditions of the emitter's flue gas and industrial process.

Shared capture: The emitter partners with one or several other emitters to jointly manage their CO_2 capture activities. One strategically (over)sized CO_2 capture facility is built – typically on the premises of one of the emitters – and, for example, short pipelines are installed to transport the flue gases of the partnering emitters to the capture facility [36]. In this case, the emitters typically jointly own and operate the CO_2 capture facility and share the CAPEX and OPEX for the construction and operation thereof, which are lower on a per emitter basis due to economies of scale [37]. Further, additional costs associated with activities such as community consultation, federal or cantonal approvals, or negotiations with property owners, can be reduced on a per emitter basis [36]. Further, the individual revenue from the sales of credits is expected to remain unchanged and risks associated with the capture activity are shared. Compared to the full integration of the capture activity, this option is typically characterized by lower costs and risks due to the shared management and organization of the capture activity. A fundamental prerequisite for this option is that the emitters are in close proximity to each other, for example, as part of an industrial cluster.

At this point, it should be mentioned that there are also more subtle forms of the shared capture option. Emitters can not only partner to jointly capture both of their emissions but can also pool resources in other ways. The following example illustrates this form of cooperation: A cement emitter and a waste-to-energy emitter both do not have enough heat available to achieve a high capture efficiency and therefore can only capture around 50% of their emissions. Provided that the two emitters are close to each other, it can make sense in such cases to pool the heat and transfer it to one of the emitters. In this way, only one capture facility needs to be built, but in the end, it will have a significantly higher capture efficiency and will therefore capture a similar amount of CO_2 as the two individual facilities with lower efficiency.

Outsourced capture: The emitter completely outsources the CO_2 capture activity to a third party, basically taking the role as a provider of flue gas [38]. In this case, the emitter neither owns nor operates the CO_2 capture facility and does not bear any CAPEX or OPEX for the construction and operation thereof. Instead, the emitter pays a service fee to the third party mandated to carry out the capture activity. The emitter typically claims the full revenue from the sales of credits and transfers a large part of the risks associated with the capture activity to the third party. The latter, however, is expected to be compensated by a markup in the service fee. Overall, this setup seems rather unlikely due to several reasons. As mentioned before, capture facilities are typically specifically built for an emitter on the emitter's premises, and tailored to the conditions of the emitter's flue gas and industrial process. At the same time, the capture facility will likely have an impact on the existing industrial and business processes of the emitter, for example due to its energy consumption or required space.

In general, the outsourcing of the capture activity can also be set up in a shared approach, where several emitters partner and completely outsource their capture activities to a third party which would build one capture facility – typically on the premises of one of the emitters – and, for example, install short pipelines to transport the flue gases of the emitters to the capture facility. In this approach, the partnering emitters split the costs for the service fee as well as the generated revenues. However, this approach bears similar challenges regarding the inherent linkage between the capture activity and the emitter's industrial process as described in the previous paragraph for the individual outsourcing.

4.1.2 Management and organization of transport and storage activity

Integrated transport and storage: The emitter fully integrates the CO_2 transport and storage activities into its existing business processes. In this case, the emitter typically owns and operates the CO_2 transport infrastructure and storage facility and bears the CAPEX and OPEX for the construction and operation thereof. At the same time, it can claim the full revenue from the sales of credits but also bears the full risks associated with the transport and storage activity. A vertical integration beyond CO_2 capture would involve substantially different activities, require know-how of multiple industries and processes and face high risks and investment costs [39; 40]. In view of the existence of actors that specialise in transport and storage activities and invest in the required infrastructure, it seems highly unlikely that emitters would vertically integrate beyond the activity of capturing CO_2.

Shared transport and storage: The emitter partners with one or several other emitters to jointly manage and organize their CO_2 transport and storage activities. In this case, the emitters typically jointly own and operate the CO_2 transport infrastructure and storage facility and share the CAPEX and OPEX for the construction and operation thereof. At the same time, they share the revenue from the sales of credits but also share the risks associated with the transport and storage activity. Compared to the integration of transport and storage activities, this option is typically characterized by lower costs and risks due to the shared approach. However, it still requires know-how of multiple industries and processes and faces high risks and investment costs [39; 40]. Again, in view of the existence of actors that specialise in transport and storage activities and invest in the required infrastructure, it seems highly unlikely that emitters would vertically integrate beyond the activity of capturing CO_2.

Outsourced transport and storage: The emitter completely outsources the CO_2 transport and storage activities to one or several third parties. In this case, the emitter neither owns nor operates the CO_2 transport infrastructure and storage facility and does not bear the CAPEX and OPEX for the construction and operation thereof. Instead, the emitter pays a service fee to the third parties mandated to carry out these activities. The emitter typically claims the full revenue from the sales of credits and transfers a large part of the risks associated with the transport and storage to the third party – the latter, however, is expected to be compensated by a markup in the service fee. This option can also be approach in a shared setup, where several emitters decide to partner and completely outsource the CO_2 capture activity to a third party, therefore splitting the costs for the service fees as well as the generated revenues.

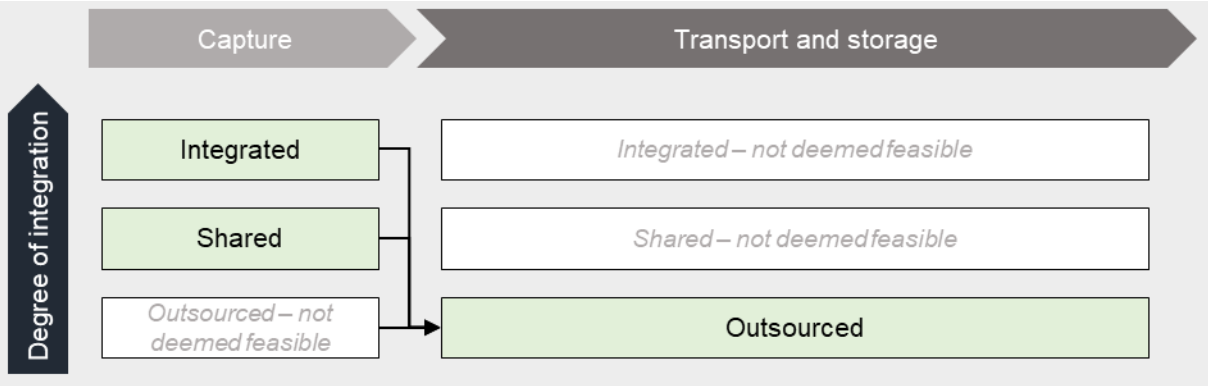
4.1.3 Conclusion on the management and organization of the capture as well as the transport and storage activities

The options discussed above for managing the capture activity have different cost-risk profiles, but do not differ fundamentally in these regards. However, one critical aspect is the inherent linkage between the capture activity and the emitter's industrial process, which likely makes the complete outsourcing of this activity unfeasible. Rather, it will be the emitters that organize and manage their capture activity, either in an integrated or shared approach. This is fundamentally different for transport and storage activities, where existing providers likely supply their infrastructure and services in any case and to whatever project they are part of. Further, both the cost of investing in such transport and storage infrastructure and the associated risks (e.g., the risk of stranded assets) are much more profound. In this respect, it can be assumed that emitters will generally not integrate these activities into their business processes, neither independently nor in a shared approach.

In the following, the analysis focuses on two general setups for the management and organization of CCTS and CCUS value chains (see Figure 4). Based on the comparison of the six options above, these are the setups that were deemed most relevant and realistic from a Swiss emitter's perspective. At the same time, it should be noted that, in principle, other setups of CCTS and CCUS value chains are also conceivable and certain ones may become more important in the future.

- Integrated capture and outsourced transport and storage: The "Integrated capture" setup (see section 4.2.1)
- Shared capture and outsourced transport and storage: The "Capture cluster" setup (see section 4.2.2)

Figure 4: Two general setups for the management of CCTS and CCUS value chains emitters can choose from.



4.2 Setup of full CCTS and CCUS value chains

This section assesses the two full value chain setups by combining the activities outlined before. Further, the setups are placed in the context of the two CCTS and CCUS pathways and supplemented with real-world examples. CCUS and CCTS pathways can exhibit similar or varied degrees of integration for each of the two phases, differing on a case-by-case basis unique to each business model.

4.2.1 Integrated capture and outsourced transport and storage: The "Integrated capture" setup

In this setup, the emitter owns and operates a capture facility and completely outsources the transport and storage activities to one or several third parties.

In the case of CCTS value chains with long transport routes and different means of transport, it is unlikely that there are many players in the market that single-handedly cover the entire value chain following the capture of CO_2. Hence, emitters would have to negotiate with a variety of transport and storage providers and would need to manage, organize, and set up individual contracts for each step of the value chain. The coordination effort required for this is likely to be well beyond the capabilities of an individual emitter. A possible way to mitigate this is to not directly set up transport and storage with the respective providers, but to mandate a service company with the task of doing so. An existing service offering is currently provided by the company Airfix for CCTS of biogenic CO_2 emitters. The company offers a one-stop-shop solution that even goes beyond the setup of transport and storage activities, but also includes the management of financing, the selection of and negotiations with capture providers, and the sale of credits [41].

In the case of CCUS value chains, the abovementioned challenges regarding management and organization of the transport and storage activities are fundamentally less severe. The full value chain is within Switzerland, with short transport routes and many different (however small) storage facilities, which makes it much more likely to find a third party that covers both the transport and storage activity. An existing offering is currently provided by the company neustark for CCUS value chains. Neustark transports and durably stores CO_2 with their mineralization technology in collaboration with concrete recycling facilities. Further, they even offer to cover the capture activity (which basically constitutes a fully outsourced setup) [28].

An example from practice for the integrated capture and outsourced transport and storage setup, independent of the pathway, is provided by Entsorgung + Recycling Zürich (ERZ), that plans to capture CO_2 from its sewage sludge treatment plant. With a tender in May 2023, ERZ sought bidders for the transport and storage activities. In principle, the company aimed to establish a CCTS value chain but was also open to a CCUS solution with storage in recycled concrete. The bidders were asked to offer prices per ton of CO_2 for transport and storage of up to 25,000 tons of CO_2 per year. To minimize investment risks, ERZ aimed for a contract term of at least 10 years [42].

Another way to disentangle the complexity of the transport and storage activities of this setup is by pooling the captured CO_2 of various emitters that have opted for this setup and, while capturing CO_2 in an integrated and individual manner, have decided to outsource the transport and storage activities. These emitters can partner to jointly organize and manage the remaining activities of the value chain. This reduces complexity and costs, as certain economies of scale can be claimed, mainly due to a larger amount of CO_2 to be transported and stored, but also in the negotiation process. In addition, the negotiation power can be strengthened towards certain storage providers that are only willing to negotiate with providers of CO_2 that are able to deliver certain amounts. Independent of whether a single emitter enters this setup or if several emitters partner to organize and manage the remaining activities of the value chain, it is desirable to coordinate with as few third parties as possible.

4.2.2 Shared capture and outsourced transport and storage: The "Capture cluster" setup

In the shared-outsourced setup, several emitters jointly own and operate one CO_2 capture facility and completely outsource CO_2 transport and storage activities to one or several third parties. Overall, this setup bears the same challenges regarding the outsourcing of transport and storage activities as outlined for the capture cluster setup. However, one major advantage is that the partnering emitters have already joined forces due to their joint capture activity and can act as a single entity towards the transport and storage providers, leaving them with even stronger negotiation power. At the same time, involving more emitters can increase complexity and organizational efforts regarding aligning the different interests and requirements.

Such setups do currently not exist in Switzerland yet. This is likely due in large part to the fact that few emitters have yet to consider implementing CCTS or CCUS. Other reasons could be the geographical distance between many emitters as well as different timelines for planning and implementation. In principle, it can be assumed that a conglomerate of emitters could also use the services of Airfix or Neustark or take the approach of the ERZ – and thereby exploit even more efficiently the economies of scale described in the previous section for pooling of captured CO_2.

4.2.3 Conclusion on the setup of full CCTS and CCUS value chains

Overall, the specific setup of the value chain management and organization will likely mainly depend on the chosen CCTS or CCUS pathway and the availability of other emitters to potentially enter a capture cluster. Further, it will depend on the availability of companies offering services to cover transport and storage activities. As described above, the Swiss landscape currently has offerings that aim to cover the transport and storage activities for both CCTS and CCUS value chains, however, it is important to note that this is a developing market, and it can be expected that additional players are to enter the market in the next years.

Compared to the integrated capture setup, the capture cluster setup reduces costs and risks for many potential CCTS and CCUS projects and can also enable CO_2 capture from emitters with smaller emission volumes [36]. Notably, the choice of the setup is not directly driven by the regulatory landscape. Further, in general, the choice of the setup for the management and organization of the value chain is rather independent of the industry the emitter is part of. The feasibility of developing a capture cluster would need to be assessed on a case-by-case basis.

Overall, considering the revenue streams as outlined in section 2 as well as the costs for the different pathways described in section 3, the following can be determined: The choice of the setup for the management and organization of the full value chain definitely has a decisive impact on costs, risks and complexity of the respective value chain. However, overall and based on the current revenue and cost assumptions, even the most efficient setup is not able to establish a viable business model. This makes it all the more important to explore additional revenue streams and supporting financing instruments (see section 5).

5 Supporting revenue streams and financing

As revenues through the sales of CO_2 credits will likely not fully cover the costs of CCTS and CCUS in the short-term emitters will want to explore additional revenue streams and supporting financing instruments. This section therefore explores the current possibilities and limitations of supporting revenue streams as well as giving an overview of different financing mechanisms that are available to support the implementation of CCUS and CCTS infrastructure.

5.1 Increased customer charges

One option to generate additional revenue to support a viable CCTS or CCUS business model is to increase the prices of products or services that are provided by the respective emitter as part of its core business activities. Due to the high level of variation between the three industries – their processes, products, end customer and regulatory settings – the possibilities and impacts of increasing consumer charges differ.

Overall, it is important to note that the possibilities for generating additional sales listed below represent initial approaches, but not concrete proposals for solutions. In many cases, a change in regulations would be required, while in other cases the short- and longer-term effects on the respective market would need to be examined in detail.

5.1.1 Waste-to-energy industry

Waste-to-energy plants generate the main part of their revenue from service fees for the incineration of industrial and municipal solid waste, followed by the sale of their output heat and electricity [43]. In Switzerland, there are currently 29 waste-to-energy plants, incinerating over 4 million tons of waste while producing roughly 1,800 GWh of electricity and 4,000 GWh of heat [44]. Considering the 'polluter pays' principle as well as current regulations for prices of heat and electricity, an increase of prices for generated heat and electricity to (partially) finance the implementation of CCTS and CCUS seems highly unlikely [45]. Instead, as the incineration process is the source for the CO_2 emissions, an increase in customer fees is likely to focus on these service fees instead, aligning with the polluter pays principle. An increase in such service fees could take several forms, each with its own challenges.

One approach to generate additional revenue is to increase the service fee for the incineration of industrial and municipal solid waste. However, an earlier study showed that costs for CCTS and CCUS could only be (partially) passed on to customers if the waste-to-energy industry were to be legally required to implement CCTS or CCUS. For the waste-to-energy emitter KVA Linth, the study estimated that the price of a 35-litre waste bag in the Canton of Glarus would need to increase by CHF 0.6-0.8 in order to generate enough revenue to cover the estimated costs of CHF 156-190 per ton of CO_2 for the implementation of a first-of-a-kind CCTS chain [46]. Notably, this approach could incentivize the affected households to decrease municipal waste. Further, the increase of prices for waste bags only in cantons in which emitters implement CCTS or CCUS certainly follows the 'polluter pays' principle. At the same time, considering the Swiss-wide need for CCTS and CCUS deployment as well as the fact that the resulting CO_2 reductions or removals benefit the whole society, it could also be considered to increase prices of waste bags in the whole of Switzerland, independent of where the CCTS or CCUS project is implemented, and to stepwise increase the prices with every new CCTS or CCUS project going operational.

Another approach that addresses the risk of leakage is based on the centrally administered OCRCS Contamination Fund that finances the investigation, monitoring, and remediation of polluted sites in Switzerland [47]. The fund is financed by fees on the deposit of waste in landfills, which amount to CHF 5-22 per ton of waste deposited. The revenue generated is expected to be used to remediate up to 4,000 sites over the next 20 years, at an estimated total cost of CHF 5 billion [48]. A similar fund could be established to finance the implementation of CCTS and CCUS for the waste-to-energy industry. For each ton of waste delivered to a waste-to-energy emitter, a certain fee could be paid into the fund – regardless of whether the respective emitter has implemented CCTS or CCUS, therefore mitigating the risk of leakage. The generated funds could then be used to finance the implementation of CCTS or CCUS for emitters that are ready for implementation or where it is most cost-effective to do so [49].

A more recent report by Airfix suggests a slightly different approach to finance a fund as described above by introducing an additional fee for plastics at the point of purchase instead of incineration – similar to the anticipated recycling fee regulated in the Ordinance on the return, take-back and disposal of electrical and electronic equipment [50]. With this, a national fund to support the implementation of CCTS and CCUS for waste-to-energy could be created. Notably, the fee would not be directly paid by waste-to-energy customers, but rather by anyone purchasing products containing plastics. This approach would require government involvement and is estimated to cover the cost of several CCTS and CCUS projects over the next years, while being hardly noticeable to the consumers of plastic products [51]. However, considering that the fee technically only covers the emissions from non-biogenic sources (from plastic incineration), an increase in the fee of waste treatment for the consumer as outlined above would still need to be implemented, however, at roughly 50% lower price.

5.1.2 Cement industry

The Swiss cement industry is characterized by privately owned companies. Currently, three companies produce approximately 4.1 million tons of cement at four locations in Switzerland, covering the majority of inland cement demand [52; 53]. Cement emitters generate their main revenue from the sale of cement, though the profit margin is comparatively low [52]. An increase in the price of cement to generate additional revenue for the implementation of CCTS or CCUS should be assessed not only focusing on the cement emitter but also looking at the end-user of the product.

A recent case study found that the implementation of CCTS or CCUS results in a significant increase in the cost of the raw material cement of around 60%. However, as cement typically only accounts for a small fraction of the total cost of the end product – for example, a building or a bridge – the overall cost increase of the end product due to an increase of the cement price to account for the implementation of CCTS or CCUS remains marginal at around 1%. At the same time, overall CO_2 emissions associated with the infrastructure project would be reduced by around 50% [54; 55].

Similar to the introduction of higher prices for waste bags in the waste-to-energy industry, this approach bears a certain risk for leakage in a scenario where only a few cement emitters implement CCTS or CCUS. In that case, infrastructure developers could purchase cement at emitters that have not implemented CCTS or CCUS yet and therefore still offer lower prices. Given the low number of net imports, this risk could potentially be mitigated with a focus on the Swiss cement landscape. Further, increasing prices for cement could have disproportionately higher impact on smaller infrastructure projects and therefore low-income households. An increase in cement prices to account for the additional costs of implementing CCTS or CCUS could constitute a substantial 5-10% increase in the overall construction costs for low-cost housing compared to the approximately 1% as outlined before [56].

5.1.3 Chemical and pharma industry

There are four large emitters in the chemical and pharma industry in Switzerland that emit more than 100,000 tons of CO_2 per year and are part of the scienceindustries (Business Association Chemistry Pharma Life Sciences), with many other large pharma companies only locating their headquarters and not manufacturing processes in Switzerland. The chemical and pharma industry is an extremely competitive global market, facing market competition not only outside of Switzerland or more broadly the EU, but also internally in Switzerland. Production can relatively easily be moved internally to a different facility even inside the EU from for example Switzerland if producing there is not cost-effective. Therefore, the chemical and pharma industry operates in a dynamic market, that varies between size, product ranges, capital availability, and global market outreach.

The product range of the chemical and pharma industry is highly heterogenic. Accordingly, customers and consumers as well as regulations around product pricing differs widely. Most revenue in the industry is generated from the sale of chemical products such as pharmaceuticals, as well as intermediary products for various industries such as plastics or food [57]. Further, prices for pharmaceuticals are highly regulated, whereas fewer limitations exist regarding pricing of other chemical products [58-60].

Production processes and product outputs are much more heterogeneous and complex in the chemical and pharma industry compared to cement (one product) and waste-to-energy (one process). To follow the "polluter pays" principle, a life cycle analysis would need to be conducted for every product and process to precisely allocate emissions and shift costs of CCTS/CCUS to the consumer. Owing to the complex product and process landscape there is no simple and direct, while still accurate approach to distribute emissions, compared to the other analyzed industries.

Overall, given the highly diverse product range of the chemical and pharma industry, strict regulations around the pricing of medicinal products, the low costs for CC compared to companies' overall production costs and the missing direct link of CO2 emissions to the industries products (e.g., compared to the cement industry), it is unlikely that the costs of CC for chemical and pharma companies will be passed on directly to intermittent or end consumers.

5.2 Carbon capture and utilization (CCU)

In this section, the sale of CO_2 as a feedstock for carbon capture and utilization (CCU) is explored. CCU refers to the chemical capture of CO_2 from an emissions source and its subsequent utilization in products, such as carbonated drinks or fuels. These types of products last a relatively short amount of time and at the end of their life cycles, the CO_2 that was used in the manufacturing process is released back into the atmosphere. In this regard, the utilization of CO_2 in non-durable products leads to the shifting of the emissions towards a later stage rather than durable CO_2 emission reductions. Although CCU can play a critical role in the mitigation of climate change, the Swiss federal government is cautious regarding its implementation since many utilization applications, such as the production of synfuels from fossil CO_2, are not very energy efficient and therefore not compatible with Switzerland's net-zero target [61-63].

However, CCU can be seen as an interim solution potentially support the later implementation of CCTS or CCUS by providing emitters with an incentive to build capture facilities and generating temporary revenues through the sale of CO_2 until CCTS and CCUS value chains become economically more viable. By means of example, this is an approach that is also used by CDR startups exploring to deploy their removal technology in CCU to generate alternative revenue streams until the market matures enough for their CDR business model to become viable [64].

An analysis in Switzerland shows several CCU opportunities in industries such as food products, or textiles. However, most use cases currently only provide for little potential of CO_2 utilization and are limited regarding their scalability [62]. Overall, the price for CO_2 as a feedstock varies widely depending on the use case, ranging from under EUR 10 to over EUR 400 per ton of CO_2 in some instances, underlying the volatility and unpredictability of the CO_2 market is [65].

Synthetic fuels are expected to be one of the future key drivers for demand of CO_2 as a feedstock. Various incentives for synfuel production via CCU exist, for example through exemptions and compensation mechanisms specifically in the mineral oil tax, compensation obligation for fuel importers, or the Sustainable Aviation Fuel (SAF) quota. Already as of today, if a company produces a biogenic fuel that meets a certain level of criteria regarding considerations such as the life cycle impacts, even if the feedstock CO_2 used comes from industrial sources, they are exempt from the mineral oil tax [66; 67]. Further, under a proposed compensation obligation under the revised CO_2 Act, specific blending quotas for renewable fuels that lead to similar exemptions in the mineral oil tax, could further increase the market demand for biogenic fuels as of 2025. Similarly, suppliers of aviation fuels will be obliged to blend renewable synthetic aviation fuels for airplanes refueled in Switzerland (EU plans a blending quota of 2% from 2025, rising to 63% in 2050). With this, a pull factor to incentivize market demand for biogenic fuels or SAFs and therefore CO_2 can potentially be established, where the CO_2 used as a feedstock can also originate from an industrial source. In parallel, the federal government will support innovative companies that implement pilot plants to produce renewable synthetic aviation fuels with CHF 25-30 million per year [68]. Whether a specific CCU project qualifies for the abovementioned policy instruments needs to be discussed with the Federal Offices on a case-by-case basis [12].

5.3 Financing mechanisms

Another way for emitters to kickstart the implementation of CCTS and CCUS and temporarily bridge the currently existing financial gap in their potential business models, is to exploit funding instruments available in Switzerland. Currently, several funding mechanisms exist on the Swiss national level that provide avenues for CCTS or CCUS projects to receive funding, such as the Climate and Innovation Act, SWEET, and Stiftung Klimarappen. These funding sources have different mechanisms, but all provide a different focus on the development of novel technologies including CCTS and CCUS. Notably, emitters that are part of the ETS or receive funding from other sources are not eligible for these funding mechanisms.

5.3.1 Climate and Innovation Act

The Climate and Innovation Act mainly sets the framework for Switzerland's climate policy and serves as a working basis for the future preparation of ordinances that will specify the law. Further measures for achieving the climate targets will need to be anchored step by step in separate laws, such as the revised CO_2 Act. Through the Climate and Innovation Act, the federal government will support companies financially on the path to climate neutrality and reserves CHF 200 million annually until 2030 for the implementation of novel, climate-friendly technologies, and processes. This includes CCTS, CCUS, and CDR, but also other technologies such as heat pumps. In principle, the subsidy is open to all companies, primarily aiming at so-called "early-movers". Emitters that already receive federal funding elsewhere or are integrated into an instrument for reducing GHG emissions, such as the Swiss ETS, are not eligible for funding. As for durable storage, the Climate and Innovation Act explicitly mentions underground storage and demolished concrete and therefore includes both CCTS and CCUS. Further, it is mentioned that the federal government can also hedge the risks of investments in public infrastructure. This can include, for example, CO_2 pipelines and CO_2 storage facilities [1]. Notably, the ability to receive funding under the Climate and Innovation Act is tied to the submission of a net-zero roadmap for the respective emitter [69].

5.3.2 Swiss Energy research for the Energy Transition (SWEET)

SWEET is a funding program initiated by the SFOE with the primary objective to accelerate innovations that are critical for the implementation of Switzerland's long-term climate strategy. The program runs until 2032, with different calls for proposals addressing different pre-defined topics, which are then addressed by interdisciplinary consortia, that collaborate over a period of approximately 6-8 years [70]. Together with the FOEN, a call focused on hard-to-decarbonize emissions and industries in the context of the country's net-zero goal by 2050 will be launched in January 2024. In this context, the call explicitly refers to cement and waste-to-energy as hard-to-decarbonize industries and positions CCTS, CCUS, and CDR as possible solutions. Building on previous projects, such as DemoUpCARMA, a certain focus will be laid on CCTS, CCUS, and CDR value chains that demonstrate the whole process of CO_2 capture, transport, and durable storage in Switzerland, either in geological formations or durable products such as building materials [71].

5.3.3 Climate Cent Foundation

The Climate Cent Foundation ("Stiftung Klimarappen") used to be a voluntary measure by Swiss fuel importers between 2005 and 2012 that levied a surcharge of CHF 0.01-0.015 per litre of fuel under the CO_2 Act in force at the time. The foundation used the income to finance climate protection projects to reduce GHG emissions in Switzerland and abroad. After the activities were completed, the foundation had remaining assets. In May 2022, the federal government and the foundation renewed their agreement on the use of the remaining funds of around CHF 50 million [72]. The projects that will be funded have already been selected – nevertheless, this policy instrument is listed here as an example of the funding opportunities that can be created by the federal government. In August 2023, the foundation communicated five projects that will be supported with the CHF 50 million until 2030. Three CCUS projects with total expected durable storage of 49,500 tons of CO_2 in building materials until 2030 and two CCTS projects with total expected durable storage of 34,800 tons of CO_2 in geological formation abroad until 2030 [73].

6 Conclusion and outlook

The topic of business models for CCTS and CCUS for Switzerland is rather new and unexplored in both academia and practice – especially regarding the unique challenge Swiss emitters face for the implementation of CCTS value chains with long transport routes and storage abroad. The current regulatory landscape in Switzerland, the foreseen pathways for decarbonization, as well as the opportunities and limitations for certain setups for the management and organization of such value chains constitute building blocks that shape the options for business model development. This report provides an extensive overview of these building blocks, showcasing the different options and considerations emitters have when developing their business models.

As for the four building blocks of the report, the following conclusions emerge and can serve as a starting point for further in-depth analysis:

First, the regulatory framework significantly impacts the viability of CCTS and CCUS business models. The inclusion or exclusion of specific industries or origins of CO_2 in the Swiss ETS, the adoption of the revised CO_2 Act, as well as price and demand dynamics on the VCM make it very difficult for emitters to assess the stability and durability of future revenue streams.

Second, the value chain structures for CCTS and CCUS exhibit fundamental differences, especially in terms of activities, costs, and associated costs. Since CCTS requires cross-border transport, CCUS is the pathway with significantly lower costs and complexity. Due to this, an individual emitter is likely to opt for CCUS. However, if the national perspective is taken and the available short- and long-term storage potentials of both pathways are considered, it becomes evident that only a few, rather small emitters will be able to pursue CCUS.

Third, the management and organization of the capture, transport, and storage activities vary with integrated, shared, and outsourced options presenting different cost-risk profiles. Capture activities are closely tied to industrial processes, making complete outsourcing unlikely, while transport and storage are more amenable to outsourcing since they involve substantially different activities, require know-how of multiple industries and processes, and face high risks and investment costs. In general, two setups for the management and organization of full value chains can be foreseen: (i) an integrated capture setup, in which the emitter owns and operates a capture facility and completely outsources the transport and storage activities to one or several third parties; and (ii) a capture cluster, in which several emitters jointly own and operate one CO_2 capture facility and completely outsource transport and storage activities to one or several third parties. The specific setup for value chain management depends on the chosen CCTS or CCUS pathway and the potential for other emitters to collaborate in capture clusters. Further, the choice of setup is influenced by project-specific factors, such as cost reduction and risk mitigation, rather than industry affiliation.

Fourth, considering the current costs of CCTS and CCUS value chains and the uncertainties regarding the stability and longevity of revenues, as of today, there is no fundamentally viable business model for the implementation of CCTS or CCUS. In other words: In most cases and for most emitters, there is no business case yet to pursue this activity. Therefore, it is all the more important to identify supporting revenue or financing streams to establish economic viability and accelerate deployment. These can be either detached from the actual CCTS or CCUS business activity – for example, by increasing customer charges for prices of the emitter’s products or services generated within their core business – or by leveraging additional policy instruments that support the financing of early movers – for example, under the Climate and Innovation Act.

Abbreviations

CCTS	Carbon capture, transport, and storage
CCUS	Carbon capture, utilization, and storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
DETEC	Federal Department of the Environment, Transport, Energy and Communications
ETS	Emissions trading system
ERZ	Entsorgung + Recycling Zürich
FOEN	Federal Office for the Environment
GHG	Greenhouse gas
VBSA	Swiss Association of Waste Treatment Plant Operators
VCM	Voluntary carbon market
SWEET	Swiss Energy research for the Energy Transition
VCS	Verified Carbon Standard
FOT	Federal Office for Transport
CCU	Carbon capture and utilization
SAF	Sustainable aviation fuels

References

[1] *Klima- und Innovationsgesetz: Abstimmung am 18. Juni 2023*. Bundesamt für Umwelt. Retrieved 8 October 2023 from https://www.bafu.admin.ch/bafu/de/home/themen/thema-klima/klima--dossiers/klimaschutzgesetz.html

[2] *CO2-Abscheidung und Speicherung (CCS) und Negativemissionstechnologien (NET)*. (2022). Der Bundesrat. https://www.newsd.admin.ch/newsd/message/attachments/71551.pdf

[3] SwissPRTR. https://www.prtr.admin.ch/publicwebSite/Abfrage.aspx

[4] *Langfristige Klimastrategie der Schweiz*. (2021). Der Bundesrat. https://www.bafu.admin.ch/bafu/de/home/themen/klima/fachinformationen/emissionsverminderung/verminderungsziele/ziel-2050/klimastrategie-2050.html

[5] Osterwalder, A., Pigneur, Y. (2010). *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*.

[6] Boons, F., & Lüdeke-Freund, F. (2013). *Business models for sustainable innovation: state-of-the-art and steps towards a research agenda*. https://www.sciencedirect.com/science/article/pii/S0959652612003459

[7] Bundesgesetz über die Reduktion der CO2-Emissionen, (2022). https://www.fedlex.admin.ch/eli/cc/2012/855/en

[8] *Emissionshandelssystem (EHS)*. Bundesamt für Umwelt. Retrieved 8 October 2023 from https://www.bafu.admin.ch/bafu/en/home/themen/thema-klima/klimawandel-stoppen-und-folgen-meistern/schweizer-klimapolitik/emissionshandel.html

[9] *EU Carbon Permits*. Trading Economics. Retrieved 8 October 2023 from https://tradingeconomics.com/commodity/carbon

[10] Pietzcker, R. C., Osorio, S., Rodrigues, R. (2021). Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector. *Applied Energy*, *293*. https://doi.org/10.1016/j.apenergy.2021.116914

[11] Botschaft zur Revision des CO2-Gesetzes für die Zeit nach 2024, (2022). https://www.fedlex.admin.ch/eli/fga/2022/2651/de

[12] Wenger, S. (2023). DemoUpCARMA Online Workshop "Policy Options ETS". In.

[13] Verordnung über die Reduktion der CO2-Emissionen, (2023). https://www.fedlex.admin.ch/eli/cc/2012/856/en

[14] Vereinbarung zwischen der Schweizerischen Eidgenossenschaft vertreten durch das Eidg. Departement für Umwelt, Verkehr, Energie und Kommunikation (UVEK) und den in Anhang 1 aufgeführten thermischen Kehrichtverwertungsanlagen vertreten durch den Verband der Betreiber Schweizerischer Abfallverwertungsanlagen (VBSA), (2022). https://www.newsd.admin.ch/newsd/message/attachments/70634.pdf

[15] *Massnahmen der Schweiz zur Verminderung ihrer Treibhausgasemissionen*. Bundesamt für Umwelt. Retrieved 8 October 2023 from https://www.bafu.admin.ch/bafu/de/home/themen/klima/fachinformationen/verminderungsmassnahmen.html

[16] *17. Newsletter CO2-Kompensation in der Schweiz, 1. Juni 2022*. (1 June 2022). https://www.bafu.admin.ch/bafu/de/home/themen/thema-klima/klima--newsletter/newsletter--kompensation-von-co2-emissionen-/17-newsletter-co2-kompensation-in-der-schweiz-01-06-2022.html

[17] *CO2-Kompensation*. (2022). Bundesamt für Umwelt. Retrieved 8 October 2023 from https://www.bafu.admin.ch/bafu/de/home/themen/klima/fachinformationen/verminderungsmassnahmen/kompensation.html

[18] What are carbon markets and why are they important? Retrieved 8 October, 2023, from https://climatepromise.undp.org/news-and-stories/what-are-carbon-markets-and-why-are-they-important

[19] *The Voluntary Carbon Market | 2022–2023*. (2023). South Pole. https://go.southpole.com/vcm-report-2023?_gl=1*ivq1l3*_ga*MzI1OTI0MDQ3LjE2ODkwNjI5NTg.*_ga_CJML96C07Q*MTY4OTA2Mjk1Ny4xLjEuMTY4OTA2Mjk4Ni4zMS4wLjA

[20] *Program Overview*. Verra. Retrieved October 8 2023 from https://verra.org/programs/verified-carbon-standard/

[21] Spilker, G., Nugent, N. (2022). Voluntary carbon market derivatives: Growth, innovation & usage. *Borsa Istanbul Review*, *22*, 109-118. https://doi.org/10.1016/j.bir.2022.11.008
[22] Favasuli, S., Sebastian, V. (2021). Voluntary carbon markets: how they work, how they're priced and who's involved Retrieved 8 October, 2023, from https://www.spglobal.com/commodityinsights/en/market-insights/blogs/energy-transition/061021-voluntary-carbon-markets-pricing-participants-trading-corsia-credits
[23] Smith, S. M., Geden, O., Nemet, G., Gidden, M., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., Repke, T., Riahi, K., Schenuit, F., Steinhauser, J., Strefler, J., Valenzuela, J. M., and Minx, J. C. (2023). *The State of Carbon Dioxide Removal - 1st Edition*. https://static1.squarespace.com/static/633458017a1ae214f3772c76/t/63e3d4602156db24bc18c91c/1675875445298/SoCDR-1st-edition.pdf
[24] Gabrielli, P., Campos, J., Becattini, V., Mazzotti, M., Sansavin, G. (2022). *Optimization and assessment of carbon capture, transport and storage supply chains for industrial sectors: The cost of resilience*. https://www.sciencedirect.com/science/article/pii/S1750583622002158
[25] *Energieperspektiven 2050+*. (2021). Bundesamt für Energie. https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.html
[26] *German Carbon Transport Grid*. (2023). OGE.
[27] Oeuvray, P., Becattini, V., Mazzotti, M. (2022). *Carbon Capture, Transport and Storage (CCTS) supply chain assessment for early movers* 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, Lyon, France. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4285232
[28] *We remove CO_2 from the atmosphere – and store it permanently*. Neustark. Retrieved 7 October 2023 from https://www.neustark.com/
[29] Tiefenthaler, J., Braune, L.. Bauer, C., Sacchi, R., Mazzotti, M. (2021). Technological Demonstration and Life Cycle Assessment of a Negative Emission Value Chain in the Swiss Concrete Sector. *Frontiers in Climate*, *3*. https://doi.org/10.3389/fclim.2021.729259
[30] Rosa, L., Becattini, V., Gabrielli, P., Andreotti, A., Mazzotti, M. (2022). Carbon dioxide mineralization in recycled concrete aggregates can contribute immediately to carbon-neutrality. *Resources, Conservation and Recycling*, *184*. https://doi.org/10.1016/j.resconrec.2022.106436
[31] Habert, G., Miller, S. A., John, V. M. Provis, J. l:, Favier, A., Horvath, A., Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*. https://doi.org/10.1038/s43017-020-0093-3
[32] J., T. (2021). *Concrete – the carbon sink for a climate neutral Switzerland?* https://ethz.ch/content/dam/ethz/special-interest/mavt/process-engineering/separation-processes-laboratory-dam/documents/education/CCSnotes/2021/Week7/Concrete%20%E2%80%93%20the%20carbon%20sink%20for%20a%20climate.pdf
[33] *CO2 aus der Luft entfernen*. (2022). Bundesamt für Umwelt. https://www.bafu.admin.ch/bafu/de/home/themen/klima/dossiers/magazin-2022-2-dossier.html
[34] Muslemani H., L. X., Kaesehage K., Wilson J. (2020). Business Models for Carbon Capture, Utilization and Storage Technologies in the Steel Sector: A Qualitative Multi-Method Study *Special Issue "Carbon Capture, Utilization and Storage Technology"*, *8*. https://doi.org/10.3390/pr8050576
[35] *Unlocking Private Finance to Support CCS Investments*. (2021). Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2022/01/Unlocking-Private-Finance-For-CCS-Thought-Leadership-Report-1-1.pdf
[36] *Understanding Industrial CCS Hubs and Clusters*. (2016). Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2019/08/Understanding-Industrial-CCS-hubs-and-clusters.pdf
[37] *The Global Status of CCS: 2013*. (2013). Global CCS Institute. https://www.globalccsinstitute.com/archive/hub/publications/115198/Global-Status-CCS-2013.pdf
[38] *Applying the Midstream Model to Carbon Capture Projects*. Shearman & Sterling. Retrieved 8 October 2023 from https://www.shearman.com/en/perspectives/2022/01/applying-the-midstream-model-to-carbon-capture-projects

[39] *How new business models are boosting momentum on CCUS*. (2023). IEA. Retrieved 8 October 2023 from https://www.iea.org/commentaries/how-new-business-models-are-boosting-momentum-on-ccus
[40] *Carbon Capture, Utilization and Storage (CCUS): Barriers, Enabling Frameworks and Prospects for Climate Change Mitigation*. (2022). The Oxford Institute for Energy Studies. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/01/OEF-130.pdf
[41] *We support biogenic emitters in setting up carbon removal projects*. Airfix. Retrieved 7 October 2023 from https://www.airfixcarbon.com/solutions/solutions-for-biogenic-co2-emitters/
[42] *CO2-Rückgewinnung aus der Klärschlammverwertungsanlage* (26 May 2023). https://www.stadt-zuerich.ch/ted/de/index/departement/medien/medienmitteilungen/2023/mai/230526a.html
[43] Pan, S.-Y., Du, M. A., Huang, I.-T., Liu, I.-H., Chang, E.-E., Chiang, P.-C. (2015). Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. *108*, 409-421. https://doi.org/10.1016/j.jclepro.2015.06.124
[44] *Abfallverwertung*. (8 October 2023). VBSA. https://vbsa.ch/fakten/abfallverwertung/
[45] *Strompreise*. Eidgenössische Elektrizitätskommission ElCom. Retrieved 8 October 2023 from https://www.elcom.admin.ch/elcom/de/home/themen/strompreise.html
[46] *Feasibility of a demonstrator for the carbon capture and storage value chain in CH with a waste-to-energy plant*. (2021). Sustainability in Business Lab (sus.lab). https://www.suslab.ch/_files/ugd/87acd3_a81f2328a7ed4beaa453c552b82f9273.pdf
[47] *Was ist der VASA Altlasten-Fonds?* Bundesamt für Umwelt. Retrieved 8 October 2023 from https://www.bafu.admin.ch/bafu/de/home/themen/altlasten/fachinformationen/altlastenfinanzierung/was-ist-der-vasa-altlasten-fonds-.html
[48] *Abgabeerhebung VASA* Bundesamt für Umwelt. Retrieved 8 October 2023 from https://www.bafu.admin.ch/bafu/de/home/themen/altlasten/fachinformationen/altlastenfinanzierung/abgabeerhebung-vasa.html
[49] Quartier, R. (2022, 22 April, 2022). [Interview].
[50] Verordnung über die Rückgabe, die Rücknahme und die Entsorgung elektrischer und elektronischer Geräte, (2023). https://www.fedlex.admin.ch/eli/cc/2021/633/de
[51] Bischof, S., Marks, D., Reymond, A. (2023). *What we need to unlock biomass carbon removal and storage in Switzerland*.
[52] Obrist, M. D., Kannan, R., Schmidt, T. J., Kober, T. (2021). Decarbonization pathways of the Swiss cement industry towards net zero emissions. *Journal of Cleaner Production*, *288*. https://doi.org/10.1016/j.jclepro.2020.125413
[53] *Members*. Cemsuisse. Retrieved 8 October 2023 from https://www.cemsuisse.ch/en/members/
[54] Subraveti, S. G., Rodríguez Angel, E., Ramírez, A., Roussanaly, S. (2023). Is Carbon Capture and Storage (CCS) Really So Expensive? An Analysis of Cascading Costs and CO2 Emissions Reduction of Industrial CCS Implementation on the Construction of a Bridge. *Environmental Science & Technology*, *57*, 2595–2601. https://doi.org/10.1021/acs.est.2c05724
[55] Rootzén, J., Johnsson, F. (2016). Managing the costs of CO2 abatement in the cement industry. *Climate Policy*, *17*(6), 781-800. https://doi.org/10.1080/14693062.2016.1191007
[56] Miller, S. A., Habert, G., Myers, R. J., Harvey, J. T. (2021). Achieving net zero greenhouse gas emissions in the cement industry via value chain mitigation strategies. *One Earth*, *4*(10), 1398-1411. https://doi.org/10.3929/ethz-b-000511497
[57] *Firmen & Produkte*. scienceindustries. Retrieved 8 October 2023 from https://www.scienceindustries.ch/portrait/firmen-produkte/gesamtuebersicht
[58] *Regulierung*. Schweizer Medizintechnikverband. Retrieved 8 October 2023 from https://www.swiss-medtech.ch/regulierung
[59] *Gesetzgebung Arzneimittel und Medizinprodukte*. Bundesamt für Gesundheit. Retrieved 8 October 2023 from https://www.bag.admin.ch/bag/de/home/gesetze-und-bewilligungen/gesetzgebung/gesetzgebung-mensch-gesundheit/gesetzgebung-arzneimittel-medizinprodukte.html
[60] Conti, C., Künzler, O., Müller, M., Mayoraz, J.-F., Feitzinger, D., Herzfeld, A. (2020). *The Pharma Legal Handbook*. WengerPlattner. https://www.wenger-plattner.ch/media/filer_public/35/01/350171ab-140c-463a-a881-c73b9313dc47/plh_switzerland_final_new_design.pdf

[61] *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (2023). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.001
[62] Guarato, P. (2021). *Carbon Capture, Utilization and Storage in Switzerland. Volume 1 – The Technological and Scientific Framework*. https://serval.unil.ch/resource/serval:BIB_6D805A77E421.P001/REF.pdf
[63] Gabrielli, P., Gazzani, M., Mazzotti, M. (2020). The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO2 Emissions Chemical Industry. *Industrial & Engineering Chemistry*. https://doi.org/10.1021/acs.iecr.9b06579
[64] Akeret, O., Krüger, M., Mark, J., Probst, B., Thorsdottir, G., von Roten, A. (2023). *Surviving in a Nascent Market - Unveiling Key Challenges and Strategies for European Carbon Removal Startups*. https://cdr.remove.global/cdr-report-eth-sus.lab-x-remove
[65] *Putting CO2 to Use*. (2019). IEA. https://iea.blob.core.windows.net/assets/50652405-26db-4c41-82dc-c23657893059/Putting_CO2_to_Use.pdf
[66] *Mineralölsteuer*. Bundesamt für Zoll und Grenzsicherheit. Retrieved 8 October 2023 from
[67] *Biogene Treibstoffe*. Bundesamt für Umwelt. Retrieved 8 October 2023 from https://www.bafu.admin.ch/bafu/de/home/themen/thema-wirtschaft-und-konsum/fachinformationen-wirtschaft-und-konsum/biogene-treibstoffe.html
[68] *Klimaschutz in der Luftfahrt: BAZL zeigt in Bericht Bedeutung nachhaltiger Treibstoffe auf*. (15 December 2022). https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-92234.html
[69] Bundesgesetz über die Ziele im Klimaschutz, die Innovation und die Stärkung der Energiesicherheit, (2022). https://www.fedlex.admin.ch/eli/fga/2022/2403/de
[70] *SWEET overview*. Bundesamt für Energie. Retrieved 8 October 2023 from https://www.bfe.admin.ch/bfe/en/home/research-and-cleantech/funding-program-sweet/sweet-overview.html
[71] Energie, B. f. (2021). Upcoming calls for proposals of the SWEET funding programme. https://www.nlt.admin.ch/f/view.aspx?1EE9774CB52EC8585B864E1988DB864EB9A8DCB52EC998AC16994B6593
[72] *Klimaschutz: Bund erneuert Zusammenarbeit mit der Stiftung Klimarappen*. (16 May 2022). https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-88808.html
[73] *Stiftung Klimarappen fördert fünf Schweizer Projekte im Bereich Negativemissionstechnologien mit 50 Millionen Franken*. (24 August 2023). https://www.klimarappen.ch/resources/Medienmitteilung_NET-Projekte_230824.pdf

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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Appendix III to WP4 report – 30 November 2023

Appendix III - Engineering documents

Optimal design and assessment of post-combustion CO_2 capture integration with Jura Cement (public version)

DESIGN BASIS

JURA CEMENT PLANT

CONFIDENTIAL

Form TDT01-rev02

00	17.10.23	First Issue	MCC	FB	FB
REV.	**DATE**	**DESCRIPTION**	**PREPARED**	**CHECKED**	**APPROVED**

REVISION INDEX SHEET

REV. / PAGE	00	01	02	03	04	05	REV. / PAGE	00	01	02	03	04	05	REV. / PAGE	00	01	02	03	04	05
1	X																			
2	X																			
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5	X																			
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9	X																			
10	X																			
11	X																			

CONTENTS

1 INTRODUCTION

This document contains the design basis for the new CO2 capture plant to be installed

1.1 Capacity

Maximum recovery of CO2 from given flue gas

1.2 Flexibility

The flexibility target for each plant is 70% - 105% referred to “Compound Operation”

1.3 Availability

Plant Availability is not less than 95% on 11 months (1 yearly general revision of 30 days)

2 CASALE BATTERY LIMITS

Battery limits of Casale are from existing flue gas stack up to delivery of sequestrated CO2 as compressed gas (option 1) or liquefied stream (option 2).

Utilities distribution inside CO2 capture plant is in Casale scope, while utilities production is out Casale scope. Optimal heat/utilities integration of the new CO2 capture plant with the existing plant will be agreed among all parties.

3 FLUE GAS AT PLANT BL

	Unit	Average 1 Compound operation (80% of the time)	Average 2 Direct operation	Range
Flue Gas Flow Rate at Stack Inlet	Nm3/h	241340	210'000	
Flue Gas Temperature at Stack Inlet	°C	200	200	after RTO
Flue Gas Pressure at Stack Inlet	bar a	0.98	0.98	
Flue Gas Composition (mol% or ppmv)				
H2O	%wet	11.2	14	Up to 19
N2 + Ar	%wet	64.2	60	
O2	%wet	7	7	1-10 Will be reduced by RTO
CO2	%wet	15.5	21.25	
SO2	mg/Nm3 dry @ 10% O2	86	350	5-450
SO3		5-40	5-40	
Nox	mg/Nm3 dry @ 10% O2			300-600 < 200 after RTO
NO2		0 while in operation	0 while in operation	
PM (mg/Nm3)	mg/Nm3 dry @ 10% O2	3.8	3.8	
CO	mg/Nm3 wet	15	15	

- Short term variability (20-30 s peaks) of combustion related parameters is at the moment relatively high as the plant is operated with only 10% traditional fuels. Frequency of the peaks is variable depending by handling characteristics of alternative fuels.

4 CO2 PRODUCT

4.1 Option 1 (compressed CO2)

	Unit	
CO2 Product Pressure	bar g	35
CO2 Product Temperature	°C	< 45
CO2 Purity	% wt	> 99.8
H2O	ppm wt	< 50
O2	ppm wt	< 100

4.2 Option 2 (liquefied CO2)

	Unit	
CO2 Product Pressure	bar g	22
CO2 Product Temperature	°C	-37
CO2 Purity	% wt	> 99.966
H2O	ppm wt	< 30
O2	ppm wt	< 10

5 UTILITIES SPECIFICATION AT PLANT BL

5.1 COOLING WATER

At the moment water availability is scarce.

	Unit	
Supply Temperature	°C	15
Supply Pressure	barg	6
Return Temperature (max allowable)	°C	-
Return Pressure (min allowed)	barg	Atmospheric
Flow Rate (maximum available)	m3/h	20
Cooling Water Quality (Chlorides)	ppm	-

5.2 DEMIN WATER

None

5.3 STEAM

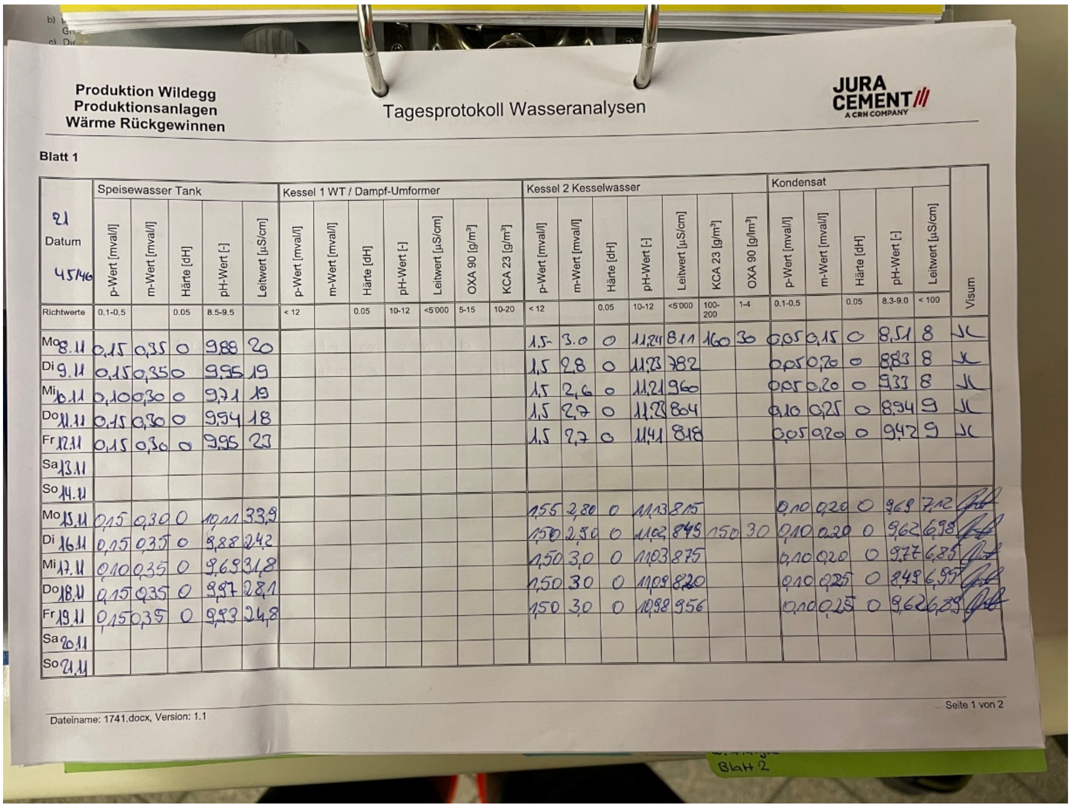
Steam 1 (produced with NG as backup for district heating)

	Unit	
Steam Supply Temperature	°C	175
Steam Supply Pressure	barg	9.4
Steam Condensate Return Temperature	°C	80-100
Flow Rate (maximum available)	ton/h	6
Unit cost	CHF/ton	-

5.4 HOT WATER

Hot water is presently used for district heating

	Unit	
Supply Temperature	°C	130
Supply Pressure	barg	Up to 12
Return Temperature	°C	70 (present return from district heating)
Return Pressure (min allowed)	barg	4
Flow Rate (maximum available)	m3/h	52 (present flowrate for district heating but extra heat is available)
Water Quality		See attached files here below



Produktion Wildegg
Produktionsanlagen
Wärme Rückgewinnen

Tagesprotokoll Wasseranalysen

JURA CEMENT A CRH COMPANY

Blatt 1

21 Datum 45/46	Speisewasser Tank p-Wert [mval/l]	Speisewasser Tank m-Wert [mval/l]	Speisewasser Tank Härte [dH]	Speisewasser Tank pH-Wert [-]	Speisewasser Tank Leitwert [µS/cm]	Kessel 1 WT / Dampf-Umformer p-Wert [mval/l]	Kessel 1 m-Wert [mval/l]	Kessel 1 Härte [dH]	Kessel 1 pH-Wert [-]	Kessel 1 Leitwert [µS/cm]	Kessel 1 OXA 90 [g/m³]	Kessel 1 KCA 23 [g/m³]	Kessel 2 Kesselwasser p-Wert [mval/l]	Kessel 2 m-Wert [mval/l]	Kessel 2 Härte [dH]	Kessel 2 pH-Wert [-]	Kessel 2 Leitwert [µS/cm]	Kessel 2 KCA 23 [g/m³]	Kessel 2 OXA 90 [g/m³]	Kondensat p-Wert [mval/l]	Kondensat m-Wert [mval/l]	Kondensat Härte [dH]	Kondensat pH-Wert [-]	Kondensat Leitwert [µS/cm]	Visum
Richtwerte	0.1-0.5		0.05	8.5-9.5		< 12		0.05	10-12	<5'000	5-15	10-20	< 12		0.05	10-12	<5'000	100-200	1-4	0.1-0.5		0.05	8.3-9.0	< 100	
Mo 8.11	0,15	0,35	0	9,88	20								1,5	3.0	0	11,24	811	160	30	0,05	0,15	0	8,51	8	JL
Di 9.11	0,15	0,35	0	9,95	19								1,5	2,8	0	11,23	782			0,05	0,20	0	8,83	8	JL
Mi 10.11	0,10	0,30	0	9,71	19								1,5	2,6	0	11,21	960			0,05	0,20	0	9,33	8	JL
Do 11.11	0,15	0,30	0	9,94	18								1,5	2,7	0	11,23	804			0,10	0,25	0	8,94	9	JL
Fr 12.11	0,15	0,30	0	9,95	23								1,5	2,7	0	11,41	818			0,05	0,20	0	9,42	9	JL
Sa 13.11																									
So 14.11																									
Mo 15.11	0,15	0,30	0	10,11	33,9								1,55	2,80	0	11,13	815			0,10	0,20	0	9,69	7,12	[illegible]
Di 16.11	0,15	0,35	0	9,88	24,2								1,50	2,50	0	11,02	849	150	30	0,10	0,20	0	9,62	6,98	[illegible]
Mi 17.11	0,10	0,35	0	9,69	31,8								1,50	3,0	0	11,03	875			0,10	0,20	0	9,77	6,85	[illegible]
Do 18.11	0,15	0,35	0	9,97	28,1								1,50	3,0	0	11,09	820			0,10	0,25	0	8,49	6,95	[illegible]
Fr 19.11	0,15	0,35	0	9,93	24,8								1,50	3,0	0	10,98	956			0,10	0,25	0	9,62	6,89	[illegible]
Sa 20.11																									
So 21.11																									

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Seite 1 von 2

5.5 ELECTRICITY

Electric power supply at BL is 16000 V, 3 ph, 4 wires, 50 Hz.

Spare electric power supply is 10 MW
Electricity cost: 0.06CHF/kWh

Electrical supply		16 kV AC, 3 ph., 50 Hz
Electrical Distribution		8 kV AC, 3 ph., 50 Hz
	Motors > 500 kW	8 kV AC, 3 ph., 50 Hz
Process Power Network	Motors > 500 kW (variable speed)	6.9 kV AC, 3 ph., 0…50 Hz
	Motors < 500 kW	500 V AC, 3 ph., 50 Hz, TN-S
Infrastructure Power Network		400 V AC, 3 ph., 50 Hz, old → TN-C / new → TN-S
	Small Consumers (Lighting etc.)	230 V AC, 3 ph., 50 Hz, TN-S
	Instruments / Sensors	48 V DC (Minus grounded)

6 SITE CONDITIONS

Plant site is located in Möriken-Wildegg, AG (Switzerland)
The climatic conditions of the site are the following:

Meteorological Data

Barometric Pressure	Min. / Max.	940 / 1000 hPa
Temperatures	Min. / Max.	-14 / +40 °C
Humidity (relative)	Min. / Max.	47 / 98 %
	Average	70 %
Rainfall	Day / Year	38 / 980 mm
Snowfall	Max.	400 mm
Seismic Data	Danger Zone 1 (SIA 261)	a_{gd} = 0.6 m/s^2

6.1 Temperature

- Min. design temperature for outdoor equipment	-14	°C
- Process design temperature (dry bulb) (air coolers design)	20	°C

6.2 Barometric Pressure

- Process design pressure	735	mmHg

6.3 Relative Humidity

- Design relative humidity and temperature (for air coolers)	70% R.H. @ 20°C

7 UNIT OF MEASURES

Dimension	Symbol
Acceleration	m/s^2
Area	m^2, mm^2
Composition or Concentration	wt%, ppm_{wt}, vol%, ppm_{vol}
Conductivity	µS/cm
Density	kg/m^3
Electricity – Current intensity	A, Ma
Electricity – Energy	kWh
Electricity – Power	MW, kW, W
Electricity – Voltage	kV, V
Electricity – Frequency	Hz
Electricity – Resistance	Ohm
Enthalpy	kcal/kg
Flow – mass	t/h, kg/h
Flow – liquid (volumetric)	m^3/h
Flow – gas/vapor (volumetric)	m^3/h, Nm^3/h (1)
Flow – molar	kmol/h, Nm^3/h (1)
Force	Kgf
Heat	Kcal
Heat Duty	Gcal/h, kcal/h
Heat transfer coefficient	kcal/(h m2 °C)
Heating value	kcal/kg
HHV (@15°C, 101.3 kPa)	kcal/Sm3
LHV (@15°C, 101.3 kPa)	kcal/Sm3
Length, linear	m, mm
Level	%, m, mm
Mass	t, kg
Mass transfer	kg/(h m2)
Molecular Weight	kg/kmol
pH	pH
Pipe (nozzle size)	In
Power	MW, kW, W
Pressure – Absolute	mm H2O a, bar a
Pressure – Gauge	mm H2O g, bar g
Pressure – Difference	mm H2O, bar
Radiation	kcal/(m^2/h)
Sound, Noise	dB (A)
Speed – Linear	m/s, km/h
Speed – Rotating (or Rotation)	Rpm
Specific Heat	kcal/(kg °C)
Surface Tension	dyn/cm
Temperature	°C, °K
Temperature Difference	°C, °K
Thermal conductivity	kcal/(h m °C)
Time	y, h, min, s
Torque	Kgf.m
Viscosity – Dynamic	cP
Viscosity – Kinematic	cSt
Volume – liquid	m3
Volume – gas/vapor	m3, Nm3 (1)

(1) Normal conditions: 0°C & 1.01325 bar abs
(2) Standard: 15°C & 1.01325 bar abs

8 CODES AND STANDARDS

Pressure Vessels	ASME Section VIII, div. 1 or div. 2
	AD 2000 (AD Merkblatter)
Heat Exchangers	ASME Section VIII, div. 1 or div. 2
	TEMA CLASS "R"
Material Specification	ASME Section II A, B, C;
Rotating Equipment	API 610, API 611, API 612
	API 617, API 674, API 675
	API 682, API 685, API 673
	ASME B 73.1, ASME B 73.3
	ISO 2858, ISO 5199,
	Vendor Standards
Piping	ASME B31.3
Flanges, Valves and Fittings	relevant ANSI-ASME standards
Instrumentation	ANSI
	ISO
	API
	IEC
	ISA
Electrical Installations	relevant IEC standard
Safety and Fire	API 2001.
Hazardeous Area	API-RP 505
	Applicable IEC standard
	Recommended Practice for Explosion-protected Electrical installations in General Industries

PROCESS DESCRIPTION FOR INTEGRATION WITH EXISTING PLANT

JURA CEMENT PLANT

Form TDT01-rev02

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3	X																			
4	X																			

CONTENTS

1 HEAT INTEGRATION

There is no need of heat integration for solvent regeneration, it is provided by internal recuperation of energy within the system: a combination of flue gas heat, compressed flash steam and compressed lean flash steam. (Reference process description in A14380S-E-PRZ-1003-00)

The plant is optimized for lowest electricity consumption, but if required by Customer, it can be optimized for maximum supplied valuable heat.

2 EXCESS AND MAKE UP DEMI WATER

The hot flue gas is cooled in the flue gas quencher C-1003 (quenching column) by direct contact with circulation treated water supplied from top of flue gas quencher. Therefore, a stream of excess water is extracted and shall be recovered in a water treatment system.

The treated flue gas stream and the CO2 extracted carry with them an amount of water that shall be reintegrated. A stream of demi make-up water is then necessary and it shall enter in the CO2 cooling recirculation right after the air condenser AE-1002.

CASALE	Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland **DemoUpCARMA - WP4 - Task 3**	**Proj. No.:** A14380 **Doc. No.:** A14380S-E-PRZ-1003 **Rev.:** 01 **Sheet No.:** 1 of 6
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PROCESS DESCRIPTION FOR CARBON DIOXIDE REMOVAL TECHNOLOGY

Jura Cement PLANT

Form TDT01-rev02

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4	X	X																		
5	X																			
6	X	X																		

CONTENTS

1 GENERAL DESCRIPTION AND PROCESS FLOW SCHEME

The CO_2 removal unit is designed to recover about 90% of CO_2 in the flue gas and to be optimized for low electric consumption. The flue gas of the existing cement plant is extracted from the stack and fed to the removal unit by a flue gas compressor, after being quenched.

The unit consists of four main sections.

- Flue gas pre-treatment section
- CO_2 absorption section
- Solvent regeneration section
- CO_2 compression/liquefaction section

Please refer to the Process Flow Diagram sheets (document Nr. A14380S-E-PDG-1001/1002/1003) and relevant Heat & Material balances.

2 FLUE GAS PRETREATMENT SECTION

The temperature of the flue gas from the cement plant is too high to feed the CO_2 absorber. Lower flue gas temperature in fact is preferred to reduce the work required to compress the flue gas (via compressor K-1001) for the correct conditions to be met for CO_2 absorption in the CO_2 absorber (C-1001).

Furthermore, pretreatment is useful to decrease the amount of particulates in flue gas (3.8 mg/Nm_3 dry @ 10% O_2) and SO2 concentration (86-350 mg/Nm3).

1 The hot flue gas, therefore, is cooled in the flue gas quencher C-1003 (quenching column) by direct contact with circulation water supplied from top of flue gas quencher. The quencher is a packed column. The circulation quenching water is pumped by P-1001 pump and cooled in a cooling water air exchanger AE-1001. pH of the circulating water is controlled to abate SO_2.

A compressor K-1001 is installed downstream the flue gas quencher to pressurize the flue gas for optimum capture conditions in the CO_2 absorber, as well as to overcome the pressure drop across flue gas quencher. The compressor is driven by an electric motor and part of the power is recovered with the expander T-1001, which expands the lean flue gas before entering the stack.

1 Before entering the absorber column, the flue gas passes through a heat recovery section, where it is cooled down by lean flue gas in E-1004 and E-1002 exchangers and it provides heat for the regenerator reboiler E-1001 in the E-1003 exchanger producing steam. Condensate is pumped back from the reboiler through P-1002 pump.

3 CO_2 ABSORPTION SECTION

The cooled flue gas from the heat recovery section (E-1004, E-1003 and E-1002) is then introduced into the bottom section of CO_2 absorber C-1001. The flue gas moves upward through the bottom packing, while the lean solvent is supplied from the top of the absorption section into the packing.

The flue gas contacts with the solvent on the surface of the packing, where CO_2 in the flue gas is absorbed by the solvent (rich solvent).

The treated gas from the top of the absorber passes the heat recovery section and the expander cited before and is then routed as treated flue gas stream.

In normal operation, the rich solution leaves the absorber from the bottom and is driven by the pressure difference between the absorber and the rich solution drum.

The rich solution pump P-1003 is required to overcome the hydrostatic pressure to the rich solution drum V-1001 and the pressure drop of the liquid lines before the absorber is at operational pressure, however is not in service during normal operations.

4 SOLVENT REGENERATION SECTION

The regeneration column C-1002 is constituted by three sections.

The upper part is the CO_2 washing and cooling section, where the carbon dioxide is cooled down by mean of a recirculation performed by the pump P-1005 and air heat exchanger AE-1002.

The rich solution is fed from the rich solution drum (V-1001) to the top of the lower section of the regenerator column, where it is contacted by the stripping stream. The rich solvent is steam-stripped in the regenerator, and it is regenerated resulting in lean solvent.

Duty for this regeneration is provided by a combination of three processes within the system:

- Heat absorbed from the flue gas compressor discharge and used to generate low pressure steam that is then transferred to the reboiler providing heat for solvent regeneration (via steam drum V-1005 in a dedicated reboiler exchanger E-1001). Steam is generated by recovering inlet compressed flue gas heat in E-1003 exchanger.
- Hot water is extracted from the recuperation cooler in the middle section of the regenerator, then sent to V-1002A/B condensate drums. Flashed steam is compressed in K-1003 and fed to the lower part of the regenerator bottom section, while the water is pumped by P-1006 pump in the upper part of the middle section.
- The regenerated solution at the stripper bottom shows a low residual loading of CO_2. It is sent to the V-1004 lean solution drum where the stripped steam and CO_2 gas is fed back to the lower part of the regenerator after passing through K-1002 compressor.

The leaner and colder solvent exiting the bottom of V-1004 is then pumped back to the upper stage of the absorber with the pump P-1004, after passing through the filter F-1001.

5 CO_2 COMPRESSION

The CO_2 stream coming from C-1002 is compressed in CO_2 compressor. The machine is expected to be a 4-stage integrally geared centrifugal compressor (to be confirmed by vendor). At about 20 barg, corresponding to 3^{rd} stage outlet pressure, CO_2 will be dehydrated in PU-2001.

PU-2001 unit is based on solid adsorbent: gas is physically rather than chemically adsorbed to the surface of the adsorbent. One vessel is in absorption mode and one in regeneration mode. Regeneration is accomplished recycling back part of the dry CO_2 after heating to about 120-170°C (depending on the type of desiccant).

Alternatively, glycol-based systems could also be considered.

The dehydrated CO_2 is then further compressed up to 36 barg, cooled in the aftercooler AE-2001 and delivered to BL at 35 barg.

Heat from interstage coolers can be recovered for district heating.

6 CO_2 LIQUEFACTION

The CO_2 stream coming from C-1002 is compressed in CO_2 compressor. The machine is expected to be a 3-stage integrally geared centrifugal compressor (to be confirmed by vendor). At about 22 barg, corresponding to 3^{rd} stage outlet pressure, the CO_2 will be dehydrated in PU-3001.

Heat from interstage coolers can be recovered for district heating.

PU-3001 unit is based on solid adsorbent: gas is physically rather than chemically adsorbed to the surface of the adsorbent. One vessel is in absorption mode and one in regeneration mode. Regeneration is accomplished recycling back part of the dry CO2 after heating to about 120-170°C (depending on the type of desiccant).

Alternatively, glycol-based systems could also be considered.

1 The dehydrated CO_2 is then liquefied and subcooled by means of a conventional chiller, using propene (R1270) as working fluid in the refrigeration package PU-3002.

CO_2 is delivered to BL at 22 barg and -37°C.

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BLOCK DIAGRAMS

Jura Cement PLANT

Form TDT01-rev02

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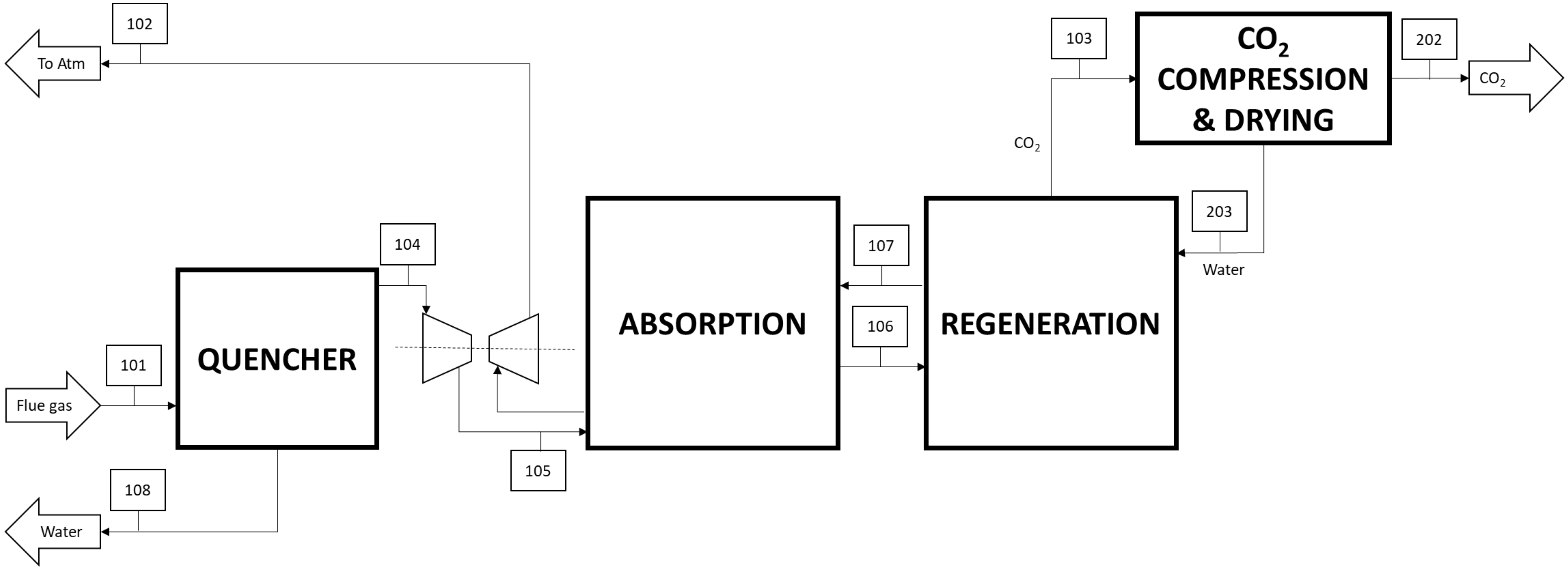
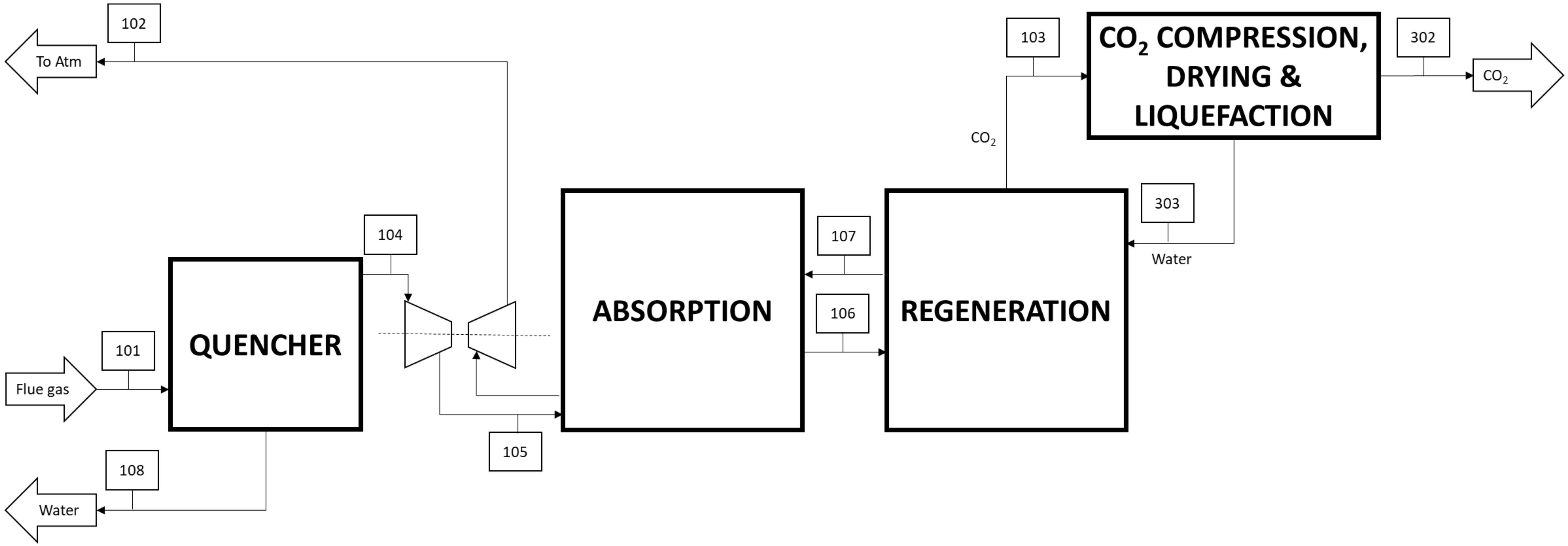
5	X																			

CONTENTS

1 CO_2 COMPRESSION



2 CO_2 LIQUEFACTION



CASALE	**DemoUpCARMA - WP4 - Task 3** Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland	**Proj No.:** A14380 **Doc. No.:** A14380S-E-PZQ-1001 **Rev.:** 01 **Sheet No.:** 1 of 5
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HEAT & MATERIAL BALANCE
JURA CEMENT PLANT - COMPOUND OPERATION

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CASALE

DemoUpCARMA - WP4 - Task 3

Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland

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HEAT & MATERIAL BALANCE - DATA

1	Stream Name		101	102	103	104	105	106	107	108	109	201	202	203	301	302	303
2 3	Description		Flue gas from cement plant	Flue gas to atmosphere	CO2 to compression/liquefaction	Flue gas to compressor	Flue gas to absorber	Rich solution to regenerator	Lean solution to absorber	Excess water from flue gas cooler	Make up water	CO2 to compressor	Compressed CO2	Process Condensate	CO2 to compressor	Liquefied CO2	Process Condensate
4	Vapour Mole Fraction		1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	1.0	0.0	0.0
5	Temperature	°C	200	64	45	47	119	100	97	59	33	45	45	45	45	-37	45
6	Pressure	barg	0.0	0.0	0.1	-0.1	3.4	0.2	8.4	4.0	6.0	0.1	35.0	1.6	0.1	22.0	2.0
7	Mass Flow	t/h	319.3	261.6	69.0	319.2	319.2	3,600.0	3,530.5	0.1	11.0	68.6	66.1	2.5	68.6	66.1	2.5
8	Norm. Volume Flow	Nm3/h	241,189	218,133	36,967	241,202	241,202					36,742	33,642		36,742		
9	Mass Density	kg/m3	0.7	0.9	1.8	1.0	4.0	1276.0	1268.0	981.2	1001.3	1.8	72.6	992.6	1.8	1105.3	992.6
10	Molecular weight		29.7	26.9	41.8	29.7	29.7			18.0	18.0	41.8	44.0	18.0	41.8	44.0	18.0
11																	
12																	
13																	
14																	
15																	
16																	
17	Molar Composition (wet)	%mol															
18		H2O	11.20%	17.19%	8.37%	11.15%	11.15%			100.00%	100.00%	8.37%	0.00%	99.92%	8.37%	0.00%	99.91%
19		N2	66.30%	73.35%	0.00%	66.34%	66.34%			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20		O2	7.00%	7.74%	0.00%	7.00%	7.00%			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
21		CO2	15.50%	1.71%	91.63%	15.51%	15.51%			0.00%	0.00%	91.63%	100.00%	0.08%	91.63%	100.00%	0.09%
22																	
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29																	
30																	
31																	
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35																	
36	See notes on Sheet 5.																

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HEAT & MATERIAL BALANCE - DUTY LIST

		ITEM	DESCRIPTION	DUTY OR POWER		
1						
2						
3	**PFD:**	**E-PDG-0001**				
4		TK-1001	FLUE GAS COMPRESSOR-EXPANDER	*11000*	kW	NET POWER
5		K-1002	LEAN SOLUTION DRUM COMPRESSOR	*5700*	kW	
6		K-1003 A/B	SEMI LEAN FLASH COMPRESSOR			
7	**PFD:**	**E-PDG-0002**				
8		K-2001	CO2 COMPRESSOR	*5700*	kW	
9	**PFD:**	**E-PDG-0003**				
10		K-3001	CO2 COMPRESSOR	*5150*	kW	
11		PU-3002	*PROPENE (R1270) REFRIGERATION PACKAGE*	*6400*	kW	
12						
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14						
15						
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34						
35						
36	See notes on Sheet 5.					

HEAT & MATERIAL BALANCE - NOTES

General Notes:

(i) The process conditions and flow quantities listed on this document are those expected and may be altered as required to produce the desired production rate and/or product quality.

(ii) Powers listed in Heat & Material Balance Duty List are subject to Vendor Confirmation.

Notes:

CASALE	**DemoUpCARMA - WP4 - Task 3** Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland	**Proj No.:** A14380 **Doc. No.:** A14380S-E-PZQ-1002 **Rev.:** 01 **Sheet No.:** 1 of 5
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HEAT & MATERIAL BALANCE
JURA CEMENT PLANT - DIRECT OPERATION

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3	X	X																				
4	X	X																				
5	X																					

DemoUpCARMA - WP4 - Task 3
Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland

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HEAT & MATERIAL BALANCE - DATA

1	Stream Name		**101**	**102**	**103**	**104**	**105**	**106**	**107**	**108**	**109**	**201**	**202**	**203**	**301**	**302**	**303**
2 3	Description		Flue gas from cement plant	Flue gas to atmosphere	CO2 to compression/liquefaction	Flue gas to compressor	Flue gas to absorber	Rich solution to regenerator	Lean solution to absorber	Excess water from flue gas cooler	Make up water	CO2 to compressor	Compressed CO2	Process Condensate	CO2 to compressor	Liquefied CO2	Process Condensate
4	Vapour Mole Fraction		1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	1.0	0.0	0.0
5	Temperature	°C	200	*57*	*45*	*45*	*122*	*102*	*97*	*62*	*34*	*45*	45	45	*45*	-37	45
6	Pressure	barg	0.0	0.0	0.1	-0.1	*3.2*	0.2	8.2	4.0	6.0	0.1	35.0	1.6	0.1	22.0	2.0
7	Mass Flow	t/h	283.8	*206.3*	*81.8*	*277.2*	*277.2*	*3,600.0*	*3,525.8*	*6.6*	*10.9*	*81.8*	*78.8*	*2.9*	*81.8*	*78.8*	2.9
8	Norm. Volume Flow	Nm3/h	209,857	*171,570*	*43,828*	*201,796*	*201,796*					*43,828*	*40,157*		*43,828*		
9	Mass Density	kg/m3	0.8	1.0	1.8	*1.1*	*4.0*	*1279.0*	*1271.0*	*979.2*	*1000.8*	*1.8*	72.6	992.6	*1.8*	1105.3	992.6
10	Molecular weight		30.3	*27.0*	*41.8*	*30.8*	*30.8*			18.0	18.0	*41.8*	44.0	18.0	*41.8*	44.0	18.0
11																	
12																	
13																	
14																	
15																	
16																	
17	Molar Composition (wet)	%mol															
18		H2O	14.00%	*12.13%*	*8.37%*	*10.51%*	*10.51%*			99.99%	100.00%	*8.37%*	0.00%	99.92%	*8.37%*	0.00%	99.91%
19		N2	57.75%	*73.45%*	0.00%	*60.09%*	*60.09%*			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20		O2	7.00%	*10.17%*	0.00%	*7.28%*	*7.28%*			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
21		CO2	21.25%	*4.25%*	*91.63%*	*22.11%*	*22.11%*			0.00%	0.00%	*91.63%*	100.00%	0.08%	*91.63%*	100.00%	0.09%
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34																	
35																	
36	See notes on Sheet 5.																

HEAT & MATERIAL BALANCE - DUTY LIST

		ITEM	DESCRIPTION	DUTY OR POWER		
1						
2						
3	**PFD:**	**E-PDG-0001**				
4		TK-1001	FLUE GAS COMPRESSOR-EXPANDER	*8500*	kW	NET POWER
5		K-1002	LEAN SOLUTION DRUM COMPRESSOR	4300	kW	
6		K-1003 A/B	SEMI LEAN FLASH COMPRESSOR			
7	**PFD:**	**E-PDG-0002**				
8		K-2001	CO2 COMPRESSOR	*6800*	kW	
9	**PFD:**	**E-PDG-0003**				
10		K-3001	CO2 COMPRESSOR	*6150*	kW	
11		PU-3002	PROPANE REFRIGERATION PACKAGE	*7650*	kW	
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36 See notes on Sheet 5.

CASALE	**DemoUpCARMA - WP4 - Task 3** Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland	**Proj No.:** A14380 **Doc. No.:** A14380S-E-PZQ-1002 **Rev.:** 01 **Sheet No.:** 5 of 5
		Client Proj. No.: **Client Doc. No.:**

HEAT & MATERIAL BALANCE - NOTES

General Notes:

(i) The process conditions and flow quantities listed on this document are those expected and may be altered as required to produce the desired production rate and/or product quality.

(ii) Powers listed in Heat & Material Balance Duty List are subject to Vendor Confirmation.

Notes:

Appendix IV to WP4 report – 30 November 2023

Appendix IV - Engineering documents

Optimal design and assessment of post-combustion CO_2 capture integration with KVA Hagenholz (public version)

DESIGN BASIS

ERZ WtE PLANT

Form TDT01-rev02

01	05.08.22	Revised where Indicated	FB	GGN	FB
REV.	**DATE**	**DESCRIPTION**	**PREPARED**	**CHECKED**	**APPROVED**

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9	X																			
10	X																			

CONTENTS

1 INTRODUCTION

This document contains the design basis for the new CO2 capture plant to be installed

1.1 Capacity

The capacity is 1211 MTD of CO2 (available in feed – minimum removal 90%)

1.2 Flexibility

The flexibility target for each plant is 50% - 110%.

1.3 Availability

Plant Availability is not less than 95% on annual basis.

2 CASALE BATTERY LIMITS

Battery limits of Casale are from existing flue gas stack up to delivery of sequestrated CO2 as compressed gas (option 1) or liquefied stream (option 2).

Utilities distribution inside CO2 capture plant is in Casale scope, while utilities production is out Casale scope. Optimal heat/utilities integration of the new CO2 capture plant with the existing plant will be agreed among all parties.

3 FLUE GAS AT PLANT BL

	Unit	Average 1	Range
Flue Gas Flow Rate at Stack Inlet	Nm3/h	207'180	50 - 110%
Flue Gas Temperature at Stack Inlet	°C	40 (3)	38 - 42
Flue Gas Pressure at Stack Inlet	mbar g	0	+/- 2
Flue Gas Composition (mol% or ppmv)			
H2O	%vol	6.0 (4)	
N2 + Ar		Balance	
O2	(%vol)	5.0	
CO2	(%vol)	12.4	
SO2	(1)	< 5	< 5
SO3	(1)	<1	< 1
NOx as NO2 (90% is NO, rest NO2)	(1)	60	20 – 80
PM (mg/Nm3)	(1)	0.2	< 10
NH3	(1)	1	< 5
CO	(1)	< 25	< 50
TOC	(1)	< 10	< 10
HCl	(1)	< 2	< 5
HF, HBr	(1)	< 0.5	< 2
Heavy Metals (Σ Pb, Zn…)	(1)	< 0.1	< 0.1
Hg	(1)	< 0.01	< 0.05
Cd		< 0.01	< 0.05
Dioxins, Furans PCDD/F	(2)	< 0.1	< 0.1

1) mg/Nm3 (dry, referred to 11% O2)
2) ng TE/Nm3 (dry, referred to 11% O2)
3) Temperature before cooling is 60°C, sensitivity to this parameter to be addressed
4) Saturated

Turn-down and off-design operation will be addressed in later stages.

4 CO2 PRODUCT

4.1 Option 1 (compressed CO2)

	Unit	
CO2 Product Pressure	bar g	35
CO2 Product Temperature	°C	< 45
CO2 Purity	% vol	> 99.8
H2O	ppm vol	< 50
O2	ppm vol	< 100

4.2 Option 2 (liquefied CO2)

	Unit	
CO2 Product Pressure	bar g	22
CO2 Product Temperature	°C	-37
CO2 Purity	% wt	> 99.966
H2O	ppm wt	< 30
O2	ppm wt	< 10

5 UTILITIES SPECIFICATION AT PLANT BL

5.1 COOLING WATER

District heating return line can be used as cooling water. Values are indicative, not a must or a restriction. Water must be returned and must not be contaminated.

In the plant there is no provision for cooling water. Cooling water at lower temperature than district heating return line must be made available using ACC's, eventually heat pumps.

	Unit	
Supply Temperature	°C	50
Supply Pressure	barg	10 (ca 8 to 12)
Return Temperature (max allowable)	°C	80
Return Pressure (min allowed)	barg	8
Flow Rate (maximum available)	m3/h	summer: 300, winter: 1'000
Unit cost	CHF/m3	free to 4, for orientation
Cooling Water Quality (Chlorides)	ppm	water-steam-cycle quality

5.2 DEMIN WATER

Values are indicative, not a must or a restriction. The demin water supply serves multiple systems, eg steam turbine WSC, district heating network.

	Unit	
Supply Temperature	°C	ambient
Supply Pressure	barg	0
Flow Rate (maximum available)	ton/h	15-30
Unit cost	CHF/ton	60
Demineralized quality		water-steam-cycle quality

5.3 STEAM

Steam 1 (preferred)

Values are indicative, not a must or a restriction. The source of steam is a steam turbine bleed. The steam is needed for district heating and power generation too.

	Unit	
Steam Supply Temperature	°C	105
Steam Supply Pressure	barg	0.2
Steam Condensate Return Temperature	°C	< 100
Flow Rate (maximum available)	ton/h	150 for orientation
Unit cost	CHF/ton	25 for orientation

Steam 2 (2nd preferred)

Values are indicative, not a must or a restriction. The source of steam is a steam turbine bleed. The steam is needed for district heating and power generation too.

	Unit	
Steam Supply Temperature	°C	150
Steam Supply Pressure	barg	2.5
Steam Condensate Return Temperature	°C	< 100
Flow Rate (maximum available)	ton/h	50 for orientation
Unit cost	CHF/ton	25 for orientation

Steam 3 (if needed)

Values are indicative, not a must or a restriction. This steam can be imported, if needed.

	Unit	
Steam Supply Temperature	°C	210
Steam Supply Pressure	barg	11
Steam Condensate Return Temperature	°C	<100
Flow Rate (maximum available)	ton/h	50-100 for orientation
Unit cost	CHF/ton	35 for orientation

5.4 HOT WATER

The source of hot water is the district heating feed line. Water must be returned and must not be contaminated.

	Unit	
Supply Temperature	°C	100
Supply Pressure	barg	14
Return Temperature (max allowable)	°C	80
Return Pressure (min allowed)	barg	12
Flow Rate (maximum available)	m3/h	summer: 300, winter: 1'000
Unit cost	CHF/m3	6 for orientation
Water Quality		water-steam-cycle quality

5.5 ELECTRICITY

Electric power supply at BL is 22 kV, 3 ph, 4 wires, 50 Hz.

The supposed standard voltage rating for various utilization loads are as follows:

Items	AC/DC	Rated Voltage	Phase/Wire
Motors 150 kW and above Up to 150 kW	 AC AC	to be defined by Casale 400 V	3/3 3/3

Maximum electric power supply is 20 MW

6 SITE CONDITIONS

Plant site is located in Zürich (Switzerland)
The climatic conditions of the site are the following:

6.1 Temperature

- Min. design temperature
  for outdoor equipment — -20 °C
- Process design temperature (dry bulb)
  (air coolers design) — 35 °C

6.2 Barometric Pressure

- Process design pressure — 960 mbar

6.3 Relative Humidity

- Design relative humidity and temperature
  (for air coolers) — TBD % R.H. @ TBD °C

7 UNIT OF MEASURES

Dimension	Symbol
Acceleration	m/s^2
Area	m^2, mm^2
Composition or Concentration	wt%, ppm_{wt}, vol%, ppm_{vol}
Conductivity	µS/cm
Density	kg/m^3
Electricity – Current intensity	A, Ma
Electricity – Energy	kWh
Electricity – Power	MW, kW, W
Electricity – Voltage	kV, V
Electricity – Frequency	Hz
Electricity – Resistance	Ohm
Enthalpy	kcal/kg
Flow – mass	t/h, kg/h
Flow – liquid (volumetric)	m^3/h
Flow – gas/vapor (volumetric)	m^3/h, Nm^3/h (1)
Flow – molar	kmol/h, Nm^3/h (1)
Force	Kgf
Heat	kJ
Heat Duty	MJ/h, kJ/h, kW
Heat transfer coefficient	W/m3
Heating value	kJ/kg
HHV (@15°C, 101.3 kPa)	kJ/Nm3
LHV (@15°C, 101.3 kPa)	kJ/Nm3
Length, linear	m, mm
Level	%, m, mm
Mass	t, kg
Mass transfer	kg/(h m2)
Molecular Weight	kg/kmol
pH	pH
Pipe (nozzle size)	DN (mm)
Power	MW, kW, W
Pressure – Absolute	, bar a mbara
Pressure – Gauge	, bar g, mbarg
Pressure – Difference	, bar, mbar
Radiation	W/m2
Sound, Noise	dB (A)
Speed – Linear	m/s, km/h
Speed – Rotating (or Rotation)	Rpm
Specific Heat	kcal/(kg °C) kJ/kg K
Surface Tension	dyn/cm
Temperature	°C, °K
Temperature Difference	°C, °K
Thermal conductivity	kcal/(h m °C) W/m K
Time	y, h, min, s
Torque	Nm
Viscosity – Dynamic	cP
Viscosity – Kinematic	cSt
Volume – liquid	m3
Volume – gas/vapor	m3, Nm3 (1)

(1) Normal conditions: 0°C & 1.01325 bar abs

(2) Standard: 15°C & 1.01325 bar abs

8 CODES AND STANDARDS

Generally European Standards (EC, DIN, ISO)

See Apendix ERZ AV 2, 4

PROCESS DESCRIPTION FOR INTEGRATION WITH EXISTING PLANT

ERZ WtE PLANT

Form TDT01-rev02

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01	23.11.22	Revised where indicated	GGN	FB	FB
02	**05.07.23**	**Revised where Indicated**	**MCC**	**FB**	**FB**
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5	X		X																	
6	X		X																	

CONTENTS

1 HEAT INTEGRATION

The heat that is needed for solvent regeneration is provided by means of low pressure steam (steam 2 according to design basis).

Source of this heat is the extraction of a steam turbine for electricity generation. Subtraction of this steam reduces the power generation and also the heat for district heating purposes.

Heat for district heating can be compensated recovering heat from CO2 recovery unit and CO2 compression, either directly or through a heat pump.

Following sources of heat have been identified:

1. Direct heat recovery
    - CO2 compressor intercoolers (E-2001/E-2002/E-2003/E-2004 or E-3001/E-3002/E-3003)
    - CO2 condenser (E-1004)
2. Recovery through heat pump
    - Wash water cooler (E-1001)
    - Semi-lean solution cooler (E-1002)
    - Lean solution cooler (E-1006)

2

Heat supplied to the reboiler (110% load):	< 40 MW
Heat recovery (110% load):	34.4 MW (CO2 compression case)
	33.9 MW (CO2 liquefaction case)

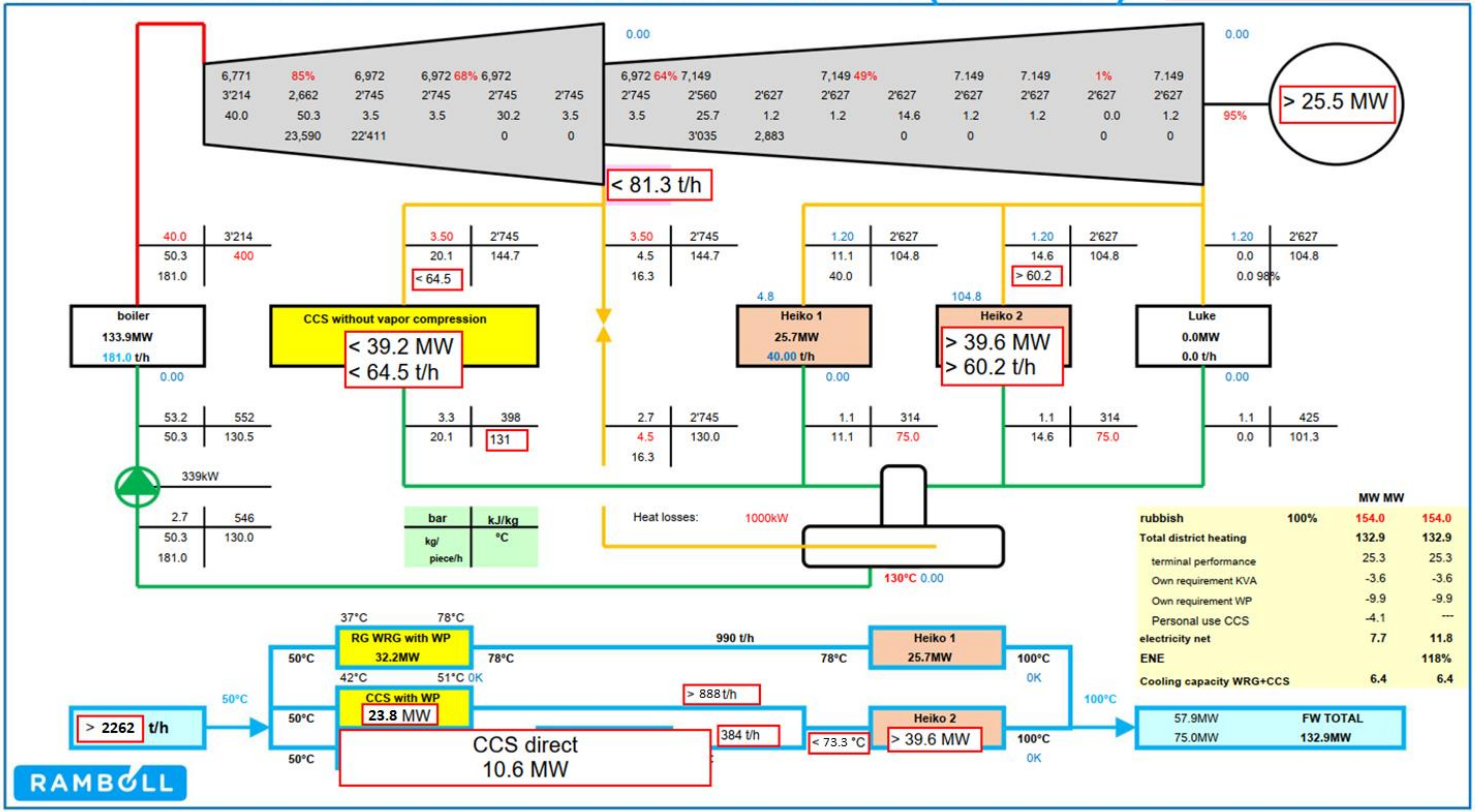
2 BLOCK DIAGRAM

In the following pages it is presented a mark-up of the heat integration block diagram for both CO2 compression case and CO2 liquefaction case.

2

WDK WITH CCS – CIRCUIT CALCULATION (WINTER)

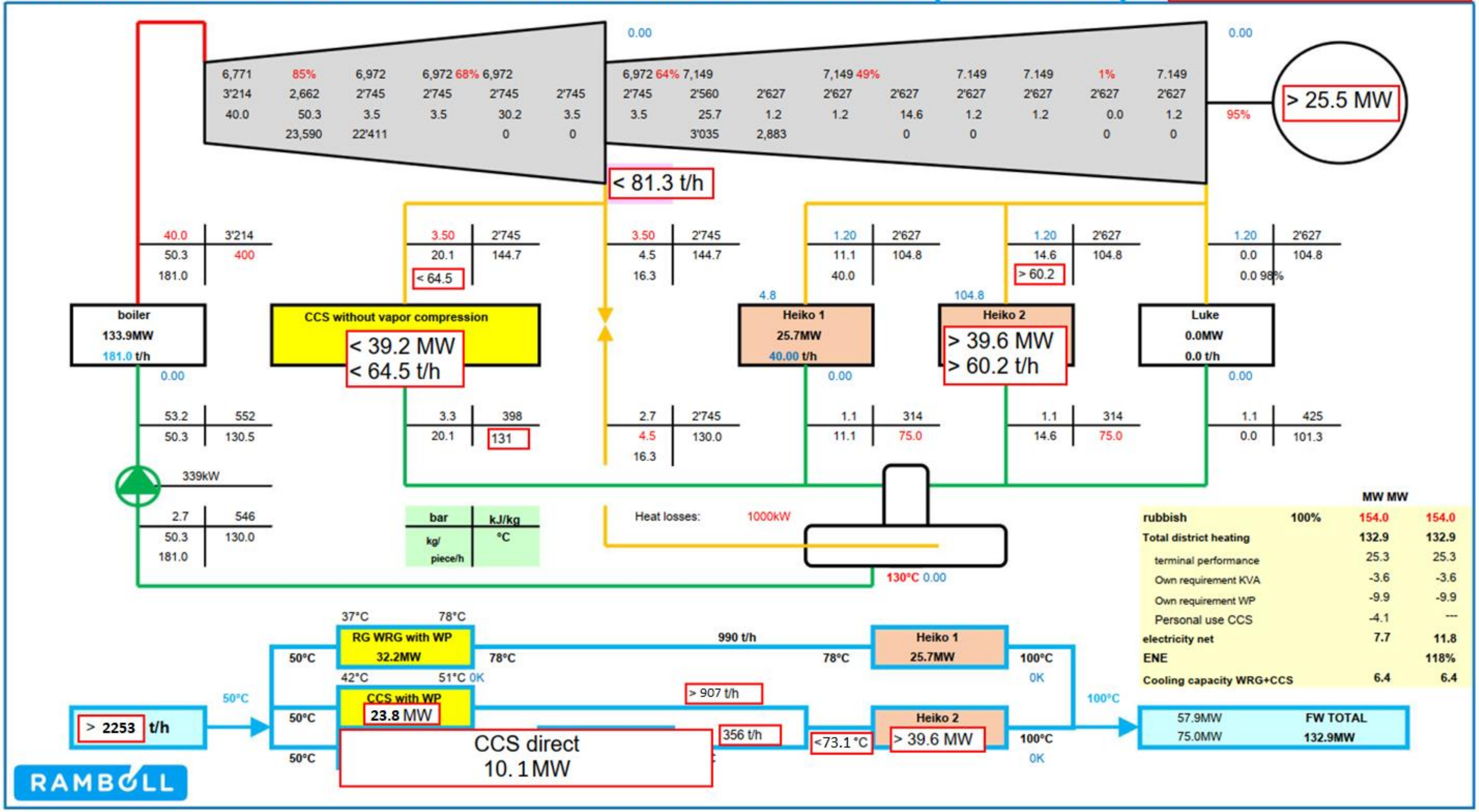
CO2 COMPRESSION CASE



2

WDK WITH CCS – CIRCUIT CALCULATION (WINTER)

CO2 LIQUEFACTION CASE



PROCESS DESCRIPTION FOR CARBON DIOXIDE REMOVAL TECHNOLOGY

ERZ WtE PLANT

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CASALE	Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland **DemoUpCARMA - WP4 - Task 3**	**Proj. No.:** A14380 **Doc. No.:** A14380S-E-PRZ-0003 **Rev.:** 02 **Sheet No.:** 2 of 6 **Client Proj. No.:** **Client Doc. No.:**

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CONTENTS

1 CO_2 CAPTURE

Flue gas from waste incinerator plant is sent to K-1001 blower to increase pressure up to 1.07 bar(a) and then fed to the absorber column C-1001.

The entire absorber column is divided into four sections. The mass transfer zone of the absorber is split into absorber beds C1 (Bulk Absorber) and C2 (Lean Absorber) followed by an emissions reduction zone comprising of two stages — an OASE® aerozone and then a Backwash section on top of the entire absorber column with water pump-around loop and E-1001 cooler.

The Feed Gas enters the bulk absorber bed C1 at the bottom and is further routed to the lean absorber bed C2. The cooled lean OASE® blue solution is fed to the top of the mass transfer zone of the upper lean absorber bed C2 and then the gas and the liquid are getting in contact in a counter-current flow in both absorber beds. Thus, the mass and energy exchange are performed in the packing sections installed in both absorber beds C1 and C2.

An interstage cooler E-1002 is installed in order to cool down the semi loaded amine solution from the bottom of the upper lean absorber C2. The (cooled) semi loaded amine solution leaves E-1002 and then is fed to the top of the bottom bulk absorber C1.

The treated gas from the upper lean absorber bed C2 passes the two stages of the emissions reduction section and is then routed as treated flue gas stream.

The rich solution leaves the bulk absorber bed C1 and is pressurized by the rich solution pump P-1003 before being heated up in the solvent/solvent heat exchanger E-1003. The pressure increase by the rich solution pump P-1003 is required to overcome the hydrostatic pressure to the low pressure flash column C-1002, the pressure drop of the liquid lines and the solvent/solvent heat exchanger E-1003. Further, it also minimizes flashing of the CO_2 from the solution and a subsequent two-phase flow in E-1003. After passing the let-down valve, the solution is fed to LP Flash column C-1002. Downstream LP flash C-1002 there is the regenerator C-1003 with the same diameter. The majority of the absorbed CO2 is stripped off with steam generated in the stripper reboiler E-1005. The regenerated solution at the stripper bottom shows a low residual loading of CO_2. The heat from this hot stream is partly transferred to the rich solution in the solvent/solvent heat exchangers E-1008 and E-1003 and is thereby recovered. The lean solution is then cooled down further in the lean solution cooler E-1006 and fed back to the top of the mass transfer zone of lean absorber bed C2.

The acid off gas stream released from the top section of the regenerator is routed through the regeneration back wash section. It enters the condenser AE-1004, where part of the steam is condensed and returned as reflux condensate stream to the backwash section at the top of the regenerator. The remaining water vapor and the CO_2 product gas leaves the condenser for downstream processing.

This system is able to supply CO2 with < 100 ppmv of O_2 (dry basis). In case a stricter requirement is needed (e.g. < 10 ppmv for liquefied CO_2) this can be also achieved within OASE® blue unit at a bit higher CAPEX and OPEX..

2 RECLAIMING SYSTEM SECTION (CONTINUOUS OPERATION)

In the flue gas of the reformers are present SO_2, NO_x and oxygen. In the CO_2 absorber they can react with the solvent, forming some heat stable salts (HSSs).

These HSSs accumulate and could be potential cause of corrosion in the system pipe works and equipment and could also be the source of solution foaming during the normal operation of the system (carry-over of solution, dirtying of the exchangers, poor CO_2 recovery efficiency).

The reclaimer is provided in order to remove the HSSs accumulated in the solvent. The reclaimer operates continuously and is based on an ion-exchange process.

The waste stream from reclaimer is a low-concentration water solution of predominantly salts of organic and inorganic acids and can be sent to the conventional water treatment plant for further processing.

3 CO_2 COMPRESSION

The CO_2 stream coming from V-1001 is compressed in CO_2 compressor. The machine is expected to be a 4-stage integrally geared centrifugal compressor (to be confirmed by vendor). At about 20 barg, corresponding to 3rd stage outlet pressure, CO_2 will be dehydrated in PU-2001.

PU-2001 unit is based on solid adsorbent: gas is physically rather than chemically adsorbed to the surface of the adsorbent. One vessel is in absorption mode and one in regeneration mode. Regeneration is accomplished recycling back part of the dry CO_2 after heating to about 120-170°C (depending on the type of desiccant).

Alternatively, glycol based systems could also be considered.

The dehydrated CO_2 is then further compressed up to 36 barg, cooled in the aftercooler AE-2001 and delivered to BL at 35 barg.

Heat from interstage coolers can be recovered for district heating.

4 CO_2 LIQUEFACTION

The CO_2 stream coming from V-1001 is compressed in CO_2 compressor. The machine is expected to be a 3-stage integrally geared centrifugal compressor (to be confirmed by vendor). At about 22 barg, corresponding to 3rd stage outlet pressure, the CO_2 will be dehydrated in PU-3001.

Heat from interstage coolers can be recovered for district heating.

PU-3001 unit is based on solid adsorbent: gas is physically rather than chemically adsorbed to the surface of the adsorbent. One vessel is in absorption mode and one in regeneration mode. Regeneration is accomplished recycling back part of the dry CO2 after heating to about 120-170°C (depending on the type of desiccant).

Alternatively, glycol based systems could also be considered.

2 The dehydrated CO_2 is then liquefied and subcooled by means of a conventional chiller, using propylene (R1270) as working fluid in the refrigeration package PU-3002.

CO_2 is delivered to BL at 22 barg and -37°C.

BLOCK DIAGRAMS

ERZ WtE PLANT

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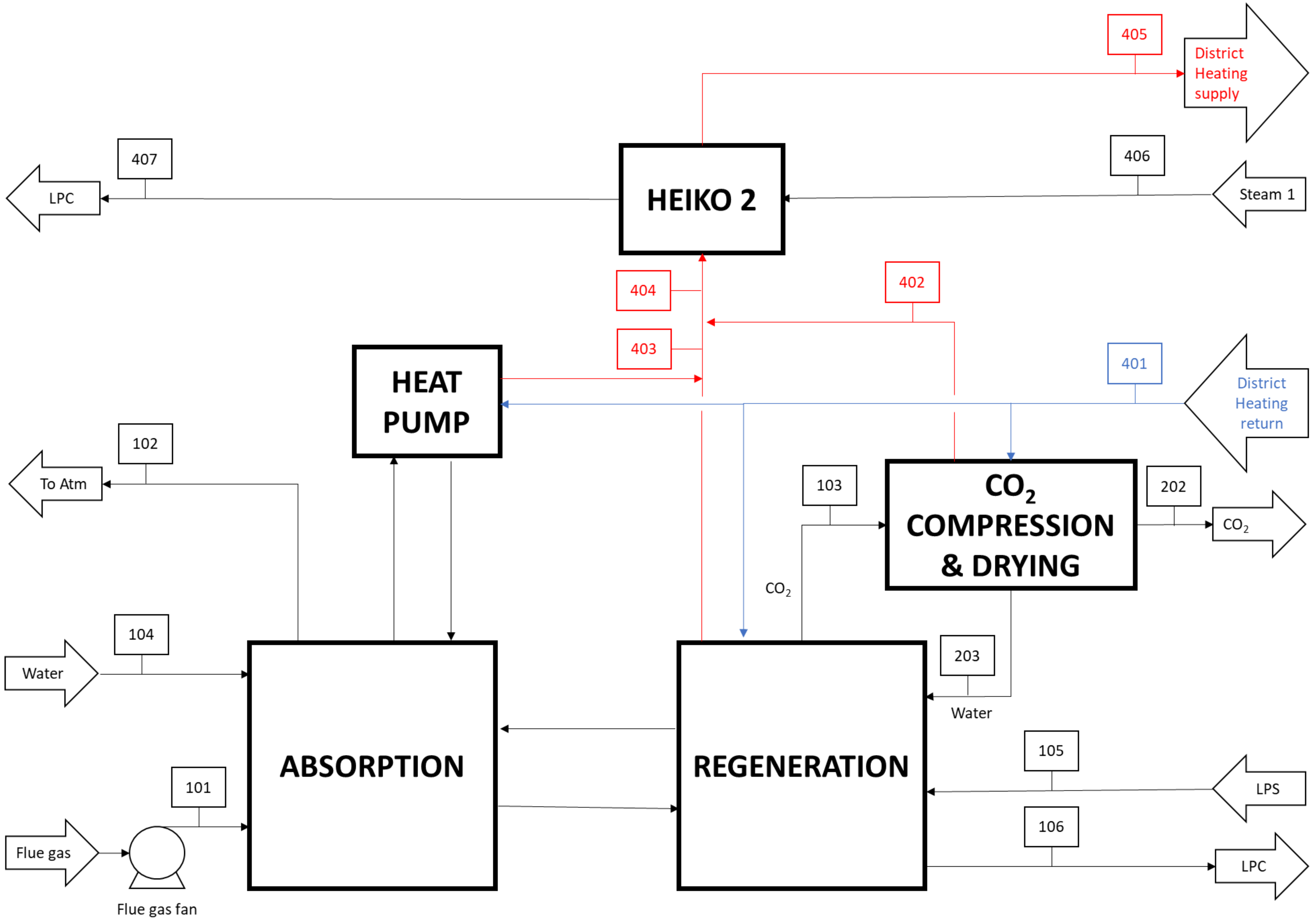
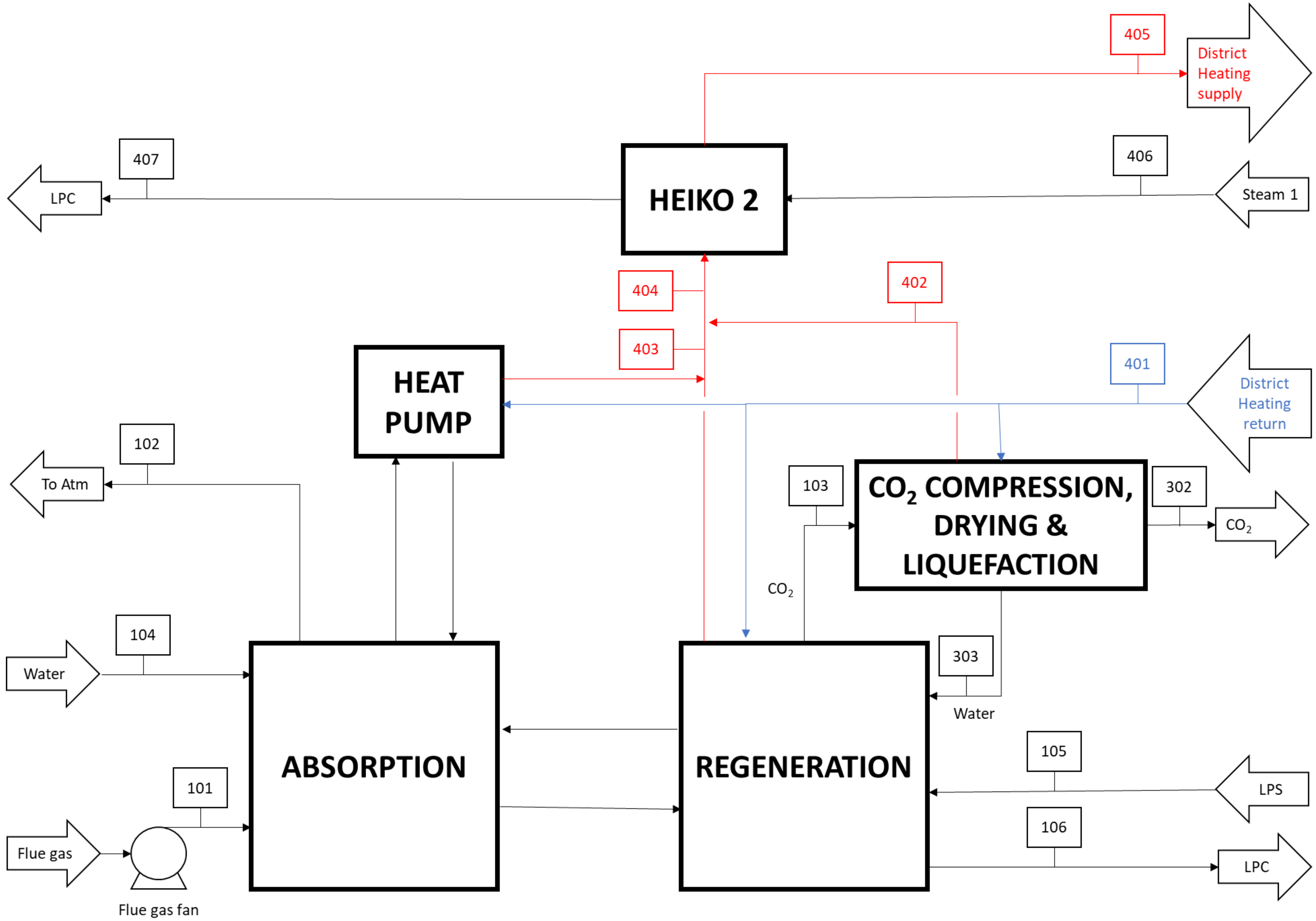
CONTENTS

1 CO_2 COMPRESSION



2 CO_2 LIQUEFACTION



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HEAT & MATERIAL BALANCE
ERZ WtE PLANT
110% LOAD (RATING CASE) 1

00	05.08.22	First Issue	FB	GGN	FB
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2	X	X																				
3	X																					
4	X	X																				
5	X	X																				
6	X																					

CASALE	**DemoUpCARMA - WP4 - Task 3** Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland	**Proj No.:** A14380 **Doc. No.:** A14380S-E-PZQ-0001 **Rev.:** 00 **Sheet No.:** 3 of 6 **Client Proj. No.:** **Client Doc. No.:**

HEAT & MATERIAL BALANCE - DATA

1	Stream Name		**101**	**102**	**103**	**104**	**105**	**106**		**201**	**202**	**203**		**301**	**302**	**303**	
2 3	Description		Flue gas to absorber	Flue gas to atmosphere	CO2 to compression/liquefaction	Demi water make-up	LPS to reboiler	LP steam condensate		CO2 to compressor	Compressed CO2	Process Condensate		CO2 to compressor	Liquefied CO2	Process Condensate	
4	Vapour Mole Fraction		1.00	1.00	1.00	0.00	1.00	0.00		1.00	1.00	0.00		1.00	0.00	0.00	
5	Temperature	°C	49	50	45	35	150	131		45	45	59		45	-37	60	
6	Pressure	barg	0.07	0.01	1.02	1.02	2.50	5.00		1.02	35.00	3.08		1.02	22.00	3.52	
7	Mass Flow	t/h	307.78	264.74	51.51	7.10	< 64.5	< 64.5		51.51	50.47	1.04		51.51	50.47	1.05	
8	Norm. Volume Flow	Nm3/h	233,434	216,979	27,001					27,001	25,705			27,001	25,704		
9	Mass Density	kg/m3	1.20	1.04	3.31	993.90	1.86	933.50		3.31	72.53	981.56		3.31	1105.11	981.09	
10	Molecular weight		29.55	27.35	42.76	18.02	18.02	18.02		42.76	44.01	18.04		42.76	44.01	18.04	
11																	
12																	
13																	
14																	
15																	
16																	
17	Molar Composition (wet)	%mol															
18		H2O	7.3%	12.1%	4.8%	100.0%	100.0%	100.0%		4.8%	0.0%	99.9%		4.8%	0.0%	99.9%	
19		N2	74.7%	80.3%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	
20		O2	4.9%	5.3%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	
21		CO2	12.2%	1.3%	95.2%	0.0%	0.0%	0.0%		95.2%	100.0%	0.1%		95.2%	100.0%	0.1%	
22		Ar	0.9%	1.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	
23																	
24																	
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35																	
36	See notes on Sheet 6.																

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DemoUpCARMA - WP4 - Task 3

Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland

HEAT & MATERIAL BALANCE - DATA

Revision marker: 1

1	Stream Name		401	402	403	404	405	406	407	CO2 COMPRESSION CASE
2-3	Description		District heating return	Hot Water from CO2 compression	Hot water from CRU	Hot water to HEIKO 2	District heating supply	Steam to HEIKO 2	Condensate from HEIKO 2	
4	Vapour Mole Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
5	Temperature	°C	50.0	76.9	72.8	73.3	100.0	105.1	75.0	
6	Pressure	barg	10.0	9.5	9.5	9.5	9.0	0.2	0.2	
7	Mass Flow	t/h	1,272.6	145.8	1,126.8	1,272.6	1,272.6	60.2	60.2	
8										
9	Molar Composition (wet)	%mol								
10		H2O	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	
11										
12	Stream Name		401	402	403	404	405	406	407	CO2 LIQUEFACTION CASE
13-14	Description		District heating return	Hot Water from CO2 compression	Hot water from CRU	Hot water to HEIKO 2	District heating supply	Steam to HEIKO 2	Condensate from HEIKO 2	
15	Vapour Mole Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
16	Temperature	°C	50.0	79.4	72.5	73.1	100.0	105.1	75.0	
17	Pressure	barg	10.0	9.5	9.5	9.5	9.0	0.2	0.2	
18	Mass Flow	t/h	1,263.6	117.8	1,145.8	1,263.6	1,263.6	60.2	60.2	
19										
20	Molar Composition (wet)	%mol								
21		H2O	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	
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36	See notes on Sheet 6.									

CASALE	DemoUpCARMA - WP4 - Task 3 Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland	**Proj No.:** A14380 **Doc. No.:** A14380S-E-PZQ-0001 **Rev.:** 00 **Sheet No.:** 5 of 6 **Client Proj. No.:** **Client Doc. No.:**

HEAT & MATERIAL BALANCE - DUTY LIST

		ITEM	DESCRIPTION	DUTY OR POWER		
1						
2						
3	**PFD:**	**E-PDG-0001**				
4		K-1001	FLUE GAS BLOWER	760	kW	
5	**PFD:**	**E-PDG-0002**				
6		K-2001	CO2 COMPRESSOR	3700	kW	
7	**PFD:**	**E-PDG-0003**				
8		K-3001	CO2 COMPRESSOR	3300	kW	
9		PU-3002	PROPANE REFRIGERATION PACKAGE	5150	kW	1
10	**PFD:**	**E-PDG-0004**				
11		PU-4001	HEAT PUMP	3200	kW	1
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36	See notes on Sheet 6.					

CASALE	**DemoUpCARMA - WP4 - Task 3** Demonstration and Upscaling of Carbon dioxide Management solutions for a net-zero Switzerland	**Proj No.:** A14380 **Doc. No.:** A14380S-E-PZQ-0001 **Rev.:** 00 **Sheet No.:** 6 of 6
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HEAT & MATERIAL BALANCE - NOTES

General Notes:

(i) The process conditions and flow quantities listed on this document are those expected and may be altered as required to produce the desired production rate and/or product quality.

(ii) Powers listed in Heat & Material Balance Duty List are subject to Vendor Confirmation.

Notes: