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Satom CCS Outline Design

Membrane and Adsorption with Metal Organic Framework Technologies



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Abbreviations

Abbreviation	Long form
CC	Carbon capture
CCU	Carbon capture and utilization
CCS	Carbon capture and storage
DH	District Heating
EfW	Energy from Waste
HPC	Hot Potassium Carbonate
MOF	Metal Organic Framework
ODR	Oléoduc du Rhône
OPAM	Ordonnance sur les accidents majeurs
PSA	Pressure swing adsorption
RAM	Rotary-adsorption machine
TSA	Temperature swing adsorption
VBSA	Swiss association of waste management companies

0. Management summary

Switzerland has set the ambitious goal of achieving climate neutrality by 2050, with carbon capture and storage (CCS) identified as a key technology for addressing unavoidable greenhouse gas emissions. Energy from waste (EfW) plants play a central role in this transition, as they emit both fossil-based and biogenic CO₂, the latter offering a unique opportunity to generate negative emissions that are essential for offsetting residual emissions in hard-to-abate sectors. In line with this national strategy and within the framework of the agreement with the federal government (Branchenvereinbarung), the Swiss Association of Plant Managers of Swiss Waste Treatment Installations (VBSA) has set the target of commissioning the first carbon capture plant at a Swiss EfW facility by 2030. Beyond reducing emissions, such projects also open pathways for synergies with district heating supply and the development of CO₂ transport and storage infrastructure.

This study focuses on the planning of a Carbon Capture (CC) plant at the Satom EfW plant in Monthey with a focus on separation via membranes and metallic organic framework technology (MOF). The entire process chain from CC core process, (pre-)purification, compression and liquefaction and transfer to the logistics facilities were considered within the scope of the study. The downstream logistics for the transport of CO₂ require for the loading of CO₂ into rail tank cars and the injection into pipeline. Several locations for possible pipeline or railway transport were identified. The Satom EfW plant is conveniently placed next to the Oléoduc du Rhône (ODR), a former crude oil pipeline, connecting the decommissioned Tamoil refinery to Italy, as well as available freight train stations at the Tamoil plant in the north and the CIMO chemical plant in the south. The subsequent transportation of CO₂ and its storage at a dedicated storage site in Italy is being envisaged in parallel by the application center of Satom, CIMO, and Syngenta.

As the base case, a CC plant size of at least 100'000 t/a liquefied CO₂ was established. This base case serves as the foundation for scaling different quantities at above-mentioned locations, resulting in a range of potential layouts, transportation modes, and associated costs. After a preliminary market analysis and supplier evaluation, four suppliers were chosen to conduct feasibility studies for their respective CC technologies to build a 100'000 t_{CO2}/a CCS plant at Satom. Ramboll analyzed and validated the data from the three membrane and one MOF technology suppliers, engaging extensively with the suppliers to review and question the data until its accuracy was confirmed. The feasibility studies yielded promising results showing that carbon capture is both technically and spatially viable at the Satom EfW plant. The area offers a high potential for realizing CCS due to the available space at the green fields Satom, Tamoil, and CIMO. Additionally, the potential for pipeline transport via the Oléoduc du Rhône and an excellent connection to the railway network, particularly at the Tamoil station with good accessibility and retrofitting options as CO₂-Hub, support the findings.

The process and energy integration are supplier-dependent and closely linked to ongoing projects such as the new line and the refurbishment of the other line within the INOSAT project. The CC plant is designed to run in bypass mode relative to the two incineration lines, ensuring that any disruptions do not affect the operation of INOSAT. The electricity demand for MOF technology is 3.4 MW_{el}, whereas membrane technologies require between 5 MW_{el} and 8.6 MW_{el}. Additionally, MOF technology relies on thermal energy and needs 14.4 MW_{th} of low-pressure steam for the regeneration of the MOF modules. This corresponds to a specific electricity consumption of 113 kWh_{el}/t_{CO2} of captured CO₂ for MOF technology, 216-542 kWh_{el}/t_{CO2} for membrane technology, and a thermal energy requirement of 1'088 kWh_{th}/t_{CO2} of captured CO₂ for MOF technology. These values cover the energy requirements from capture to liquefaction but not cooling or the heat pump.

The carbon capture plant will operate independently from INOSAT regarding waste heat integration, providing heat with 90 °C for the district heating network. Quantifiable potentials for waste heat utilization and integration with a compression heat pump only for the carbon capture plant range case from 5.4 MW_{th} to 10.1 MW_{th}. The condensation of exhaust gases from the incineration lines to 35 °C and the integration of the generated heat are outside the scope of this study and will be evaluated separately within the INOSAT project. However, two suppliers have implemented an additional condensation stage at temperatures between 26° and 28°C. The thermal energy generated by these stages, as well as by the liquefaction process, is at such a low temperature that it will not be integrated but instead cooled.

Due to the possibility of spatially separating CO₂ capturing and pre-purification from liquefaction and storage, all variants can be implemented in terms of space but require customized designs. In consultation with Satom the key scenarios and cases were provided as a 3D model in Revizto illustrating various configurations.

Investment costs for the 100'000 t_{CO2}/a base case from capturing to pipeline injection have been calculated to range from 93.2 Mio. CHF for membrane to 166.6 Mio. CHF for MOF technology, with costs per ton of CO₂ captured ranging from 60 CHF to 102 CHF. In a joint effort with two suppliers, a project roadmap was developed for a mitigated risk roadmap, with plant commissioning finalized by mid-2034. This was then compared to a fast-track project roadmap, with commissioning finalized by the end of 2030. The first key project decision points should be executed at the end of 2025 in both roadmaps. The technology appears to be ready for application in principle. However, there are risks associated with the suppliers' experience in the complex environment of process and energy integration at EfW plants, their knowledge of the Swiss market and regulations, and their ability to mobilize the necessary resources. Overall, financing security is most essential for planning reliability and reaching the 2030 commissioning goal.

Cost intensive follow-up studies carried out by the suppliers will be essential for achieving higher cost accuracy and optimized space and energy integration. The scope for cases and locations needs to be narrowed down, with final decisions on scenarios dependent on several factors including utilization of ODR, hub case possibilities, and the political framework. A critical decision point will be as soon as the end of the year, regarding the Front-End Engineering Design (FEED)/pre-FEED planning and in parallel the necessary financing to advance the project. All suppliers have expressed strong interest in realizing the project within the given limited time frame.

1. Introduction

Switzerland aims to achieve climate neutrality by 2050 as part of its Federal Council's long-term climate plan, confirmed by the public in the referendum on June 18, 2023, which legally established the net-zero goal. To achieve this target, CO₂ emissions must be substantially reduced, but there are sectors, such as construction and agriculture, where emissions are difficult or nearly impossible to eliminate. The remaining emissions must be offset through sinks, creating negative emissions.

EfW plants play an important role in this initiative as they consistently produce biogenic and fossil-based CO₂ emissions, which cannot be fully avoided through upstream waste reduction efforts. Recognizing this importance, the VBSA has set a goal to have the first carbon capture facility operational at a Swiss EfW plant by 2030. This objective highlights the necessity of incorporating CCS solutions within the national waste and energy framework to meet climate policy targets and maintain the reliability of energy generation from EfW plants. The VBSA's agreement with the federal government, represented by the Federal Department of the Environment, Transport, Energy and Communications (UVEK), obliges EfW operators to establish at least one CO₂ capture facility with an annual capture capacity of at least 100'000 tons of CO₂ by 2030. In return, Switzerland's EfW plants are exempt from the Emissions Trading System (ETS).

Implementing carbon capture at EfW facilities not only diminishes fossil CO₂ emissions but also enables the extraction of biogenic CO₂ from the atmosphere, providing a pathway for negative emissions. This makes the sector a vital contributor to Switzerland's net-zero ambitions, as achieving negative emissions will be essential.

While this is not the first carbon capture (CC) project in Switzerland, it remains among the pioneering efforts in the country. Satom aims to explore innovative technologies that are not highly developed in terms of Technology Readiness Level (TRL), as alternatives to the more commonly considered methods such as hot potassium carbonate (HPC) and amine carbon capture technologies.

Transport options for the captured CO₂ include railway logistics or via the Oléoduc du Rhône pipeline, with a final storage solution at a dedicated CO₂ storage site in Italy.

2. Design basis

Satom operates an EfW plant with currently two parallel lines. A third, new line is planned to go into operation by 2030 (project INOSAT). Once this new line (Line 2) is in operation, Line 1 will be refurbished, and Line 3 will be decommissioned. Additionally, to the new INOSAT project, there are several parallel projects in planning, including and not limited to an extension of the district heating network (DH), new turbine and heat pump concept, the integration of the waste heat from a nearby data center, and an electrolyser. This adds complexity for definition of the project and the design basis and interfaces.

The scope of INOSAT will include flue gas condensation, if it is foreseeable that CC is implemented, ensuring the flue gas enters the carbon capture plant at 40 °C. If no CC plant is built, the flue gas condensation might be built for energy integration optimization. The energy integration of the waste heat of the flue gas condensation will be carried out via an absorption heat pump. However, this has a lower priority compared to utilizing both direct and indirect waste heat from the carbon capture plant. The indirect waste heat of the CC will be integrated via a compression heat pump, allowing for a higher coefficient of performance. The waste heat potential below 40 °C is not integrated into the energy system in either summer or winter.

The Oléoduc du Rhône (ODR) is an oil pipeline commissioned in 1963 which connects the refinery in Collombey with a refinery in northern Italy through the Alps. The refinery was taken over by Tamoil in 1990 and decommissioned in the year 2015. The future operational status of the pipeline is subject to an ownership decision expected in the near term. References to the Tamoil site throughout this report relate exclusively to the geographical location and its existing infrastructure, assessed on the basis of publicly available information.

Three locations are identified for the carbon capture plant and consequent compression, purification, liquefaction and logistics. The Satom plant is located next to the Rhône River. To the north, the former Tamoil refinery is located. The ODR does not reach the location directly, therefore requiring an additional pipeline part. The Tamoil location is well connected via a railway station. The ODR connects the EfW Satom plant with the chemical plant of CIMO to the south. The CIMO location is connected via railway, the loading services are provided by Syngenta.

3. Carbon Capture Technology

3.1 Carbon Capture

3.1.1 Membranes

Membrane processes involve the physical separation of CO₂ or other gases through selective permeation. This is achieved by utilizing membrane materials that preferentially allow the passage of a type of molecule while retaining other molecules. To be selective to certain types of molecules, some membranes are developed to have chemical affinity to the species of interest, while others rely on size-exclusion (pores of determined size) to be selective.

Advantages of this method include its modular design which enables a low partial load capability, the fact that it does not require chemicals which prevent additional emissions, and its reliance on electrical power. However, there are several challenges associated with membrane processes, including a lower Technology Readiness Level (TRL) of 7-8, high power consumption, sensitivity to impurities, and limited references or case studies to draw from. Still, there are several technology providers working to develop membrane-based processes and potential users for these technologies, so the TRL is expected to increase rapidly in the next decade.

3.1.2 Adsorption using Metal Organic Frameworks

Adsorbents are solid materials that have binding sites on their surfaces, a characteristic that allows them to remove CO₂ preferentially from a gas stream. The materials generally have either a porous surface or granular structure that develops a large surface area and many potential binding sites to capture CO₂. The most common types of adsorbents for CO₂ capture are zeolites, carbon-based adsorbents, and Metal-Organic Frameworks (MOFs).

Adsorption using MOFs utilizes solid sorbents that bind CO₂ on their surfaces and release it either through a change of temperature (TSA, temperature swing adsorption) or through a change of pressure (PSA, pressure swing adsorption). Then, for desorbing the CO₂, opposite conditions (high pressure and/or low temperature) are applied.

Other advantages of using MOFs for CO₂ capture are that they do not require additional chemicals, minimal emissions, established methods from the oil and gas sector, and easy integration into existing facilities. However, MOF technology for carbon capture also faces some large challenges. Only few companies have successfully implemented production of a limited number of MOFs for industrial CO₂ capture. Other disadvantages involve the need for multiple columns, lower efficiency at low CO₂ concentrations, dependence on durable and sometimes costly sorbents, and high-pressure losses.

MOF-based adsorption has achieved a Technology Readiness Level (TRL) of 6-7, while plant setups for EfW applications are at a TRL of 5. Adsorption with MOFs from flue gas shows great potential for CO₂ capture promising broader industrial adoption in the near future.

3.1.3 CO₂-purification

The CO₂ gas from the CO₂ capture plant contains water and impurities that must be removed for transport and storage. For both processes membrane and MOF based carbon capture, the properties

of CO₂ after carbon capture are typically 1 bar, around 20-40 °C, with a purity of >90 vol.%, the remainder consisting mostly of nitrogen, oxygen and water.

To meet the specifications for final storage or utilization, the CO₂ must be further processed. This processing includes compression, drying, pre-purification and liquefaction as the final purification step before the CO₂ is stored in liquefied form. There are various methods for achieving the required purity, and the choice of CO₂ capture technology itself has only a minor influence on the compression and liquefaction processes. The final purity of the CO₂ is determined by the purification processes used in the post-treatment steps, which can be adapted to the specific requirements of the final storage site or the CO₂ utilization process. CO₂ purification usually results in a loss of separated CO₂. During the rectification stage of liquefaction, non-condensable gas components are emitted as exhaust gas together with CO₂. To minimize this effect, pre-purification of the CO₂ after compression is a feasible option. Alternatively, the exhaust gas can be returned to the separation process.

3.2 Transport options

The transport of CO₂ is not a novel technology and has been utilized in the food industry, particularly in beverage manufacturing for the carbonation of drinks. However, the substantial quantities generated by CO₂ capture processes, as well as the need for continuous operation, impose significantly higher demands on the logistics involved. When intermittent transport or system changes occur, it is recommended to use transfer points with intermediate storage to ensure smooth operation (Hub concept). CO₂ can fundamentally be transported by road, rail, inland waterways, deep-sea shipping, and pipelines. For the Satom project the most suitable transport modes are railway and pipeline due to the good railway connection and the proximity of the ODR.

Therefore, it is advantageous that the ODR is already located near the CC plant, as costs will only cover retrofitting for CO₂ and permits. The required CO₂ purity levels are not overly strict and are comparable to those of other well-known projects.

3.3 Supplier studies

As the overall project lead for the INOSAT project, Ramboll consolidated and directed the carbon-capture workstream, coordinating the technology suppliers commissioned by Satom to validate their solutions. This structured collaboration with qualified suppliers is crucial for developing an operable plant that would meet the 2030 target while ensuring efficient energy integration and plant operation. Ramboll checked the statements, performance data and CAPEX/OPEX estimates of each supplier and put them into the project plan. This made a strong and clear cost and technical feasibility forecast.

First, an initial selection of suppliers for membrane and MOF carbon capture technology based on a market evaluation was drafted, resulting in a list of 19 suitable suppliers. The suppliers were each contacted with a predefined set of criteria. The suppliers should provide technologies that are not merely theoretical but have been tested and demonstrated outside of lab conditions. Therefor by assessing their TRL, it is ensured that their solutions are proven and effective for carbon capture.

Secondly, an essential requirement is the ability to design, deliver, and commission a carbon capture plant by 2030. Suppliers must assure that they have the resources, expertise, and experience necessary to meet this ambitious timeline. It is important for the suppliers to exhibit not just technological capability but also the capacity to manage logistical and managerial challenges.

The willingness of the suppliers to support the ambitious timeline was considered for further evaluation.

In the resulting offer phase four suppliers were selected according to the costs of the studies and only if the technological advancement, market development and willingness to participate in further project development was deemed acceptable. For reasons of confidentiality, the suppliers are referred to as Membrane 1 to 3 and MOF.

4. Logistics concept

4.1 Scenario development

In the first scenario (I, Figure 1), CO₂ is captured at Satom's site and (pre-) purified, compressed and liquefied. The captured CO₂ is then injected next to the CC plant into the ODR pipeline, which borders the allocated CC area. This scenario offers several benefits in terms of simplicity of stakeholder management and technical benefits such as the heat integration on site and benefiting from reintroducing the liquefaction blow off in the CC process, as suggested by some suppliers. As there are no train tracks available, only pipeline transport was considered for Satom's site.

In the second scenario (II, Figure 1), the CO₂ is captured, (pre-) purified and compressed at Satom's site. It is then transported in gaseous phase through the ODR pipeline to the Tamoil station. An additional pipeline must be built for access to the Tamoil site, as the ODR does not reach the entire route to the allocated Tamoil area. For the Tamoil site railway transport was considered, there are two train tracks available. In this scenario due to the green field and good railway connection, a hub scenario could be possible with additional CO₂ being delivered from other capture sites. Pipeline transport was not considered for the Tamoil site since this would need a second pipeline to return the captured CO₂ back to the southern part of the ODR south of the Satom plant.

In the third scenario (III, Figure 1) the captured CO₂ is (pre-) purified and compressed at Satom's site as well and then transported in gaseous phase to the CIMO site. The site at CIMO on the other hand is connected via the ODR pipeline at Satom's site and after consequent liquefaction at CIMO the ODR pipeline could be used without an additional pipeline to send the CO₂ southwards. Additionally, the transport via railway is considered as well so that scenario III can give a direct comparison between the two transport modes of pipeline and railway. At the CIMO plant the Syngenta is assembling the trains for the CIMO plant southwards, one train track was offered as available for CC transport.

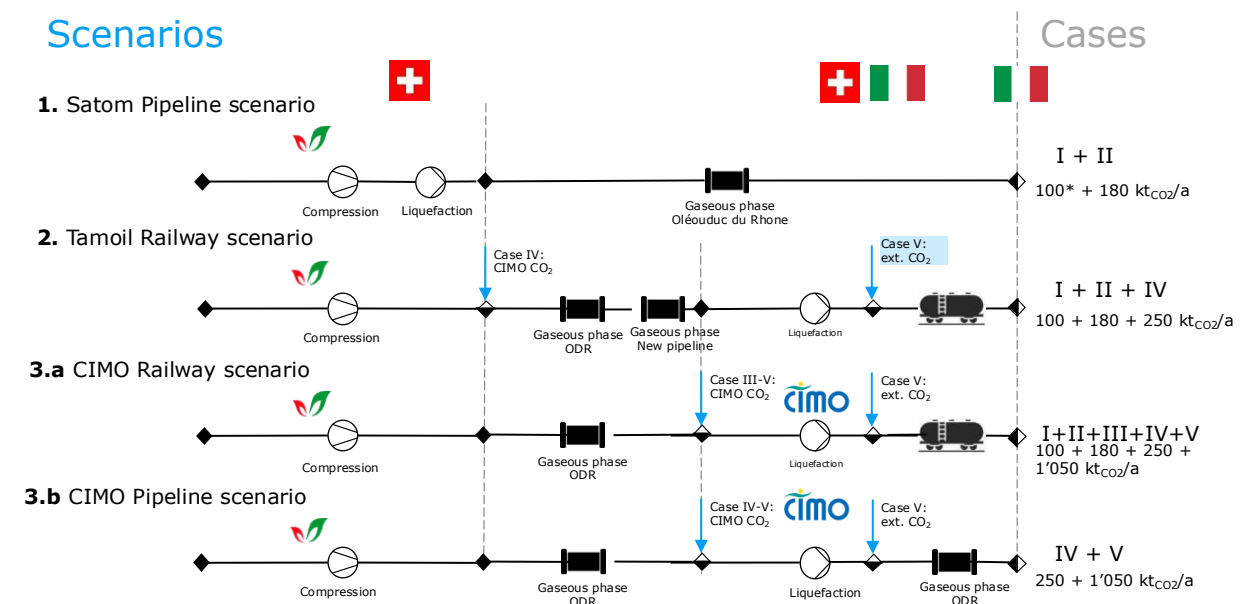


Figure 1: Logistics scenarios and cases.

4.2 Ramp up of CO₂ amount

The layout and logistic concept are differentiating depending on the amount of CO₂ that will be transported. Therefore, several cases were developed with the Satom team and competence center to be analyzed, an overview can be found in the previous Figure 1.

The base case (I) for this study is the Satom emission of 100 kt defined in the design basis and represents the plant built for the VBSAs efforts to put a plant into operation by 2030. The supplier studies are also based on this base case. The second case (II) considers the full-scale emissions of 180 kt emitted by Satom and represents a scaled-up version of the base case. For the supplier studies no other cases could be obtained, therefore their numbers were scaled accordingly as well.

As in the future the CIMO plant is considered to capture their own CO₂ emissions, the third case (III) considered adding the 70 kt emitted by CIMO at a later stage to the Full scale Satom plant of 180 kt (II) resulting in a total of 250 kt. The assessment of a carbon capture at the CIMO plant is outside of the scope of this study. This case represents a scale-up of capacities. In comparison to that, the entire process can be designed for the 250 kt from Satom and CIMO, which is represented in case IV.

Additionally, it was requested that a Hub Scenario V is represented in the layout of CIMO. In the Hub scenario the additional CO₂ from other sources would be delivered in liquid form via railway wagons and processed through the site. This includes intermediate storage and loading/unloading of the liquid CO₂ and then subsequent logistics. Together with the competence team an additional 800 kt were defined to be transferred through the hub.

5. Process integration

5.1 Process and interfaces

The process is separated into the area of Satom's EfW plant with the interface to the district heating. The carbon capture core process is situated at Satom's site. Additionally to the CC suppliers' scope, the CC heat pump and CC redundant cooling are included in the scope of the CC core process scope. The CO₂ compression, which is not part of the CC core process, is also situated on Satom's site.

The subsequent process steps are separated in the respective locations for the liquefaction and logistics; Tamoil liquefaction and logistic (rail), liquefaction onsite Satom and Pipeline transport and CIMO liquefaction with the options of railway and pipeline transport.

The CC plant main interfaces to the INOSAT plant are the flue gas integration (see following chapter) and heat integration of the direct and indirect heat with the district heating network. The specific interfaces e.g. steam differ depending on the supplier. The energy integration can be found in chapter 5.3.

5.2 Flue gas integration

The flue gas integration is set to be after the flue gas condenser. The purpose of the flue gas condenser is to cool the flue gas and reduce the volume flow. In this case the flue gas condenser is in the scope of the INOSAT project and not depicted in the flue gas integration. The operation of the CC plant involves directing the flue gases through a bypass from Satom EfW to the CC plant. After CO₂ removal, the treated flue gases are returned to the existing stack. During maintenance or disruptions at the CC plant, the bypass is designed to allow flue gases to be directed straight to the stack, as they would be in normal operation. To manage the flow of flue gas appropriately, several flaps are required. The developed concept foresees a common flue gas bypass to the CC plant for both incineration lines. To ensure that one line can operate independently of the other, the flaps must not only regulate the flow of flue gas but also prevent backflow into either incineration line.

Condensation of flue gas and CO₂ removal increases the relative concentration of the remaining gas species, resulting in a higher volumetric share. This manipulation of measurement values could potentially lead to regulatory issues. Therefore, additionally to the flue gas emission measurement 1 from the EfW plant, a second emission measurement should be considered. Additionally, this position offers the advantage of enabling traceable documentation of the flue gas parameters of the CC plant. Based on Ramboll's experiences in discussions with authorities, this is anticipated to be a regulatory requirement. Furthermore, it is crucial for performance guarantee tests during the trial and commissioning phases in relation to the suppliers.

5.3 Energy integration Carbon capture

The energy integration for all of Satom's projects is determined by the INOSAT planners and may change in the future, since this project is still ongoing. In accordance with their planning, it was defined that the CC process will include a compression heat pump. During summer, only waste heat that can be directly integrated ($> 75\text{ }^{\circ}\text{C}$) into the district heating network, without requiring additional heat pump systems, is utilized. The upper limit for direct waste heat utilization is set at 5 MW, which corresponds to the district heating capacity during summer. In winter, energy integration is maximized by using all available waste heat both directly ($> 90\text{ }^{\circ}\text{C}$) and indirectly, assisted by a compression heat pump. The district heating capacity is limited to 45 MW. The waste heat potential below $40\text{ }^{\circ}\text{C}$ is not integrated into the energy system in either summer or winter.

The energy integration is based on Case I, which corresponds to capture and liquefy at least 100'000 tons of CO_2 per year. If the CO_2 capture amount is increased to 180'000 tons of CO_2 per year (Case II), the energy integration remains the same but the additional waste heat will be cooled. In the base case the captured CO_2 is compressed to approximately 20 bar at Satom's site for the subsequent liquefaction. The pressure at the interface from the CC core process is for all suppliers at ambient pressure and the compression and liquefaction step were standardized across all suppliers. The liquefied CO_2 is then vaporized where the undercooled CO_2 accounts for the waste heat generation. The gaseous CO_2 is then compressed to the required pipeline pressure. The maximum pressure at the ODR was at a later stage defined at 40 bar, the pipeline compressor is assumed to be air cooled.

5.3.1 Waste heat utilization

Figure 2 provides a summary of the waste heat potential from all suppliers. As detailed in the preceding section, the waste heat is categorized into different temperature segments ($>100\text{ }^{\circ}\text{C}$, $60\text{--}100\text{ }^{\circ}\text{C}$, and $<60\text{ }^{\circ}\text{C}$). Additionally, MOF conditions the MOFs with fresh air before reloading them for the next cycle. This air is introduced at $10\text{ }^{\circ}\text{C}$ and released between 40 and $70\text{ }^{\circ}\text{C}$ after partially recovering the waste heat. These heat losses are denoted as "losses" in the figure.

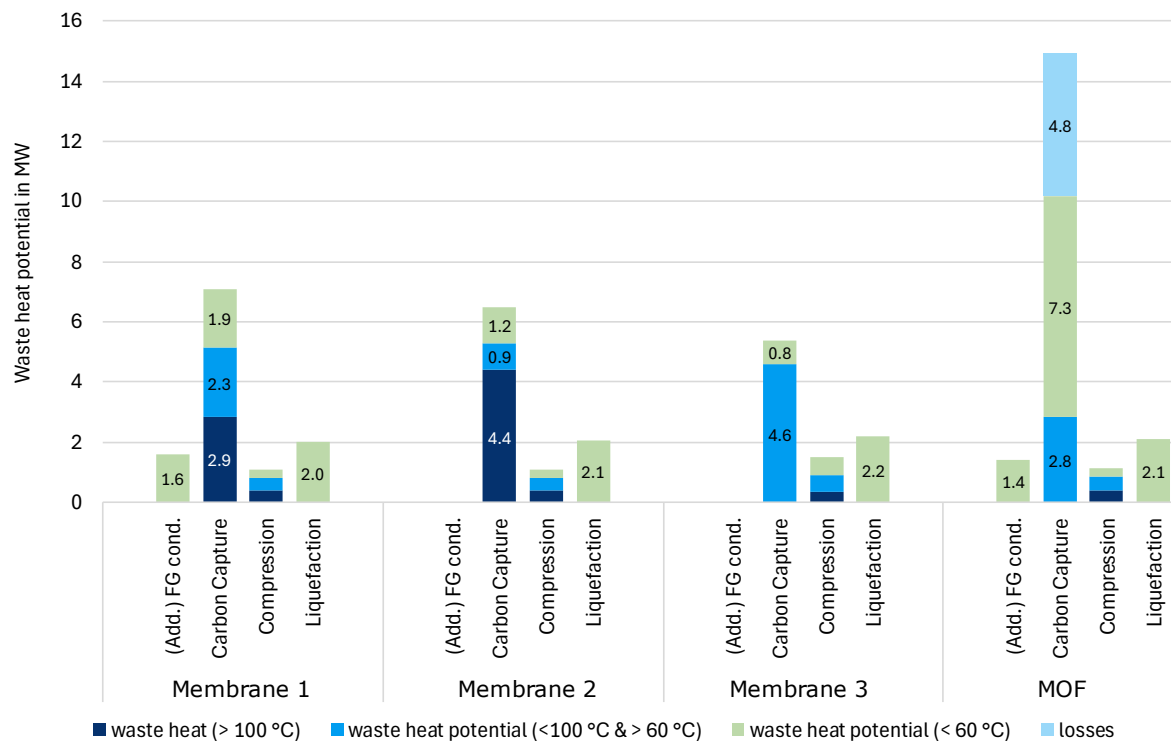


Figure 2: Waste heat potential of each CC supplier divided into temperature segments.

A waste heat potential and pinch analysis was conducted for each supplier to identify all available waste heat sources. The summary of the energy integration for each supplier during summer and winter is presented in Figure 3. For Membrane 1 and Membrane 2, the energy integration during summer is constrained by district heating limitations, thus not the full direct waste heat capacity can be integrated. Conversely, for Membrane 3 and MOF, the integration potential is relatively low in summer since the waste heat from the core capture process is at a limited temperature level, predominantly requiring the use of a heat pump.

In the winter scenario, the integration is limited by the waste heat potential. Thus, the full direct heat potential can be integrated, along with the indirect heat through the heat pump. It is important to note that the energy input for the heat pump is not shown in Figure 3; the figure focuses on the cooling side of the heat pump. The compression heat pump is designed to operate between 35 °C and 90 °C, with a coefficient of performance (COP) of 5. The design is based on supplier data with a small margin to ensure a conservative approach. During winter, the only energy that needs to be cooled pertains to the liquefaction plant and the cooling load below 40 °C, as stated in the assumptions above.

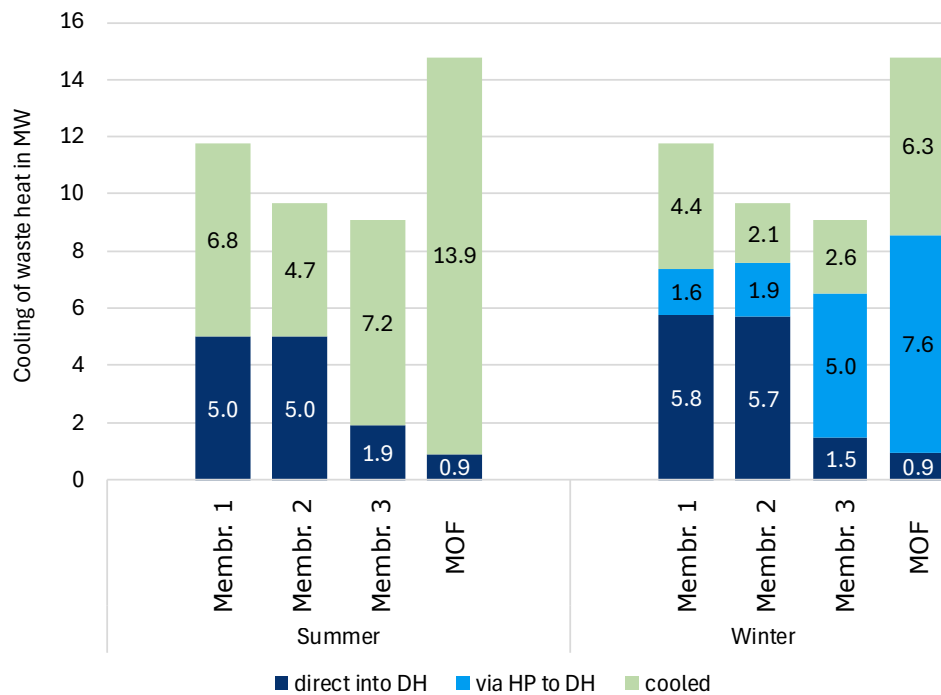


Figure 3: Overview of the energy integration for all suppliers during summer and winter. Caution: The electrical energy required to run the heat pump is not depicted in this figure.

Membrane 3 reports their direct heat potential at 80 °C, with possibilities to increase the waste heat level through more detailed future analyses. Consequently, only small amounts can be directly integrated into the district heating network, as the district heating return temperature is 90 °C during winter and 75 °C during summer.

MOF has high waste heat potential, but at a relatively low temperature. This makes it challenging to integrate the heat potential during summer. During winter, a large heat pump is necessary to reach the required district heating forward temperature.

5.3.2 Cooling

To ensure uninterrupted operation of the carbon capture plant, redundant coolers are designed to provide cooling capacity for the entire waste heat potential. This ensures continuous operation even if waste heat cannot be integrated during certain periods. The waste heat could be cooled by using river cooling with Rhône water, which makes it simple to achieve low cooling water temperatures during both winter and summer. The maximum return temperature of cooling water to the Rhone is restricted to 27 °C. This is generally not an issue, as the Rhône maintains a relatively low temperature in summer due to melted water from the surrounding mountains. Nonetheless, permission is required to use Rhône water as a cooling source. To depict a worst-case scenario where the use of Rhône water is not permitted, the air-cooled coolers are installed on the rooftops of the CC buildings in this study.

5.3.3 Energy demand

Figure 4 illustrates the energy demand of all suppliers. Additionally, the energy needed for the operation of the heat pump during winter is included. It distinguishes between electricity and steam

consumption and identifies the specific sub-processes requiring energy. The electricity consumption for the redundant cooling is not included, roughly 1 % of cooling load should be considered for electricity consumption. The electricity consumption for each supplier (including the electricity for the operation of the heat pump) is as follows.

- Membrane 1: 9.0 MW
- Membrane 2: 6.7 MW
- Membrane 3: 6.3 MW
- MOF: 5.3 MW

Additionally, MOF has a steam consumption of 14.4 MW.

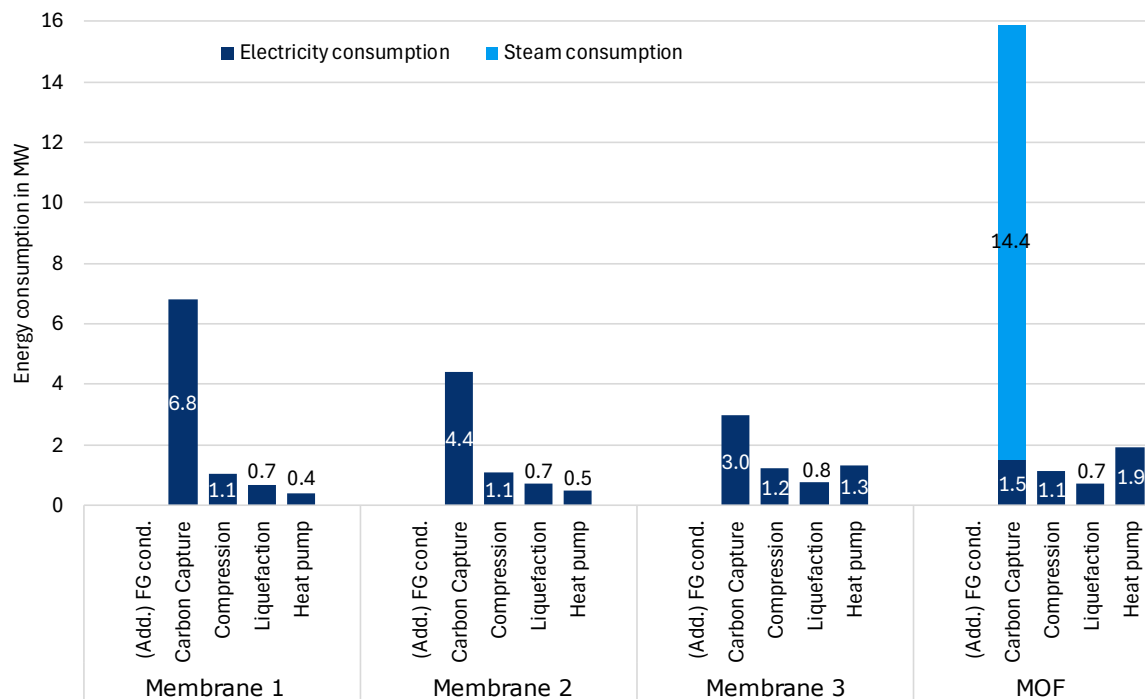


Figure 4: Energy consumption including electricity consumption for heat pump during winter.

The specific energy consumptions are depicted in the following figures. In Figure 5 the specific energy consumption is split between the electricity consumption per supplier for the CC core process and additionally in steam consumption for the supplier MOF. Each supplier study resulted in a marginally different CO₂ output (e.g. Membrane 2 104 kt_{CO2}/a and MOF 110 kt_{CO2}/a), depicted in the grey speech bubbles. The specific energy consumption was adjusted accordingly. Figure 5 refers

to the energy consumption of only the CC core process, the total process energy consumption (compression, liquefaction, heat pump) is included in the following Figure 5.

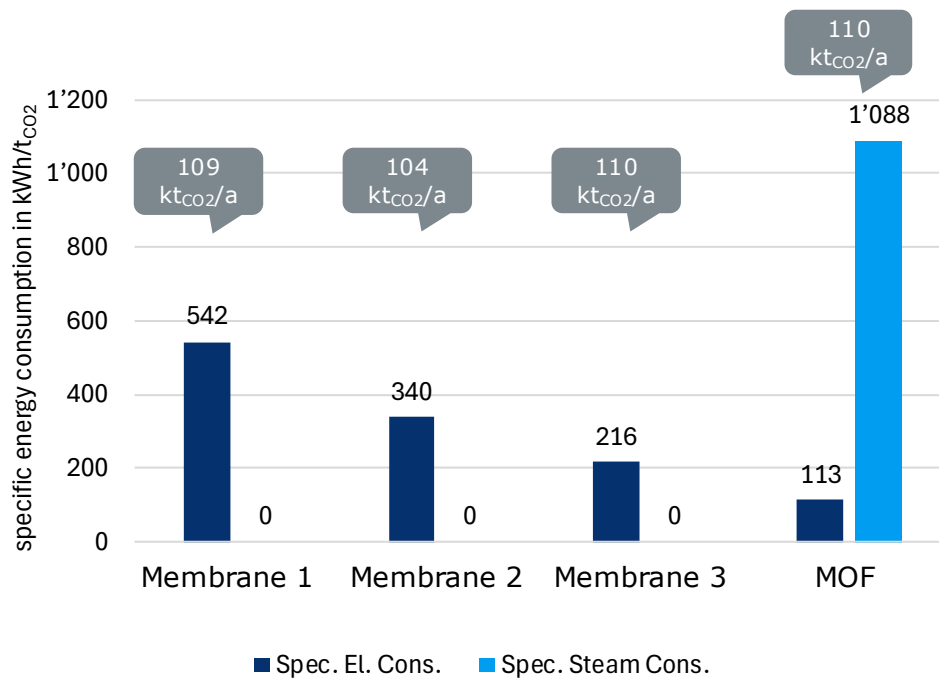


Figure 5: Specific energy consumption in kWh/t_{CO2} for the Core Process.

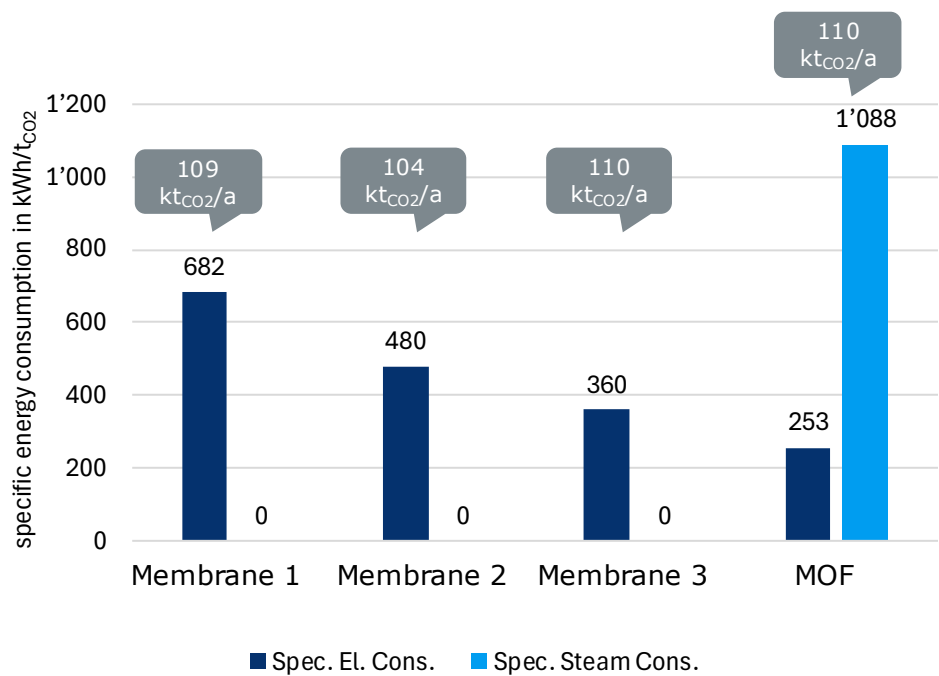


Figure 6: Specific energy consumption in kWh/t_{CO2} for the total process without cooling and heat pump.

6. Layout

6.1 Capture plant layout

The capture plant is modelled according to data from the respective suppliers for the base case of 100 kt_{CO2}/a, as in the scope of the feasibility studies only the design basis was considered. The defined Logistics cases (see next chapter) will also consider the other cases (up to 1'050 kt_{CO2}/a). The space requirements provided by the suppliers can be found in the following table.

It is noteworthy to mention that the suppliers designed the layout without specifications for space restrictions (green field) and space optimizations, e.g. with multiple storage buildings, are possible. The supplier Membrane 2 did not provide a 2D-layout, the space requirement can be assumed to be similar to the Membrane 1 and Membrane 3 space requirements. The Membrane 3 layout also included a liquefaction unit; therefore a slightly higher space requirement can be noticed.

Table 1: Space requirements of capture plant of different suppliers

Supplier	MOF	Membrane 3	Membrane 1
Space requirement	2'220 m ²	2'340 m ²	1'600 m ²

The supplier layouts from Membrane 3, Membrane 1 and MOF were translated to 3D models with assumptions from Ramboll regarding the heights, as no 3D models could be supplied by the suppliers within their feasibility study. For a more detailed 3D model, the supplier studies must be continued at a more detailed level.

6.2 Logistics layout

The logistics layouts are categorized according to the different scenarios and cases as laid out in the previous chapters (see chapter 4.1). Each location is defined by its allocated space (indicated by the grey areas in the following figures), which is ca. 31'200 m² for the Satom site, 13'900 m² for the Tamoil site and 3'300 m² for the CIMO site. For the Satom site, at the time of the report delivery, it is not clear if the entire space would be available for a CCS project. However the layout clearly shows that not the entire allocated space is required for CC and logistic process steps.

The CO₂ logistics for the respective scenarios have the need for the following components:

- Liquefaction (reaching the required product quality)
- (Redundant) Cooling of liquefaction (usually placed on roof of liquefaction building)
- Compression (for the compression into the ODR)
- Cooling of compression (usually placed on roof of compression building)
- Storage tanks (needed to buffer unsteady flows, holidays, maintenance breaks)
- Railway tracks and pumps (only applicable in railway scenarios)
- Pipes and connecting equipment (not considered at this stage of design)
- Reserved space (for additional use or unforeseen expansions, 20% of the above space)

Layout Scenario Satom

Scenario 1 - Satom
Case I - 100 kt

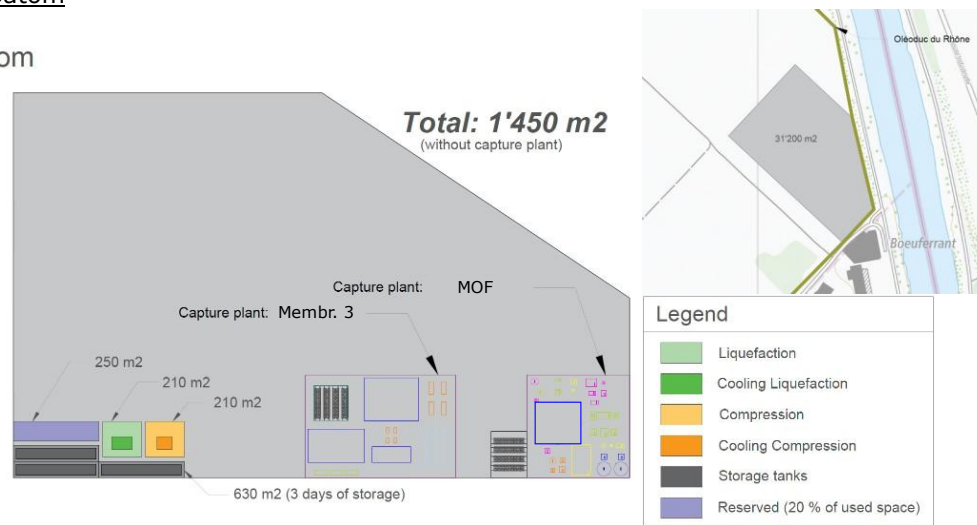


Figure 7: Satom site layout for 100 kt/a

The space requirements for the Satom scenario are easily fulfilled in the given area (grey area Figure 7), leaving plenty of space for other possible purposes in the future. The base case (100 kt_{CO2}/a) has two capture plant versions (Membrane 3 and MOF) pictured to show their respective space requirements, were even both fit in the allocated space. As mentioned, the capture plant is shown for the base case, a CC plant for a scaled-up case would need to be scaled accordingly. In the 2D layout of Satom three days of intermediate storage were considered. The storage tanks are placed as far away as possible from the Satom plant due to the risk of leakages (see chapter 8). The cooling for liquefaction and compression is placed on the rooftops of the respective buildings to minimize space requirements, the 3D models (Revizto) depict the rooftop cooling in more detail. The pipeline Scenario for the base case is depicted in the 3D model with a conservative intermediate storage capacity of five days.

Layout Scenario Tamoil Railway

Scenario 2 - Tamoil
Case I - 100 kt

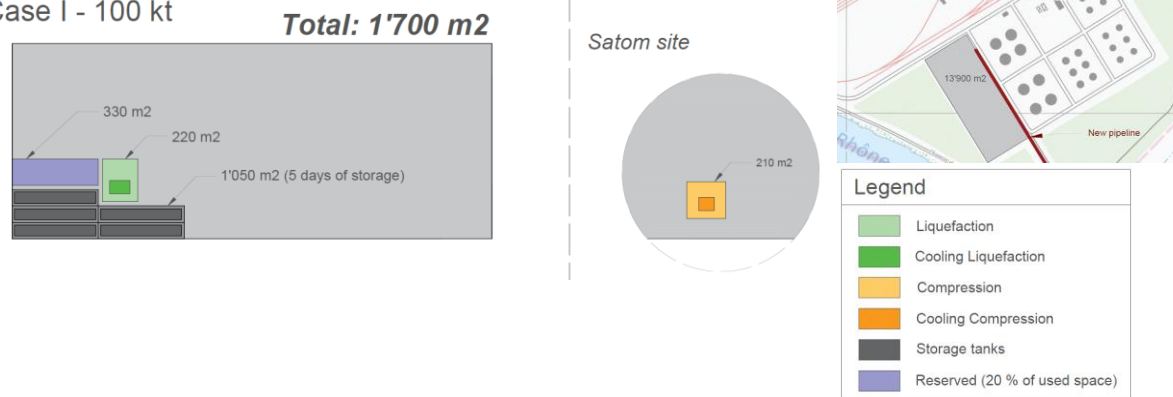


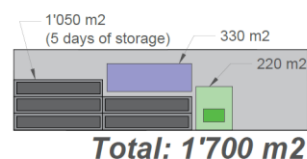
Figure 8: Tamoil site layout for 100 kt/a

The Tamoil 2D layout for the base case is shown in Figure 8. The compression for the gaseous transport is on-site at Satom and depicted in orange. In all cases included in the study for the layout (I, II, IV) the allocated space is sufficient for the liquefaction and intermediate storage for the railway transport at the Tamoil station. The tanks were chosen as lying tanks in the base case with a storage duration of 5 days due to the intermittent nature of the railway transport and boil-off from the liquefaction. The liquefaction is connected to the tanks via a pendulum line to reintroduce the gaseous boil-off of the tanks. From the liquid tanks a cryopump pumps the liquid CO₂ from the tanks to the eight train loading stations. Only the loading stations would have to be added as two railway tracks already exist.

A hub case at the Tamoil site would be beneficial due to the already existing railway infrastructure. A substantially bigger liquefaction and more storage tanks would be needed in this case, which should pose no problem given the large area available. It is not clear whether the accompanying railway logistics (shunting, etc.) of the turnover of ca. 5 trains à 30 wagons every day is possible to continuously maintain. Thus, a separate short study regarding railway logistics is advisable.

Layout Scenario CIMO Railway

Scenario 3a - CIMO Case I - 100 kt



Satom site

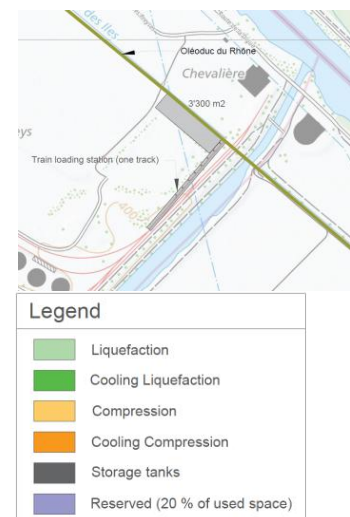
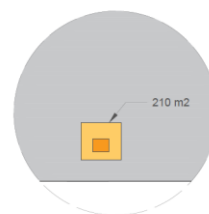


Figure 9: CIMO (railway) site layout for 100 kt/a

The CIMO 2D layout for the base case railway scenario is shown in Figure 9. The compression for the gaseous transport through the ODR to the CIMO site is depicted in orange. The gaseous CO₂ is liquefied at CIMO's site and stored. The intermediate storage tanks for 5 days of storage at CIMO were depicted as lying tanks for the base case scenario due to the abundant available space, in the other scenarios with higher CO₂ amounts vertical tanks had to be chosen to meet the space requirements of the CIMO location. In accordance with the Tamoil railway scenario, eight loading stations are foreseen for the available track. Although there are existing tracks bordering the area already, a new one would have to be built, because the current ones will still be in use for other purposes. Parallel loading is in this case not possible if no other train track is made available.

Shunting will be a lot more challenging at this site, because the other trains might use the available space down the rails already. Therefore, as with the Tamoil site, railway logistics need to be considered in detail, especially with large turnover numbers. With the assumption that 30 wagons can be shunted and loaded, the number of trains leaving the site are as follows: 1 train every 5 days for Case I (same as for Tamoil site), 1 train every 2 days for Case IV.

Layout CIMO pipeline

Scenario 3a - CIMO Case IV - 250 kt



Satom site

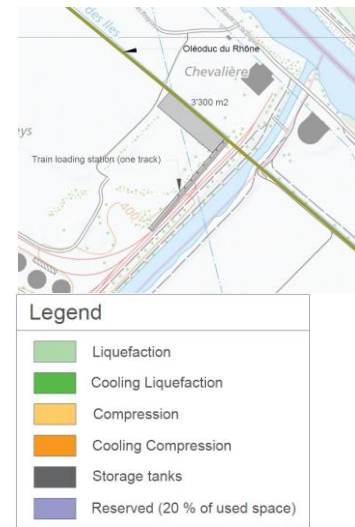
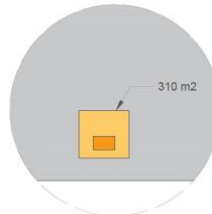


Figure 10: CIMO (pipeline) site layout for 250 kt/a

The layout for the pipeline scenario at CIMO was developed for case IV (250 kt_{CO2}/a), Figure 10, where the Satom full scale CO₂ amount (180 kt/a) and the captured CO₂ of the CIMO plant (70 kt_{CO2}/a) are transported via the ODR pipeline. A layout for the hub scenario V (1'050 kt_{CO2}/a) was developed as well. Analog to the CIMO railway scenario, the compression for the gaseous transport at Satom is depicted in orange. A buffer with vertical tanks was added to guarantee smooth injection into the ODR. Only a small intermedia space is considered, as pipeline has continuous transport and is not an intermittent mode of transport like the railway.

Like the Tamoil layout, the buffer tanks are located next to the liquefaction to reintroduce the tank boil-off to the liquefaction unit. The pipeline compression and injection for the gaseous downstream transport in the ODR are depicted in orange. For the CIMO pipeline scenario the case IV (250 kt_{CO2}/a) and V (1050 kt_{CO2}/a) are depicted as a 3D model, both are depicted with nine tanks.

Summary

Table 2 summarizes the overall space requirements for every scenario and case. The Storage tanks can be built either lying or standing. Standing tanks are more expensive and safety with regards to potential earthquakes would have to be closely checked. But in some cases (only applicable to CIMO site), lying tanks cannot be built due to space restrictions.

Table 2: Logistics space requirements by scenario/cases

Site (Scenario)	Amount of CO₂	Transport by	Comments	Space requirements
Satom	100 kt/a	Pipeline	-	1'450 m ²
	180 kt/a			2'250 m ²
Tamoil	100 kt/a	Two railway tracks	Compressor on Satom site to deliver CO ₂ via pipeline (ODR with extension)	1'700 m ²
	180 kt/a			2'900 m ²
	250 kt/a			3'800 m ²
CIMO (a)	100 kt/a	One railway track (to be built)	Compressor on Satom site to deliver CO ₂ via pipeline (ODR)	1'700 m ²
	180 kt/a			950 m ²
	250 kt/a			1'200 m ²
	1'050 kt/a			1'300 m ²
CIMO (b)	250 kt/a	Pipeline	Compressor on Satom site to deliver CO ₂ via pipeline	1'300 m ²
	1'050 kt/a			2'450 m ²

7. Economic feasibility

7.1 Investment costs

An Excel-based tool has been developed for transparent CAPEX cost calculation as Code des coûts de construction (Baukostenplan). The tool is designed so that multiple variants can be combined and compared. Future adjustments can be entered directly in the respective categories or process sections (see chapter 7.1.1). As not all scenarios and cases were included in scope of the CAPEX and OPEX calculations, three key scenarios were identified and agreed with the project team to focus on and analyzed for the base case I (100 kt_{CO2}/a) and scaled to case II (180 kt_{CO2}/a):

1. Scenario Satom Pipeline
2. Scenario Tamoil Railway
3. Scenario CIMO Railway

The supplier studies were conducted based on the 100 kt_{CO2}/a base case, which is then scaled for the Satom full scale 180 kt_{CO2}/a case. For the subsequent logistics the Satom pipeline scenario, the Tamoil railway scenario and the CIMO railway scenario were chosen for the CAPEX and OPEX calculations.

7.1.1 Methods CAPEX

The scope of the overall CAPEX estimation spans from the integration of flue gas systems up to the logistics interface, which includes the injection into the pipeline and loading of the railway wagons, but not the subsequent transport costs itself to the storage site and includes all works from ground preparation to commissioning. The CC core process data is based on the supplier studies. All cost breakdown categories other than the CC core process with data from the suppliers are based on Ramboll internal experience from projects of similar size and complexity. For the building works a similar complexity is assumed for all suppliers.

For the CAPEX CC core estimation several base assumptions were made. Cost estimations have been derived from quotations provided by suppliers for the CC core process. The total CC CAPEX estimations by the suppliers differed in scope (e.g. including the liquefaction, building costs, turnkey project, only equipment costs etc.). Therefore, comprehensive cost distribution was introduced for a standardization of the costs of the respective suppliers. The market maturity is notably lowest in Carbon Capture technology, where significant developmental progress is anticipated. The processes of compression and liquefaction were standardized across all suppliers, thereby ensuring uniformity in both interface and quality.

For the new pipeline part to Tamoil the new pipeline needs to be constructed, and the total costs were included for the applicable scenario. For the ODR it was assumed that the current pipeline owner will retain ownership, whilst Satom will modernize the pipeline and act as pipeline operator. The total CAPEX encompasses a wide range of expenses, including costs for acquiring the construction site, any necessary demolitions, financing, associated ancillary buildings, planning, as well as reserves of 3% and unforeseen expenses accounting for 15%.

The methodology and cost accuracy are therefore depending on the maturity of the project. This is in line with the Advancement of Cost Engineering (AACE) recommended practices. In the Satom project, the AACE class is defined as AACE level 4 (-30 to +50%). The (pre-) feasibility studies of the suppliers did not allow for a higher cost accuracy class and follow-up studies could allow for a higher cost accuracy class.

The overall CAPEX cost breakdown was divided into the following cost categories:

- Real estate (Land assessment studies, geotechnical reports, etc.)
- Preparation (Demolition etc.)
- Building costs (Excavation, Transport systems, cranes etc.)
- Operating facilities (Excavation, Transport systems, cranes etc.)
- Setting (e.g. landscaping, minor track constructions, etc.)
- Additional building costs (Permits, fees, Insurance etc.)
- **Process engineering (CC-core process (supplier studies), Flue gas integration, Compression, Logistics)**
- Facilities
- Planning fees
- Reserves (project changes, risk surcharge, construction reserves)
- Unforeseen events & miscellaneous

7.1.2 Results CAPEX

Summary

An overview of the total costs for the base case (100 kt_{CO2}/a) and the full-scale case (180 kt_{CO2}/a) can be found in the following tables.

Table 3: Overview CAPEX estimation Base case (100 kt_{CO2}/a)

Supplier	Unit	Satom pipeline scenario	Tamoil Railway scenario	CIMO Railway scenario
Membrane 1	Mio. CHF	101	120.1	109.6
Membrane 2	Mio. CHF	93.2	112.3	102.5
Membrane 3	Mio. CHF	115.5	134.6	125
MOF	Mio. CHF	166.6	185.7	174.2

Table 4: Overview CAPEX estimation Full-scale (180 kt_{CO2}/a)

Supplier	Unit	Satom pipeline scenario	Tamoil Railway scenario	CIMO Railway scenario
Membrane 1	Mio. CHF	143.7	164.8	152.6
Membrane 2	Mio. CHF	134.5	156.6	145.3
Membrane 3	Mio. CHF	162.2	184.3	173.4
MOF	Mio. CHF	233.2	255.2	241.7

The following graphs are focused on the category **Process Engineering**.

Satom Pipeline Scenario

The overall CAPEX for the Satom pipeline scenario with the base case (100 kt_{CO2}/a) range from 93.2 Mio. CHF to 166.6 Mio. CHF, depending on the supplier. The cost overview for the Satom pipeline scenario with the base case (100 kt_{CO2}/a) can be found in the following graph. The core Carbon capture process represents the highest costs of the process engineering CAPEX.

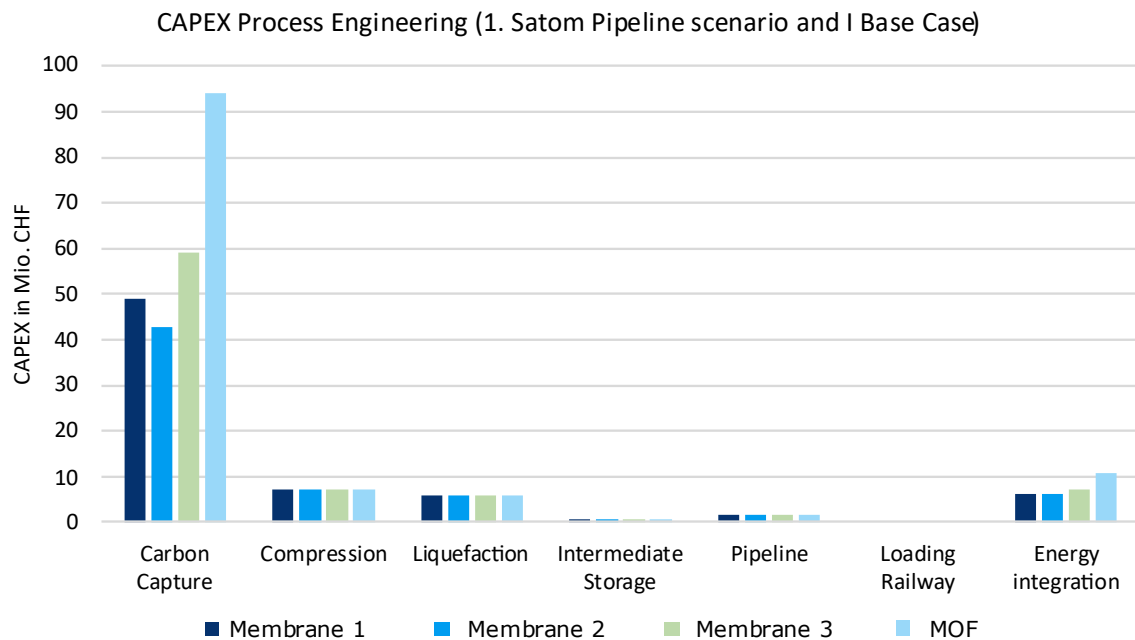


Figure 11: CAPEX process engineering cost breakdown Satom pipeline scenario base case

Tamoil Railway scenario

The overall CAPEX costs range from 112.3 Mio. CHF to 185.7 Mio. CHF. The CAPEX is increased in comparison to the first scenario in various cost categories e.g. additional process equipment (intermediate storage), railway loading costs as well as additional building and planning costs. The CAPEX process engineering breakdown is depicted in the following graph. The costs of the carbon capture core process and the compression on Satom's site remain unchanged compared to Scenario I.

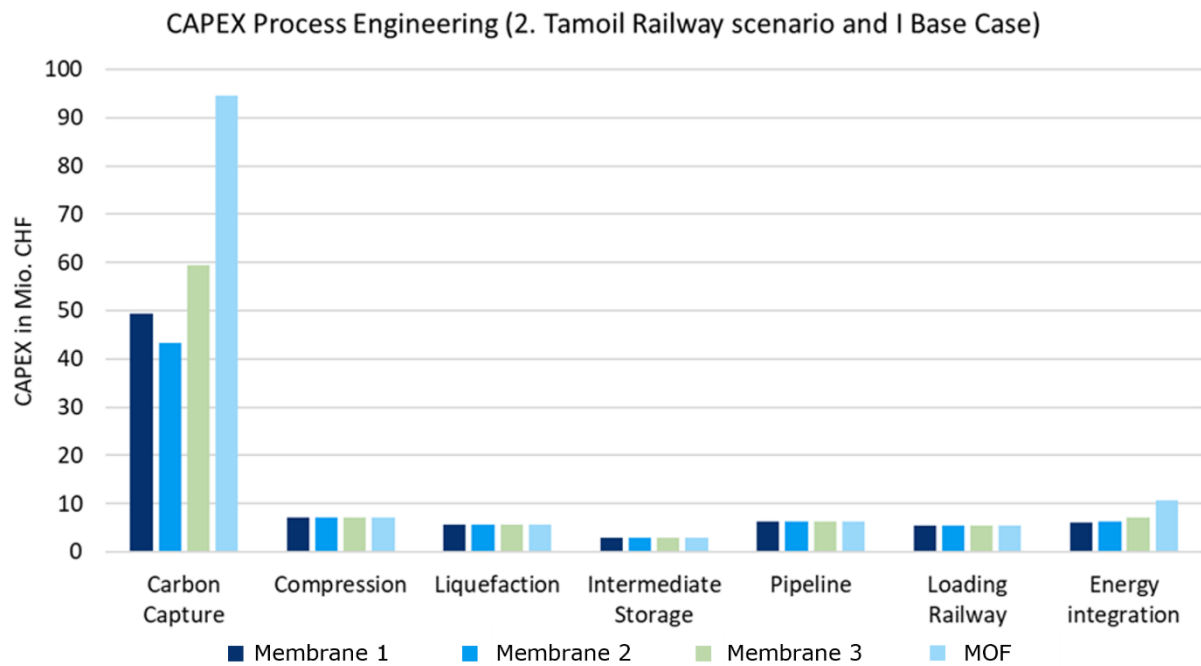


Figure 12: CAPEX process engineering cost breakdown Tamoil Railway scenario

CIMO Railway scenario

The CAPEX process engineering breakdown for the CIMO railway scenario is depicted in the following graph. In comparison to the Tamoil railway scenario, the pipeline costs are lowered since no new pipeline part must be constructed.

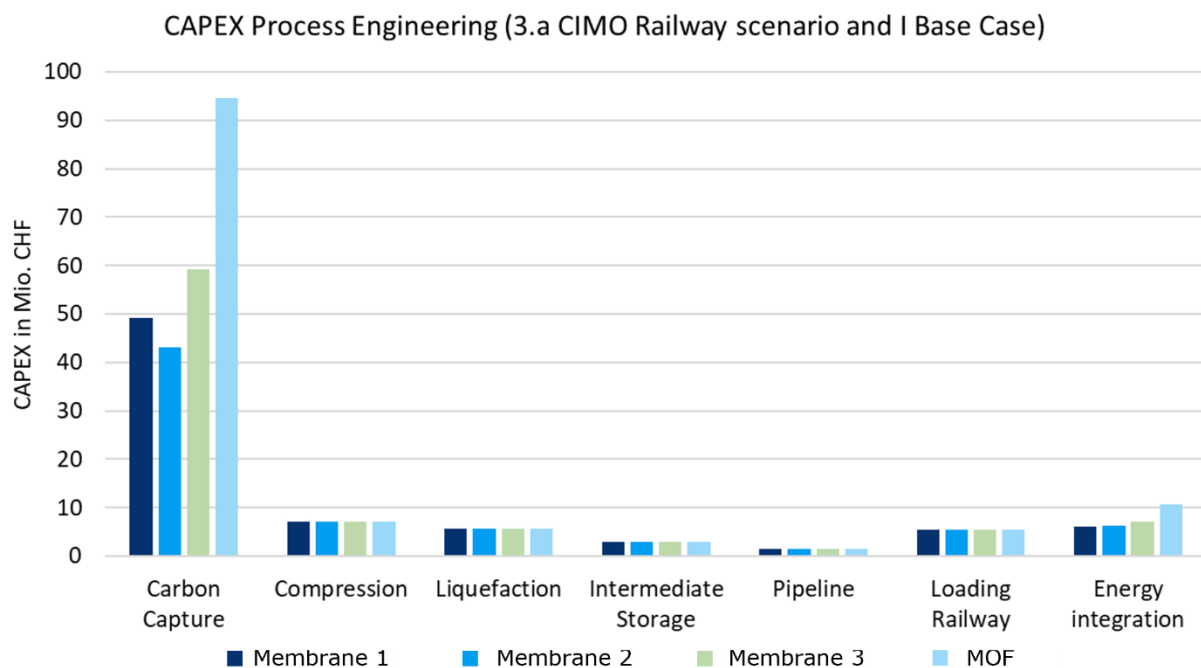


Figure 13: CAPEX process engineering cost breakdown CIMO Railway scenario

7.2 Operational costs

7.2.1 Methods OPEX

The calculation of Operational Expenditure (OPEX) is a crucial component for the cost estimation, serving as a guiding estimate for the ongoing operational costs of the facility. At this stage of project development, not all parameters can be determined with absolute precision, especially due to the INOSAT project taking place after the Carbon capture study. Consequently, the OPEX calculation is based on preliminary assumptions and estimates, providing a basis for an initial assessment of the expected operational costs. The OPEX was calculated depending on the scenario for the entire CC-process chain, including CC-core process, compression, liquefaction and logistics.

The maintenance costs were assumed as a fixed three percent of the CAPEX per process step. The capital service is assumed with a depreciation period of 20 an interest rate of 3% of CAPEX from the start of plant operation. For the CC-core process the wear parts include the membrane replacement costs, which were given in the supplier studies.

No opportunity costs were included in the OPEX calculation. The heat revenue is not included in the calculation and would provide additional incentives for the CC plant operation. Additionally, any economic benefits e.g. substitutions for CO₂ certificates were not included in the OPEX calculations.

7.2.2 Results OPEX

An overview of the CAPEX results for all scenarios can be found on the following table. The lowest OPEX costs are to be found in the Scenario I, Satom pipeline.

Table 5: OPEX costs overview for the base case (100 kt/a)

	Membrane 1	Membrane 2	Membrane 3	MOF
CO ₂ captured (kt/a)	109	104	110	110
Scenario I: Satom pipeline (Mio. CHF/a)	15.2	13.6	14.5	23.8
Scenario II: Tamoil railway (Mio. CHF/a)	17.8	16.2	17.1	26.4
Scenario III: CIMO railway (Mio. CHF/a)	17.2	15.6	16.5	25.8

8. Environment and safety

8.1 CO₂ hazard

At standard conditions (0 °C and 1 bar), CO₂ is an odorless, colorless, non-flammable gas. At elevated concentrations, CO₂ presents an asphyxiation hazard: approximately $\geq 5\%$ may cause narcotic effects, and approx. 8–10 % or higher can lead to loss of consciousness and death from suffocation within minutes. Because CO₂ is heavier than air, large releases can accumulate in low-lying or confined areas, displacing oxygen without immediate detection.

In the event of a sudden release of liquid CO₂ (typical storage conditions approx. –20 to –30 °C and 18–20 bar), rapid depressurization causes phase change and pronounced volume expansion, cooling the CO₂ and forming dry ice in the surroundings. Most credible scenarios involve leakage rather than catastrophic tank failure, leading to a gradual (though potentially hazardous) release.

Regulatory context Switzerland

Hazardous substances in Switzerland are governed by the Ordonnance sur les accidents majeurs (OPAM), which defines assessment criteria and procedures (reporting, measures, etc.) to protect the public and the environment. CO₂ is not currently listed as a hazardous substance under the quantitative thresholds of the 4th revision (2024), implying that storage may not automatically trigger the two-stage OPAM procedure. However, according to Article 1 paragraph 3 OPAM, authorities may subject installations, transport routes, or pipelines to the ordinance if their hazard potential could cause severe harm. Given the planned storage quantities, we recommend a proactive, incident-focused assessment to support public and regulatory engagement. All regulatory interpretations should be verified with the latest official OPAM publications.

8.2 Risk analysis

A comprehensive risk register was developed by identifying all risks that could affect the project, irrespective of their initial magnitude. Each risk was assigned a number and grouped into the categories technology, safety, environment, economy, management, and politics.

For each risk, the probability of occurrence was rated on a 1–5 scale (extremely low to extremely high). The potential impact was assessed on a 1–5 scale (marginal to extreme) using criteria across three dimensions: financial, reputation, and people/environment. An overall impact rating was derived from these criteria and combined with the probability rating to calculate an initial risk score (Probability $\times$ Impact).

Mitigation measures were defined for each risk, distinguishing between preventive actions that reduce likelihood and reactive actions that limit consequences. Following the assignment of these measures, residual probability and impact ratings were re-evaluated, and updated (post-mitigation) risk scores were calculated. Particular attention was given to risks with the potential to halt the project. The preventive and reactive mitigation ratings were visualized in the risk matrix (Figure 14).

The risk matrices are presented without mitigations (left) and with mitigations (right). Axes are probability (1–5) and impact (1–5). Each risk is labeled with its identifier. Green indicates low risks, yellow medium, and red high to extreme. The red-bordered zone constitutes a “no-go” area across project phases and contains potential project-stopper risks.

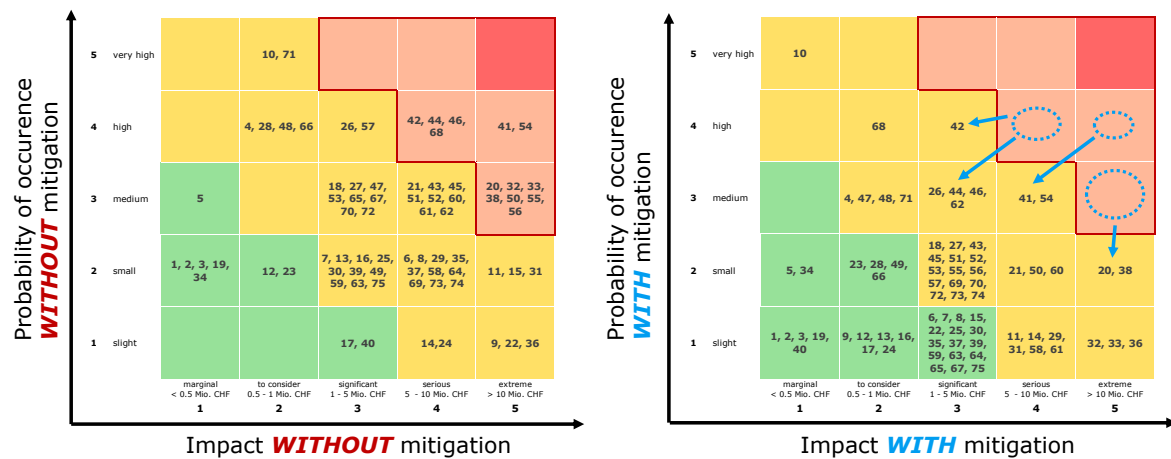


Figure 14: Risk matrixes without and with mitigation measures.

Table 6 summarizes the critical risks and corresponding mitigations. These lists are non-exhaustive and should be continued throughout all project phases. Every critical risk should be reduced to the yellow zone in the mitigated matrix. Based on the current analysis, no project shutdown risks remain provided the described mitigations are implemented. Ongoing risk management is essential as the project advances

Table 6: Critical risks and appropriate mitigation measures

Critical Risks	Mitigation Measures
Management & Planning	- Schedule gate reviews/freeze for individual systems and overall concept - Plan approval procedures with authorities at an early stage - Develop a robust financing concept - Early, mature planning to minimize uncertainty - Identify and highlight opportunities - Marketsounding; early and close contact with suppliers - Lot procedure to encourage competition - Monitor market situation - Conclude long-term contracts - Cluster/Hub approach (cooperation with other emitters) - Early involvement of logistics stakeholders
Financing	
Costs	
CO ₂ Price & Certificates	
Logistics	

9. Outlook

Financing security remains the central prerequisite for planning reliability; fast-track commissioning by end-2030 will not be achievable without timely financial commitments, while the mitigated-risk path depends on financing closure before the start of FEED.

The immediate priority is to advance the supplier studies to a more detailed level. This includes refining process design packages, completing gap lists for deliverables omitted from the (pre-) feasibility studies (for example, equipment lists, electrical consumer lists, detailed utilities balances, and preliminary control narratives), and confirming supplier-specific integration requirements at the Satom EfW plant. The scope of this follow-on work should be agreed within Pre-FEED/FEED planning early 2026, with clear milestones and acceptance criteria to secure schedule and cost accuracy improvements. In parallel, the project should narrow the scenario and site options to a single logistics concept and location. The decision should weigh the ODR pipeline realization and timing, the feasibility and operational complexity of railway logistics at Tamoil and CIMO, the potential for a hub configuration, and the political and permitting context.

For ODR, Satom should coordinate with the pipeline owner to confirm design basis assumptions (pressure, temperature, dehydration requirements), the integrity and maintenance status of relevant sections and any conditions precedent to repurposing. For railway, a focused operations study is needed at both Tamoil and CIMO to validate shunting, track availability, maneuvering space, parallel loading feasibility, and achievable loading rates within operational constraints.

Commercial preparations must keep pace with the technical plan. The project should establish the contracting strategy for FEED and EPC, prepare draft EPC frameworks, and initiate supplier down-selection consistent with the decision points set out in the roadmaps. Financing tasks should progress to term sheets and risk-allocation principles, including clarity on CAPEX/OPEX responsibility and any cost-recovery mechanisms in accordance with the VBSA financing discussions. Communications planning with the municipality and the public should be integrated with the permitting timeline to support a transparent dialogue on safety, environmental impacts, and community benefits.

If these actions are executed on schedule, the project can maintain optionality between the mitigated-risk path and the fast-track path. The fast-track variant requires accelerated financing by end-2026, early mobilization of resources, and disciplined parallelization of planning, permitting, and engineering. The mitigated-risk variant offers more delivery margin and broader de-risking but depends on timely decisions to avoid drift. In both cases, fast, well-documented decisions are essential to keep the project aligned with the 2030 objective and to position Satom and INOSAT as leaders in CCS deployment at EfW plants in Switzerland.

Technology Outlook and Sector Perspective on CCS

Energy from Waste Plants at the Intersection of Climate Policy and Waste Management

Greenhouse gas emissions from waste incineration are increasingly moving into focus, driven by Switzerland's ambitious climate strategy and rising requirements for the waste management sector. Energy from Waste (EfW) plants sit at the interface between waste management and climate policy. As the end point of the value and material flow chain, they release CO₂ emissions whose unavoidable fossil share can only be reduced to a limited extent. Carbon Capture and Storage (CCS) is one of the few options scalable within foreseeable technological development to technically mitigate the fossil share of CO₂ emissions, provided that capture and permanent storage are demonstrably achieved.

A Technology-Open CCS Approach and Site-Specific Implementation

Alongside the climate-policy framing and the question of the appropriate financing and governance architecture for scaling up CCS at EfW plants, the practical question of the most suitable technology for each individual site arises immediately. Given the diversity of boundary conditions, there is no one-size-fits-all CCS solution. Against this background, Ramboll AG carried out a CCS Outline Design project for the EfW plant in Monthey on behalf of Satom SA in 2025. The focus was placed on alternatives to the well-investigated and highly developed absorption processes based on amine scrubbing and Hot Potassium Carbonate (HPC). Particular attention was given to membrane-based CO₂ capture as a potential option for EfW plants. Ramboll supported the process from market sounding and the evaluation of technology-specific supplier studies through to integration into the site's process, energy and logistics concepts.

Technology Comparison: Amine, HPC and Membrane

Building on the supplier evaluations presented in the report, the following comparison places membrane and MOF technologies in the broader context of established absorption processes. In direct comparison, amine processes, pressure-driven processes such as HPC, and membrane processes are positioned differently for use at EfW plants. Amine processes are the most technologically mature (TRL 9) and have been proven at full commercial scale. HPC sits slightly below at TRL 8, among other reasons due to the lack of large-scale EfW references. Membrane processes generically reach TRL 7–8. However, for EfW-specific applications they are lower depending on supplier and design. They are therefore associated with higher technical and commercial risk, but offer considerable development potential.

In terms of plant layout, membrane processes can achieve a highly compact footprint for the capture unit itself thanks to their modularity and stackable, container-based construction. HPC processes tend to require the largest area and vertical space, among other reasons due to flue gas compression and expansion as well as large-diameter columns. Amine processes lie in between, with lower column heights compared to HPC. In constrained brownfield situations, this criterion can be an advantage for membrane processes.

In operation, membrane processes work without solvents and, thanks to their modular design, offer very good part-load capability. The entire process is electrically driven and requires no process steam, but has a correspondingly higher electricity demand. Operating costs strongly depend on local energy and waste-heat integration, and can be competitive with appropriate integration. HPC plants can, depending on the supplier, likewise be operated without steam from the EfW plant, but

nevertheless exhibit a high electricity demand. Due to the complex system of compressors and expanders, only limited part-load operation is possible. Amine processes offer good part-load flexibility and have the lowest electricity demand, but require substantial steam supply, which makes energy integration into EfW plants more complex.

With regard to regulatory and commercial aspects, several differences emerge. Membrane processes do not cause any additional solvent-related emissions, but they are sensitive to impurities such as dust, NO_x and SO_x. Amine processes require rigorous solvent and emission management, with strict control of amine slip and nitrosamines. HPC is regarded as uncritical in terms of additional emissions, provided no catalysts are used. However, its pressurised operation entails a risk of flue gas leakage. For stable operation, a high-performance flue gas treatment system at the EfW plant is advisable for all processes. This should reduce particulate and gaseous pollutants well below the applicable LRV (Swiss Clean Air Ordinance) limit values and reduce moisture content.

Absorption processes are the most broadly established, owing to their use in natural gas and biogas upgrading, in the chemical industry and at a small number of combustion plants. Several experienced suppliers are available on the market and are able to provide sufficiently accurate cost estimates. Membrane processes are also employed in natural gas and biogas upgrading, where they have so far been established primarily for less heterogeneous gas mixtures. For EfW plants they are therefore still associated with elevated commercial and operational risks. Demonstration plants exist, and individual suppliers can point to large-scale references, though so far none with a direct EfW context, which makes reliable cost estimation for construction and commissioning more difficult.

Outlook: Piloting, Hybrid Pathways and the Regulatory Framework

Although membrane technology is promising, it is not yet sufficiently proven in the EfW environment, whereas absorption processes are already being introduced in Switzerland.

Since completion of the Ramboll study in December 2025, several membrane suppliers have shown increasing market and project maturity. More robust data, increasingly specific design concepts and pilot plants in operation or under preparation improve the basis for targeted piloting under real EfW conditions.

A pilot project for membrane technology at a Swiss EfW plant should therefore be enabled and closely supported, in order to gain technical, economic and operational insights under real conditions and to specify regulatory requirements. A phased de-risking approach combining piloting with extended testing is recommended. Hybrid configurations, such as membrane-based early capture, i.e. an early partial capture stage with subsequent capacity extension, can open up practicable transitional pathways for large-scale projects. Under these conditions, membrane processes at EfW plants are a serious and promising alternative to amine and HPC processes. For all technologies, careful engineering with contractual safeguards for key performance parameters such as CO₂ capture rate, purity, energy consumption and plant availability is advisable.

The choice of process should nevertheless be made on a site-specific basis, taking into account space conditions, HSE requirements, energy integration (heat and power supply as well as opportunities for using waste heat in district heating supply), the supplier landscape and the project schedule. Membrane processes are particularly worth considering where space is restricted, where permitting is facilitated by solvent-free processes, and where modular scalability is required. In the overall layout, cross-technology units such as compression, liquefaction and logistics via pipeline or rail often dominate the area and height requirements. The advantage in overall footprint must therefore be assessed on a project-specific basis. This aspect applies across technologies and should be considered in the layout evaluation.

Finally, the financial and regulatory framework remains decisive. Sector-wide, earmarked financing enables technology-open decisions and the timely implementation of concrete projects with clear performance targets. This requires a clear legal mandate at federal level that enables sector-wide earmarked contributions for the scale-up of CCS at EfW plants and permits their pass-through to gate fees. Initial full-scale CO₂ capture plants should serve as learning and scaling steps in order to establish a robust basis for subsequent broad implementation.

If a viable legal basis is established without delay, the scale-up of CCS can proceed in three steps: piloting to reduce risk, realisation of a first full-scale plant, and subsequent scaling to further sites. In this way, the main learning phase could be completed by around the mid-2030s. Enabling the start now while at the same time establishing the preconditions for broad implementation is the most pragmatic and effective option.