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PICC

Process Integrated Carbon Capture – Design and Evaluation



KVA Linth



HHKW Galgenen



KSV Werdhölzli



HSLU Hochschule
Luzern

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Hochschule Luzern – Technik & Architektur
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ETH Zürich

Sonneggstrasse 28, 8006 Zürich
www.ethz.ch/de.html

Authors:

Dr. Benjamin Ong, HSLU, benjamin.ong@hslu.ch
Dario Allgäuer, HSLU, dario.allgaeuer@hslu.ch
Jonas Grand, HSLU, jonas.grand@hslu.ch
Dr. Gianfranco Guidati, ETH gguidati@ethz.ch
Prof. Dr. Beat Wellig, HSLU, beat.wellig@hslu.ch

SFOE project coordinators:

Sandra Hermle, sandra.hermle@bfe.admin.ch
Andreas Haselbacher, andreas.haselbacher@bfe.admin.ch
Elena-Lavinia Niederhäuser, elena-lavinia.niederhaeuser@bfe.admin.ch

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Summary

To achieve the policy objective of net-zero carbon emissions, deep decarbonization is essential across all sectors. Carbon capture, utilization, and storage technologies are critical in supporting Switzerland's goal of achieving net-zero carbon emissions by 2050. The Process Integrated Carbon Capture – Design and Evaluation (PICC) project presents a comprehensive methodology for integrating CO₂ capture plants into industrial processes, demonstrated across three distinct industrial settings in Switzerland: KVA Linth (waste incineration plant), KSV Werdhölzli (sewage sludge incineration plant) and HHKW Galgenen (wood-fired power plant). The primary aim is to design integrated systems that enhance energy efficiency, optimise heat recovery, and reduce CO₂ emissions, thereby supporting Switzerland's net-zero targets.

The project investigates how integrating CO₂ capture plants with various industrial point sources influence the energy efficiency and techno-economic performance of the integrated designs. The approach combines process simulation, Pinch Analysis, and system performance analysis through piece-wise steady-state simulations:

Process Simulation: Using CHEMCAD, the CO₂ capture plant was modelled to simulate steady-state operation and identify process requirements and energy requirements.

Pinch Analysis: PinCH software facilitated the design of heat exchanger networks (HEN), optimising the integration of CO₂ capture plant with existing plant systems to maximise heat recovery and minimise additional energy consumption.

System Analysis: Modelica was employed for piecewise steady-state analysis, assessing the integrated systems' performance over the year, accounting for seasonal variations.

The findings indicate that integrating CO₂ capture plants with existing industrial processes enhances overall energy efficiency compared to stand-alone systems, primarily by utilising waste heat from the capture process and aligning with the lower temperature heating demands of industrial operations and their district heating networks. Heat pumps emerged as essential components in balancing thermal demands, optimising system performance, and reducing reliance on peak load boilers and external heat supplies. This led to lower fuel consumption and emissions, effectively offsetting the trade-offs associated with reduced electricity sales. However, major barriers to CO₂ capture integration remain, particularly the limited operational data on the capital-intensive capture technologies and the sensitivity of economic feasibility to electricity market dynamics. In systems where heat pumps are used, the electricity purchase and sale prices directly influence operating costs and revenue streams. Consequently, the economic viability of integration concepts is highly dependent on site-specific factors, such as energy prices and the availability of waste heat, underscoring the importance of tailored integration strategies to ensure cost-effective emissions reductions.



Zusammenfassung

Um das politische Ziel der Netto-Null-CO₂-Emissionen zu erreichen, ist eine tiefgreifende Dekarbonisierung in allen Sektoren unerlässlich. Technologien zur CO₂-Abscheidung, -Nutzung und -Speicherung sind entscheidend, um das Netto-Null-Ziel der Schweiz bis 2050 zu erreichen. Das Projekt „Process Integrated Carbon Capture – Design and Evaluation“ (PICC) stellt eine umfassende Methodik zur Integration von CO₂-Abscheidungsanlagen in industrielle Prozesse vor, die in drei unterschiedlichen industriellen Fallstudien in der Schweiz demonstriert wurde: KVA Linth (Kehrichtverbrennungsanlage), KSV Werdhölzli (Klärschlammverwertungsanlage) und HHKW Galgenen (Holzheizkraftwerk). Das Hauptziel besteht darin, integrierte Systeme zu entwerfen, welche die Energieeffizienz verbessern, die Wärmerückgewinnung optimieren und die CO₂-Emissionen reduzieren, um so das Netto-Null-Ziel zu unterstützen.

Das Projekt untersucht, wie die Integration von CO₂-Abscheidungsanlagen mit verschiedenen industriellen Punktquellen die Energieeffizienz und die Wirtschaftlichkeit der Systeme beeinflusst. Der Ansatz kombiniert Prozesssimulation, Pinch-Analyse und Systemsimulationen:

Prozesssimulation: Mit CHEMCAD wurde die CO₂-Abscheidungsanlage modelliert, um den stationären Betrieb zu simulieren und die Prozess- und Energieanforderungen zu ermitteln.

Pinch-Analyse: Mit der PinCH-Software wurden Wärmetauscher-Netzwerke (HEN) entworfen, um die Integration der CO₂-Abscheidungsanlage in bestehende Anlagen zu optimieren, die Wärmerückgewinnung zu maximieren und den zusätzlichen Energieverbrauch zu minimieren.

Systemanalyse: Modelica wurde für schrittweise stationären Analysen eingesetzt, um das Verhalten der integrierten Systeme über das Jahr hinweg zu bewerten und saisonale Schwankungen zu berücksichtigen.

Die Ergebnisse zeigen, dass die Integration von CO₂-Abscheidungsanlagen in bestehende industrielle Prozesse ein besseres Energieeinsparungspotential bietet als eigenständige CO₂-Abscheidungsanlagen. Dies ist hauptsächlich auf die Nutzung von Abwärme aus der CO₂-Abscheidungsanlage und den niedrigeren Temperaturanforderungen der industriellen Prozesse sowie ihrer integrierten Fernwärmenetze zurückzuführen. Wärmepumpen erwiesen sich dabei als entscheidende Komponenten zur Deckung des thermischen Energiebedarfs, zur Optimierung der Systemleistung und zur Verringerung der Abhängigkeit von Spitzenlastkesseln und externen Wärmequellen. Die Integration von Wärmepumpen führte zu einem geringeren Brennstoffverbrauch und niedrigeren Emissionen, wodurch die Nachteile durch reduzierte Stromverkäufe effektiv kompensiert wurden. Dennoch bestehen weiterhin erhebliche Hürden bei der Integration von CO₂-Abscheidungsanlagen, insbesondere aufgrund begrenzter Betriebsdaten zu den kapitalintensiven Abscheidetechnologien und der hohen Sensitivität der wirtschaftlichen Tragfähigkeit gegenüber Entwicklungen am Strommarkt. In Systemen mit Wärmepumpen beeinflussen Stromkauf- und -verkaufspreise direkt die Betriebskosten und Einkommensströme. Die wirtschaftliche Tragfähigkeit von Integrationskonzepten hängt daher stark von standortspezifischen Faktoren wie Energiepreisen und der Verfügbarkeit von Abwärme ab, was die Bedeutung maßgeschneiderter Integrationsstrategien zur kosteneffizienten Emissionsminderung unterstreicht.



Résumé

Pour atteindre l'objectif politique de zéro émission nette de gaz à effet de serre, une décarbonisation profonde est essentielle dans tous les secteurs. Les technologies de capture, d'utilisation et de stockage du carbone sont cruciales pour soutenir l'objectif de la Suisse d'atteindre zéro émission nette de gaz à effet de serre d'ici 2050. Le projet « Process Integrated Carbon Capture – Design and Evaluation » (PICC) présente une méthodologie complète pour l'intégration des installations de capture de CO₂ dans les processus industriels, démontrée dans trois environnements industriels distincts en Suisse : KVA Linth (usine d'incinération des déchets), KSV Werdhölzli (usine d'incinération des boues d'épuration) et HHKW Galgenen (centrale à bois). L'objectif principal est de concevoir des systèmes intégrés qui améliorent l'efficacité énergétique, optimisent la récupération de chaleur et réduisent les émissions de CO₂, soutenant ainsi les objectifs de zéro émission nette de la Suisse.

Le projet examine comment l'intégration des processus de capture de CO₂ avec diverses sources ponctuelles industrielles influence l'efficacité énergétique et les performances technico-économiques des conceptions intégrées. L'approche combine la simulation de processus, l'analyse Pinch et l'analyse de la performance du système via des simulations.

Simulation de processus : En utilisant CHEMCAD, le processus de capture de CO₂ a été modélisé pour simuler le fonctionnement en régime permanent et identifier les exigences en matière de processus ainsi que les besoins énergétiques.

Analyse Pinch : Le logiciel PinCH a facilité la conception des réseaux d'échangeurs de chaleur, optimisant l'intégration des processus de capture de CO₂ dans les installations existantes. Cela a permis de maximiser la récupération de chaleur et de minimiser la consommation énergétique.

Analyse du système : Modelica a été utilisé pour des analyses stationnaires par morceaux, évaluant la performance des systèmes intégrés sur l'année, en tenant compte des variations saisonnières.

Les résultats indiquent que l'intégration des installations de capture de CO₂ avec les processus industriels existants offre un meilleur potentiel d'efficacité énergétique que les systèmes de capture de CO₂ autonomes. Ceci est principalement dû à l'utilisation de la chaleur perdue lors du processus de capture de CO₂ et aux exigences de chauffage à basse température des processus industriels et de leurs réseaux de chauffage urbain intégrés. Les pompes à chaleur se sont révélées être des composants clés pour couvrir les besoins en énergie thermique, optimiser les performances du système et réduire la dépendance aux chaudières de pointe ainsi qu'aux sources de chaleur externes. L'intégration de pompes à chaleur a permis de réduire la consommation de combustible et les émissions, compensant ainsi efficacement les inconvénients liés à la baisse des ventes d'électricité.

Cependant, l'intégration d'installations de captage du CO₂ reste confrontée à des obstacles majeurs, notamment en raison du manque de données opérationnelles sur ces technologies coûteuses et de la forte sensibilité de leur viabilité économique face aux évolutions du marché de l'électricité. Dans les systèmes équipés de pompes à chaleur, les prix d'achat et de vente de l'électricité influencent directement les coûts d'exploitation et les flux de revenus. La viabilité économique de l'intégration de la capture de CO₂ dépend fortement des conditions spécifiques au site, comme les prix de l'énergie et la disponibilité de la chaleur résiduelle, soulignant la nécessité de stratégies personnalisées pour atteindre des réductions d'émissions efficaces.



Main findings («Take-Home Messages»)

- Integrated CO₂ Capture Enhances Energy Efficiency: The integration of CO₂ capture with existing industrial processes improves overall energy efficiency through optimised heat recovery, aligning with Swiss energy goals to maximise resource use and reduce overall emissions.
- Heat Pumps as Key Solutions: Proper integration of heat pumps in the integrated systems effectively, using Pinch Analysis, balances heat demands and reduces dependence on external utilities.
- Economic Viability Depends on Site-Specific Conditions: The economic success of CO₂ capture integration varies by site, influenced by factors such as energy prices and waste heat availability, highlighting the importance of customised strategies to achieve cost-effective emissions reductions.
- Energy System Modelling: While the benefits of integrating heat pumps in CO₂ capture processes are scenario-dependent, the findings underscore the value of pursuing innovative technologies alongside comprehensive energy planning to maximise resource utilization and support sustainable energy transitions.



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List of abbreviations

AHP	Absorption heat pump
AIC	Absorber intercooler
CCs	Composite curves
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CED	Conceptual engineering design
CHP	Combined heat and power
CU	Cold utility
DAC	Direct air capture
DH	District heating
DHW	Domestic hot water
EEM	Energy efficiency measure



GCC	Grand Composite Curve
GTP	Biogas Treatment Plant
HEN	Heat exchanger network
HEX	Heat exchanger
HU	Hot utility
HHKW	Holzheizkraftwerk/Wood-fired power plant
HP	Heat pump
HR	Heat recovery
IC	Integration concept
KSV	Klärschlammverwertungsanlage/Sewage sludge incineration plant
KVA	Kehrichtverbrennungsanlage/Waste incineration plant
LCA	Life-cycle assessment
MEA	Monoethanolamine
MVR	Mechanical vapor recompression
PA	Pinch Analysis
PICC	Process Integrated Carbon Capture
PI	Process Integration
P2X	Power-to-X
RSS	Rich stream split
SAF	Sustainable aviation fuel
SES-ETH	Swiss Energyscope
TIC	Total installed cost
WP	Work package
WWTP	Wastewater treatment plant
SFOE	Swiss Federal Office of Energy



1 Introduction

1.1. Context and motivation

Under the Paris Agreement, Switzerland has committed to reducing its emissions by 50% by 2030 compared to 1990 levels. In addition, the Federal Council decided in 2019 that Switzerland should reduce its greenhouse gases to net zero by 2050. In order to be able to achieve these ambitious goals, a strategy was elaborated (2023). Among other things, this strategy describes the objective regarding negative emissions as follows: “Objective 2050: Switzerland’s greenhouse gas emissions that continue to occur in 2050 and are technically difficult to avoid will be completely offset with biological and technical sinks by permanently, safely and sustainably removing CO₂ from the atmosphere and storing it (negative emissions)”. Carbon capture and storage (CCS) technologies are considered in the area of technological sinks and can play a crucial role to meet the Swiss goal of net-zero greenhouse-gas emissions by 2050. Decarbonization of the industry sector is challenging due to the high complexity of the industrial systems and its heterogeneity. In addition, the process emissions resulting from chemical or physical reactions are hard to abate. With the recent Swiss electorate vote for the Climate and Innovation act, greenhouse gas emissions in Switzerland are to be reduced to net zero by 2050. The Confederation intends to approve 3.2 billion CHF in financial aid within the framework of the law, a large part of which is to flow into climate-neutral innovations. Around 1.2 billion CHF will be distributed to private-sector companies to reduce CO₂ emissions. This secures the companies’ financial assistance annually for the application of innovative, climate-friendly technologies, and processes. These include, for example, high-temperature heat pumps (HPs), but also technologies to remove CO₂.

The first concept of CO₂ capture, transport and storage for the reduction of anthropogenic CO₂ emissions was presented by Marchetti (1977). CCS encompasses the process of separating CO₂ from sources tied to industrial and energy activities, followed by the secure storage of concentrated CO₂ in designated locations, which can be onshore, offshore geological formations, or ocean storage (Pachauri et al., 2007). The first international demonstration project was the Sleipner CCS project, which started in 1996. In this project, CO₂ separated during natural gas cleaning is captured and injected into deep saline aquifers for storage and emission reduction. At the end of 2020, more than 19 million tons of CO₂ have been captured and stored since 1996 (Equinor, 2024). Researchers have pioneered an array of CCS methodologies, including amine scrubbing (Rao & Rubin, 2002), solid adsorbents (Lee et al., 2006), membrane technologies (Eisaman et al., 2011), ionic liquids (Bara et al., 2010), and the calcium looping cycle (MacKenzie et al., 2007). Monoethanolamine (MEA) represents a frequently employed amine absorber in this context. Initially, MEA absorbs carbon dioxide (CO₂) from flue gas or combustion gas, leading to the formation of carbonate and bicarbonate adducts within the absorption tower (absorber), operating at relatively low temperatures ranging from 40 to 80°C. Subsequently, the MEA-loaded mixture is directed to a stripping tower (stripper). Within the stripper, operating at higher temperatures typically between 100 and 120°C. Rochelle (2009) estimated that the energy required to capture CO₂ from a conventional coal plant ranges from 20 to 40% of the plant output. Typical values for a 90% CO₂ capture and a mass fraction of 30% MEA in the scrubber are 1.03 – 1.11 MWh/t CO₂ (Knudsen et al., 2009a), (Pasini et al., 2011). Therefore, improving the energy efficiency of the CO₂ capture plants is essential.

Process optimizations at plant level are typically involve measures such as the Absorber Intercooler (AIC), Rich Stream Split (RSS), which modify solvent flow and heat management strategies within the absorption process. Additionally, equipment-based technologies like Mechanical Vapor Recompression (MVR) can be implemented to enhance energy efficiency by reducing thermal reboiler demand. The AIC reduces the temperature within the absorber column by cooling the solvent between stages, thereby enhancing the CO₂ absorption technology. This process modification improves the driving force for CO₂ absorption, which translates into lower overall energy consumption for solvent regeneration. Based on the results presented in Cousins et al. (2011), implementing AIC can lead to a reduction in specific energy consumption by about 6.4%. In the process optimization RSS, the CO₂-rich solvent is split before it is heated and fed to the desorber. Based on the results presented in (Cousins et al., 2012), the



maximum savings are achieved when approximately 30% of the CO₂-rich solvent by-passes the heat exchanger, reducing the specific energy demand for CO₂ capture by approximately 7.1%. In the work from Li et al. (2016), the above-mentioned process optimizations AIC, RSS, and additionally the inter-heating process, in which a decoupling of the semi-poor solvent is decoupled in the desorber and pre-heated by the hot lean solvent exiting the desorber. Savings in thermal energy consumption achieved by the AIC amount to 0.6-1.8% with a simultaneous reduction of the absorber column height by 25%. The process optimization RSS as well as the inter-heating process allow a saving of 8.5% in terms of specific thermal energy demand per ton of CO₂ captured. If all three optimizations are combined, the savings are 13.6% (Li et al., 2016). In this work, the separated optimization of the CO₂ capture process is considered and it is shown how this process can be designed more efficient. The process optimizations AIC and RSS are also integrated and recommended by plant producers (Sulzer, 2022).

Also, the control of the plant in partial load operation can be relevant. In the work of Flø et al. (2016), different flexible modes of operation of the CO₂ capture plant are considered by a dynamic simulation tool. The control strategies for solvent storage, exhaust gas venting, and variable solvent regeneration are compared. It is shown that exhaust gas venting achieves 89.5 % average CO₂ capture efficiencies and energy efficiency values (1.025 MWh/t) at low investment costs (Flø et al., 2016). The flexible operation of CO₂ capture plants has been primarily investigated through studies analysing how these plants behave under transient operating conditions using dynamic simulation models (Montañés et al., 2018), using a demonstration plant at the Technology Center Mongstad. For example, the transient response of important process variables to changes in volumetric gas mass flow, solvent mass flow and reboiler capacity were tested. In general, the process stabilises within 1 hour for 20% changes in process inputs. Tests of rapid load changes (10%/min) of the flue gas mass flow showed that decentralised control structures could be employed in order to bring the process to desired off-design steady-state operating conditions within (< 60 min) (Montañés et al., 2018). Another way to optimize the capture process is to integrate the carbon capture plant into an existing process. Typical processes in which a CO₂ capture plant can be integrated are waste incineration plants, wood-fired power plants, or cement plants (Hauge et al., 2022). For this purpose, CO₂ capture by amine scrubbing (MEA) and the chilled ammonia process were investigated in Sävenäs KVA plant. The calculations showed that the efficiency of the plant is improved by 32% by integrating the amine scrubbing process (Andersson, 2020). A large energy recovery can be achieved by integrating a heat pump into the separation process. This reduces the efficiency loss to 12%.

To address the high energy demand and integration challenges of CO₂ capture plants in existing industrial sites, this project focuses on developing tailored integration strategies that optimise energy efficiency and system performance. Given that most industrial processes have complex thermal interactions and site-specific constraints, it is essential to go beyond standard process simulations and employ systematic integration methodologies. Process Integration (PI), and specifically Pinch Analysis (PA), provide a structured framework to analyse energy flows, identify heat recovery potentials, and design efficient heat exchanger networks and integration strategies. By combining PI and PA with detailed process simulation, the project aims to minimise the additional energy requirements of CO₂ capture and ensure that the integration into existing industrial systems is both technically and economically viable. In the past, PA has been used over the years to reduce the energy penalty of integrating CCS with a power generation plant by up to 50 % (Harkin et al., 2010). To reduce the energy penalty of integrating CCS to a thermal power plant, PA was conducted to optimise the process and to integrate a heat recovery steam generation unit (Valiani et al., 2017). A heat integration study was conducted on a steam methane reforming plant to reduce external energy requirements when integrated with a CCS (Limpach et al., 2023). However, the work on PA conducted on CCS is usually representation of a single period. This may be due to the limited information which leads to inadequate understanding of the integration effects on the existing system performance. Eliasson et al. (2022) used five different heat load curves to represent the excess heat availability in various seasons to investigate the relation between integrating a CCS to an energy system. The excess heat utilization is either for CCS or a district heating (DH) network. If the heat supply to the DH network is not prioritised, the specific capture cost for using the excess heat for CCS is reduced.



1.2. Project objectives

Achieving Switzerland's net-zero target requires capturing CO₂ emissions from large point sources, such as flue gas from industrial processes, and either utilising or storing the captured CO₂ permanently. While renewable sources like solar, HPs, and geothermal energy can cover many low- to medium-temperature heating demands, certain industrial processes require high-temperature heat levels that are difficult to supply without combustion. In these cases, fossil fuels will necessitate CO₂ capture and storage to mitigate emissions, while biogenic fuels (e.g., wood, waste) offer opportunities for negative emissions when their CO₂ is captured and stored. Switzerland's waste-to-energy and wood-fired combined heat and power (CHP) plants are key examples where such integration can be impactful. Figure 1 on the categorises Switzerland's most significant CO₂ point sources. Since there are different categories of CO₂ point sources, this project focuses on three types of CO₂ sources: a sewage sludge incineration plant (KSV), a wood-fired power plant (HHKW) and a waste incineration plant (KVA).

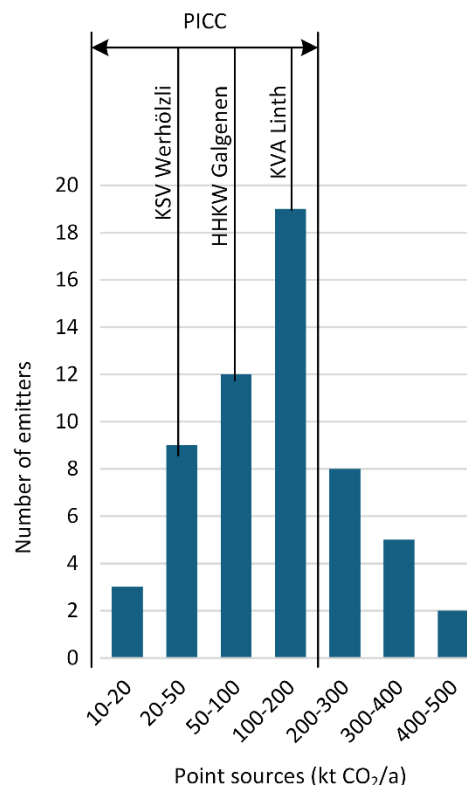


Figure 1: Size of point sources for PICC.

The primary objective of the PICC project is to develop guidelines for designing, integrating, and optimising CCS within existing industrial processes, ensuring both technical feasibility and energy efficiency. This is achieved through a combination of process simulation and PI techniques, to minimise additional energy consumption and reduce operational impacts. Two main challenges complicate the deployment of CCS systems: (1) the absence of a comprehensive CO₂ transport and storage infrastructure in Switzerland, which limits the feasibility of large-scale deployment, and (2) the significant additional high temperature energy demand, both thermal and electrical, required for CO₂ capture operations. Absorption-based CO₂ capture processes are particularly heat-intensive, with typical desorber reboiler temperatures ranging between 110 °C and 130 °C (Duss, 2022), leading to competition for heat resources within industrial plants and district heating networks. Additionally, the use of HPs or other energy recovery systems increases site electricity demand, impacting the overall energy balance and economic viability. Therefore, integrating CCS effectively into existing industrial infrastructures requires careful design to balance these energy flows and infrastructure limitations.



1.3. Procedure

To achieve the objectives of this project, the procedure is structured into eight work packages (WP):

- WP1 Definition of project variabilities
- WP2 Characterization of case studies
- WP3 Design and process simulation of the CO₂ capture plant
- WP4 Process Integration
- WP5 Techno-economic analysis of designs
- WP6 P2X evaluation
- WP7 Energy system modelling
- WP8 Report and recommendations

WP1 and WP2 involve establishing a robust data foundation to facilitate the design of CO₂ capture plants. The focus is on characterising the three industrial processes (KSV, HHKW, and KVA) with which the CO₂ capture plants will be integrated. By examining different types and sizes of point sources and their associated systems, the project aims to generalise the findings to other potential point sources. This phase includes creating simplified process flow diagrams, extracting process data, determining flue gas mass flows and composition and defining scenario for analysis. These data form the foundation for subsequent work packages.

WP3 involves designing and modelling the CO₂ capture process using CHEMCAD. This design phase is supplemented with various process optimizations to evaluate their impact on the system. Given the energy-intensive nature of the CO₂ capture process, which operates at high temperatures and pressures, WP4 focuses on integrating the CO₂ capture plant with existing industrial processes using Pinch Analysis. The goal is to maximise heat recovery and minimise the thermal and electrical impacts on the existing systems. The integrated system's behaviour is analysed throughout the year using Modelica, ensuring efficient operation under varying conditions. WP5 conducts a techno-economic analysis to assess the economic feasibility of the CO₂ capture process under the industrial processes' scenarios.

WP6 explores the potential integration of Power-to-X (P2X) technologies (such as Power-to-Hydrogen, Power-to-Methane, and Power-to-Methanol) into the industrial systems. This includes analysing the heat and mass integration possibilities of P2X processes, as well as evaluating their capital and operational costs to identify the most suitable technology pathways for enhancing system performance and CO₂ utilization.

WP7 assesses the broader impact of integrating CO₂ capture plants on Switzerland's energy system. This is achieved by modelling these effects using the Swiss Energyscope (SES-ETH) tool, originally developed at EPFL and later extended at ETHZ within the SWEET CROSS project. Results from WP3 and WP4 are used to refine the representation of CCS in SES-ETH, allowing the computation of net-zero scenarios. The model evaluates the influence of innovative features, such as heat pump integration, on system-wide energy efficiency, resource utilization, and CO₂ reduction pathways.

The integration of CO₂ capture plants at major Swiss CO₂ point sources requires significant thermal and electrical demands, which in turn impact the broader Swiss energy system. WP7 addresses this by modelling these effects using the Swiss Energyscope (SES-ETH) tool, originally developed at EPFL (Moret, 2017) and later extended at ETHZ. The representation of CO₂ capture plants in SES-ETH is refined using results from WP3 and WP4 and net-zero scenarios are computed to highlight the benefits of innovative features, such as the integration of heat pumps (Energy Center of EPFL, 2023).

WP8 culminates in compiling the findings and providing comprehensive recommendations based on the analysis carried out in the previous work packages.



2 Methodology

This chapter outlines the comprehensive approach used in this project, which combines existing frameworks and tools to design an integrated CO₂ capture plant. Figure 2 illustrates the three core components of the methodology: process simulation (using CHEMCAD), integration of processes and heat exchanger network (HEN) design (using PinCH) and piece-wise steady-state analysis of the integrated system (using Modelica). This multi-faceted approach facilitates the design and integration of the CO₂ capture plant, allows for the prediction of its annual operational performance, and enables a thorough analysis of the impacts on the integrated plant.

The process simulation of the CO₂ capture plant is conducted using CHEMCAD, which models the steady-state operation and provides detailed insights into the thermodynamic and chemical behaviour of the system. Stream data from CHEMCAD serve as the basis for integrating the capture process into existing industrial plants. This integration is performed using PinCH, where HENs are designed to maximise heat recovery and minimise external energy consumption. Finally, Modelica is used to perform a piece-wise steady-state analysis of the fully integrated system over an annual cycle, enabling the evaluation of system performance under varying operational conditions, including seasonal fluctuations.

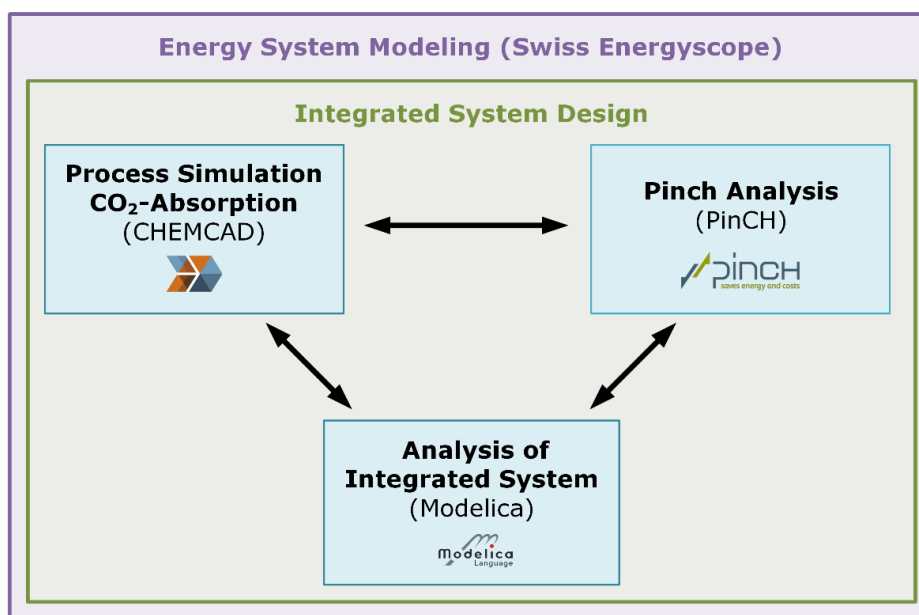


Figure 2: Integrated process design methodology.

By employing these tools, the methodology aims to enhance the energy efficiency of the integrated system, optimise the mass and energy flows and make the best use of the assets within the process. Furthermore, this integrated approach supports the development of a detailed understanding of a future net-zero energy system for Switzerland, which is achieved through energy system modelling using SES-ETH. Figure 3 illustrates the potential material and energy flows within industrial processes when integrated with the CO₂ capture process, highlighting the opportunities for heat recovery, mass integration, and improved overall system efficiency.

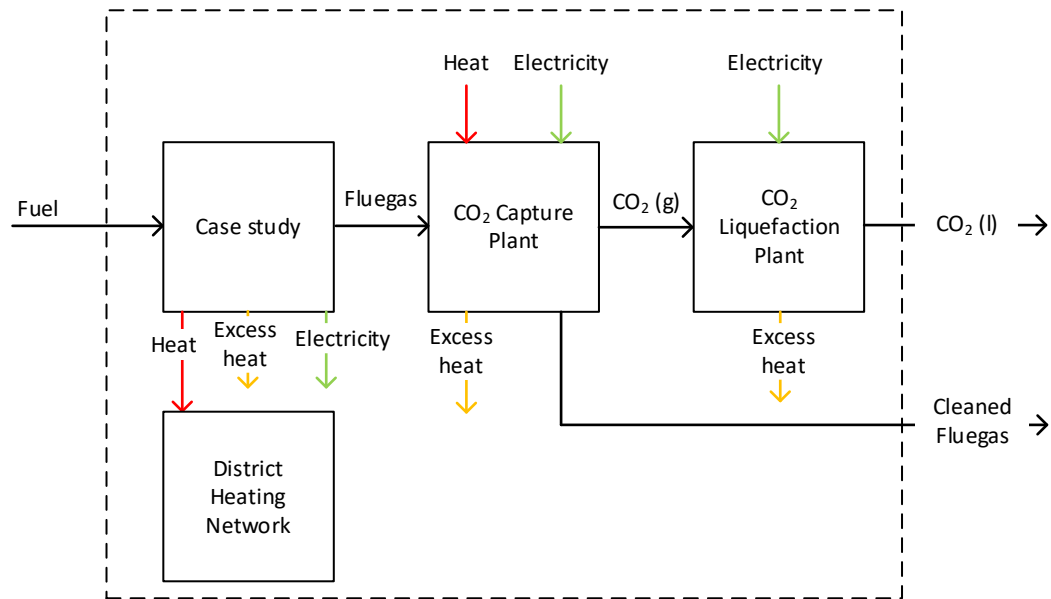


Figure 3: Schematics of the connection between the industrial processes and the CO₂ capture process.

2.1. Design and process simulation of the CO₂ capture process

The process simulation of the CO₂ capture process is performed with CHEMCAD. CHEMCAD estimates the properties of the process streams based on its embedded database, enabling the conduct of mass and heat balances over the unit operations. CHEMCAD software is also utilised to model the process flowsheet modifications aimed at achieving maximum asset optimization.

These modifications may include the incorporation of process optimization strategies, the implementation of energy efficiency measures (EEMs) and the replacement of conventional technologies with advanced and emerging alternatives. Through CHEMCAD, the process requirements for the CO₂ capture process are determined using the calculation models, which are then validated against existing literature. Figure 4 illustrates this step-by-step process.

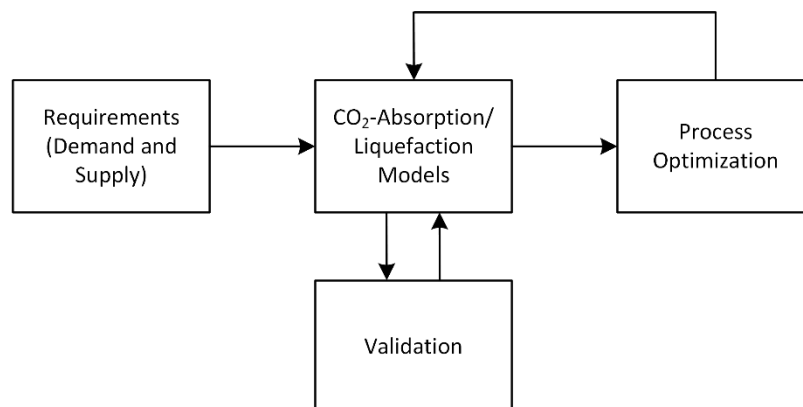


Figure 4: Work steps performed in the process simulation.

From the process simulation, stream data are extracted to be used to establish the initial heat recovery and utility demand targets of the process or conduct PA. The process optimization carried out in the work is an iterative process.



2.2. Process Integration (PI)

Process Integration represents a rigorous framework to determine the potential as well as the design to reduce energy, waste, and emissions in industrial plants. The framework applies thermodynamic laws to understand the intrinsic nature of industrial production systems with an emphasis on the efficient use of energy and water, and the minimization of environmental impacts. As the first major development in PI, PA marked the beginning of a highly successful approach to industrial heat integration (Linnhoff & Flower, 1978). PA is now a well-proven technique to identify and design economic heat recovery projects. In addition, PI provides a general framework for expressing the site-level integration of multiple processes and plants with the goal of minimising energy use, resource consumption, and environmental impact.

By using PI methods in this project, the aim is to find an optimal way to integrate CO₂ capture plant into the existing processes. This integration is done by combining the actual process requirements from the heating and cooling demands of the process (derived from the industrial partners) and the CO₂ capture process (extracted from the CHEMCAD simulation). The consideration of the operating cases (e.g., depending on seasonality) and the different possibilities of excess heat utilization of the CO₂ capture plant are of particular importance.

2.2.1. Pinch Analysis

PA is a graphical approach and a key methodology in PI. It is a systematic and practical technique for analysing the heating and cooling demands (process requirements) of an industrial process, grounded in the fundamental laws of thermodynamics. Process requirements are determined by identifying the heating or cooling demands of process streams to achieve the necessary production temperatures (e.g., a process stream must reach a certain temperature for a reaction to occur). These requirements can be identified by measuring the existing process or using simulation tools such as CHEMCAD.

By analysing these process requirements using PA, it is possible to determine the cost-optimal heat recovery and utility demand by minimising the total annual cost, which involves a trade-off between operating and investment costs.

In PA, process streams with heating and cooling demands are combined into two composite curves (CCs). The "cold CC" represents the heating demand, and the "hot CC" represents the cooling demand (Figure 5, left). The "pinch" is the point of the smallest temperature difference between the hot and cold CCs, characterised by $\Delta T_{\min}$. The horizontal overlap between the two CCs shows the potential heat recovery (HR). Moving the CCs horizontally changes the $\Delta T_{\min}$, the HR potential, and the amount of external heating and cooling required (hot utility HU, cold utility CU).

By minimising the total annual cost, the optimal temperature difference $\Delta T_{\min, \text{opt}}$ (Figure 5, right) can be identified as a trade-off between investment and operating costs. A larger $\Delta T_{\min}$ results in smaller overlapping area and, therefore, a reduced potential for HR. However, it also increases the heating and cooling demands, leading to higher energy costs but lower investment costs for the HR system due to the greater temperature differences.

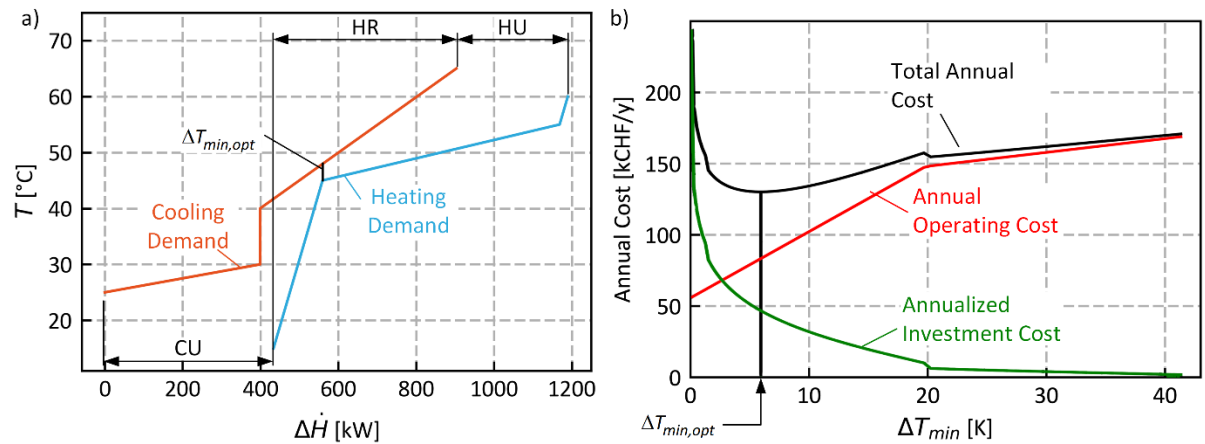


Figure 5: Exemplary CCs and cost curves. Left: CCs of the cooling (red curve) and heating (blue curve) demands showing the potential HR and HU and by the CU for the cost optimal temperature difference $\Delta T_{min,opt}$. Right: cost curves showing total annual cost (black curve), annual operating cost (red curve), and annualised investment cost (green curve). The optimal temperature difference $\Delta T_{min,opt}$ is found at the minimum of the total annual cost curve.

The Grand Composite Curve (GCC) (cf. Figure 6), derived from the CCs, is a valuable tool for visualising utility demand across different temperature levels.

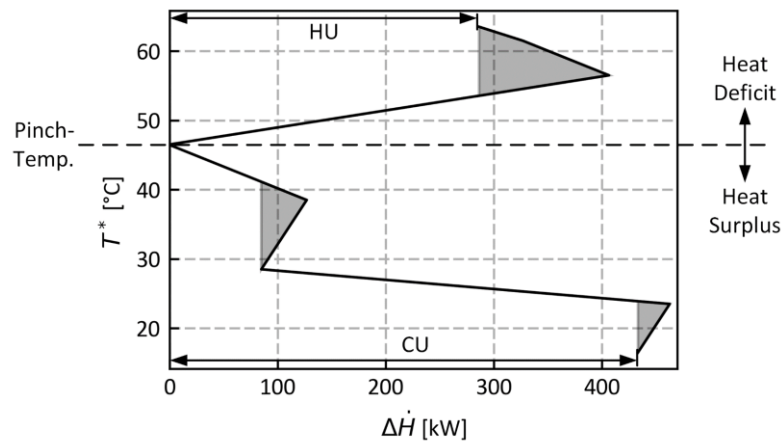


Figure 6: The exemplary GCC shows the heat deficit and surplus depending on the temperature level. Above the pinch there is a heat deficit and below a heat surplus.

Above the pinch, the GCC indicates a heat deficit, and a heat surplus below it. At the pinch point, there is neither a deficit nor a surplus. The temperatures on the GCC are shifted by $\Delta T_{min}/2$. The grey areas are called pockets, represent segment where internal process HR is possible without relying on external utilities.



2.2.2. Energy Efficiency Measure Implementation

Heat Exchanger Network

To implement the HR for the given $\Delta T_{\min, \text{opt}}$, the HEN for the process needs must be designed. To achieve the targeted HR, the design process must adhere to three main pinch rules: (1) no external cooling above the pinch, (2) no external heating below the pinch, and (3) no heat transfer across the pinch, meaning no heat transfer from a cold stream above the pinch (heating deficit) to a hot stream below the pinch (heat surplus) is allowed.

If there are multiple operating cases, the HEN design must be repeated for each of the operating cases and then combined into one overall design with works for each of the operating cases.

Heat Pumps

HPs upgrade low-temperature heat to a higher temperature by circulating a working fluid through a thermodynamic cycle. To integrate a HP correctly, the three main pinch rules must be considered to ensure a reduction of the heat deficit above the pinch and the heat surplus below the pinch. The position of the pinch point and the shape of the GCC are crucial in determining whether it makes sense to integrate a HP or whether an existing HP is correctly integrated into the process.

There are three ways to integrate a HP into a process: (1) below the pinch, (2) above the pinch, and (3) across the pinch. However, only one of these options is energetically beneficial. If a HP is integrated below the pinch (1), where the process has a heating surplus, the additional compressor power required to increase the temperature level will result in an increased need for CU (see Figure 7, left). Integrating a HP above the pinch (2) reduces the HU demand by the amount of compressor power, effectively making the HP act as an electric heater (see Figure 7, middle).

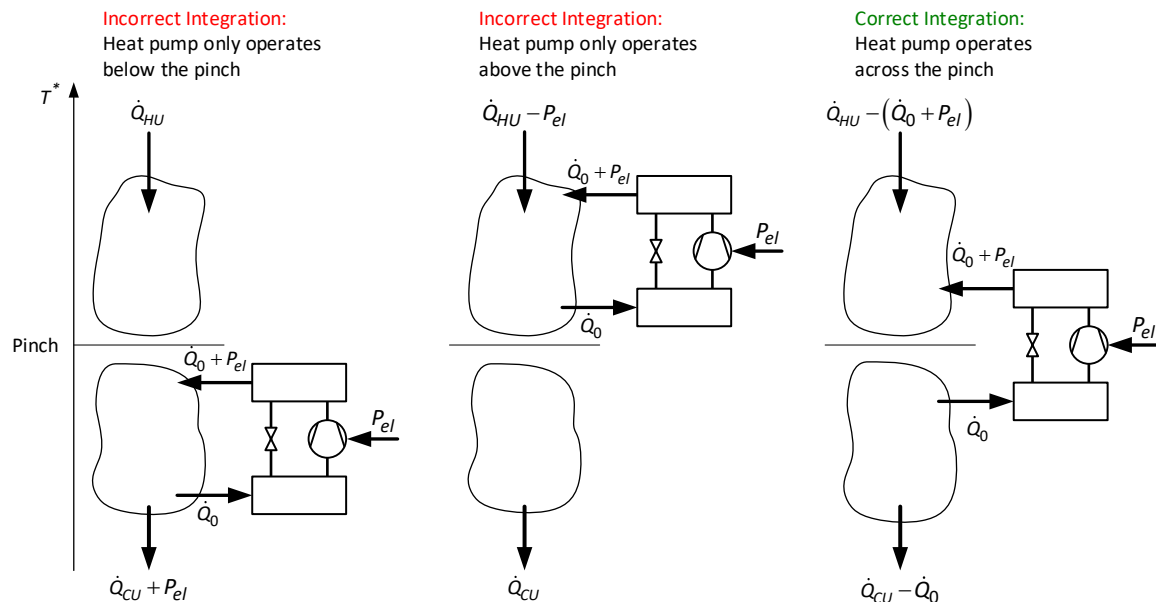


Figure 7: Correct and incorrect HP Integration into a continuous process.



By integrating a HP across the pinch (3), the heat absorption by the evaporator below the pinch reduces the heat surplus, while the heat released by the condenser above the pinch reduces the heat deficit. Although this seems to contradict the third main pinch rule, the HP effectively reverses the heat transfer from a lower to a higher temperature level, thereby simultaneously reducing the heat deficit above the pinch and the heat surplus below the pinch.

In this project, two types of HPs are evaluated: (1) absorption heat pumps (AHPs) and (2) compression HPs. These options are considered based on previous research, which has demonstrated their efficiency improvements in the context of CO₂ capture (Zhang et al., 2015). Figure 8 presents the schematics of the two different HPs.

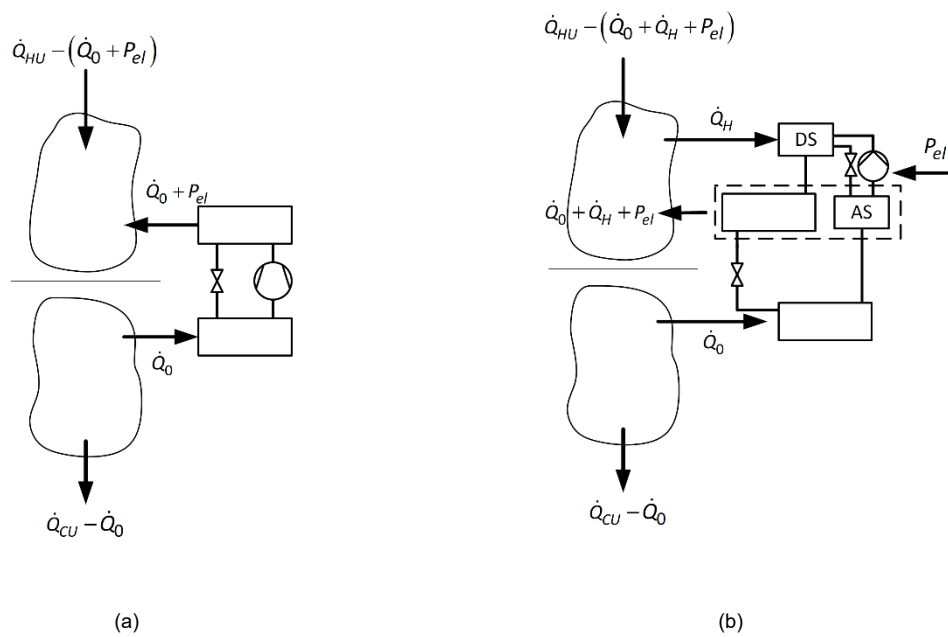


Figure 8: Schematic of the integration of (a) compression heat pump and (b) absorption heat pump into the case study.

The compression HP consumes electrical or mechanical power to valorise heat from a cold source to the hot one. An AHP consists of an evaporator, a generator, a condenser and an absorber. The generator is supplied with high-grade heat Q_g (typically steam), which drives the AHP. The evaporator recovers waste heat Q_e from the system. Thus, an AHP uses high-grade heat as compensation to transfer the heat from the cold source to the hot one. Energy savings are achieved only when both HPs operate across the pinch temperature.

2.3. Piecewise-steady state modelling

The conceptual design of processes is challenging as only few information about the selected equipment and their operation is known at this early design stage. Furthermore, the systems are increasingly integrated, and thus their design must be addressed systematically. In PA, studies are usually conducted for a predefined time slice (e.g., operation in the winter) that best reflects the operation of the plant. Due to this assumption, an optimal solution for the examined time slice may not be the optimal solution for all time slices.

To address these challenges and evaluate a derived solution concept on a yearly basis, a piecewise-steady state approach is used. The system with all its components and necessary parameters is modelled as a set of successive steady-state operation periods, i.e., no system dynamics are modelled. This



approach leads to short simulation times, and it is, therefore, an agile way of evaluating multiple different system configurations.

Thus, a Modelica models were developed for all three processes with the complete steam/waterside; additionally, parts of the flue gas are modelled. For this the following components were developed, each of which is composed of energy and mass balances:

- Steam turbine
- Generator
- Condenser
- Liquid heater/Cooler
- Heat pump/Absorption heat pump
- Mixing tanks
- Pump
- Heat exchanger (HEX)

The object-oriented and acausal approach of the models allow for easily reusable components based on mathematical equations founded on first principles. This allows for the models and methodology developed within this project to be easily reused for evaluation for further scenarios in the future.

2.4. Techno-economic analysis

To analyse the technical and economic viability of each integrated system, a techno-economic analysis is conducted. The specific tasks include calculating the costs (investment cost, operational cost, etc.), revenue the processes with integrated CO₂ capture plant and all defined integration concepts and assessment of their technical feasibility. The detailed annual simulations enable the techno-economic evaluations to be carried out more accurately. The cost calculations are composed as following:

- Investment and operating costs: These include capital expenses (C_{CO_2}) and fixed and variable operational costs for the CO₂ capture plant.
- EEM cost: Expenses related to the investment and operating costs efficiency measures, e.g. HEX (C_{HEX}) and HPs ($C_{HP/AHP}$), identified during the integration process.
- Annual operating costs: This includes reduced DH sales, decreased electricity production, and additional electricity demand from the grid, calculated using CHEMCAD and Modelica simulations.
- CO₂ transport and storage: Costs associated with the transportation and storage of captured CO₂.

This structured approach allows a thorough evaluation of both the economic and technical aspects of the integrated CO₂ capture systems, ensuring a holistic understanding of their viability.



2.4.1. Capital Cost

The capital costs are given by:

$$C_{cap} = C_{CO2} + C_{HEX} + C_{HP/AHP} \quad 1$$

CO₂ capture plant

Capital cost functions are ideally formulated using real plant costs at multiple scales. Since full datasets are rarely available, order of magnitude capital cost estimates based on at least one installation (or detailed cost calculation) are forecasted using power law estimation for the different scales of productions (Gerrard, 2000), as shown in Eq (2). The cost estimates are based on data from the various project partners and additional data from conceptual engineering designs (T. B. F. Partner AG, 2022b), (Aker Carbon Capture Norway AS, 2021), (Sulzer, 2022). There are 5 data points for different CO₂ capture capacities. This power function is compared with data from the literature (Eliasson et al., 2022):

$$C_{CO2} = c_{CO2} \dot{m}_{CO2}^{f_d} \quad 2$$

where C_{CO2} is the cost of the capture plant at size $\dot{m}_{CO2}$, c_{CO2} the nominal cost of the item at unit scale and f_d is the degression factor. The cost functions used in this study are compared to those reported in studies from ETH (Eckle & Krueger, 2021) and Dena (Deutsche Energie-Agentur GmbH (dena), 2023).

Heat exchangers

For HEX, the equipment cost is determined based on the heat transfer surface area, as it is a key sizing parameter influencing material and fabrication costs. The equipment cost for HEX, C_{HEX} , used for case studies is based on the module cost estimation functions reported in (Rast, 2018). The actual values for the cost functions are identified from cost databases. Rast (2018) compiled such data for the Swiss market. The cost functions derived from these data are applied in this work, with heat exchanger sizes and configurations determined directly from the PinCH analysis results.

Heat pump

The specific compression HP cost, C_{HP} , is extracted from Grosse et al. (2017) and Popovski et al. (2019). In this work, the specific HP cost used is 1'050 CHF/kW and it is based on the capacity of the condenser. For KVA Linth, AHP is considered, where the specific cost of AHP, C_{AHP} , extracted from literature and quotation are within the range of 600 to 700 CHF/kW. According to Herold et al. (1996), the cost of AHP is higher than a compression HP. This is due to the complexity of design and market availability. Therefore, a cost factor of 2 (compared to HP) is used for AHP.

2.4.2. Operating cost

The operating costs, C_{op} , (Table 1) are based on the fixed costs and the variable costs.

The variable operating costs include replacement of operating chemicals, wastes and utilities. The values for most of the variable operating costs are obtained from simulation results and their unit prices from the industrial partners. The fixed operating costs are dependent on the total installed cost (TIC).



Table 1: The operating cost of the integrated system.

Fixed operating cost	Ratio	Value
CO ₂ absorption	% TIC	3
CO ₂ liquefaction	% TIC	3
Heat exchanger	% TIC	1
Variable operating cost	Unit	Value (CHF/unit)
Amine make-up	t _{CO₂}	2.50
CO ₂ capture process	t _{CO₂}	0.75
Heat pump	MWh	3
Process-dependent costs	Unit	Note
Electricity price	CHF/MWh	Based on individual process*
Steam cost	CHF/MWh	Based on individual process*

*see Table 2

Amine make-up compensates for losses due to degradation, evaporation, chemical reactions with impurities, and operational purging, ensuring that the CO₂ capture efficiency remains stable over time. The cost of energy is modelled based on the process simulations performed in CHEMCAD and Modelica, which quantify the additional thermal and electrical energy demands resulting from the integration of the CO₂ capture process. The redistribution of energy flows, specifically the diversion of steam and electricity to the CO₂ capture plant, reduces the amount of electricity available for external sale, representing an opportunity cost for the operator. The loss of revenue is calculated by comparing the electricity selling price (plant-specific tariffs) with the cost of purchasing additional electricity from the grid if required. Similarly, district heating revenues are adjusted based on the remaining heat supply capacity. The electricity and heat prices used in the techno-economic analysis are derived from site-specific data provided by the industrial partners.

2.4.3. Specific costs of CO₂ capture

The total annual cost (TAC), CHF/a, of the integrated design is given by:

$$TAC = \frac{i_r(1+i_r)^n}{(1+i_r)^n - 1} C_{cap} + C_{opa} \quad 3$$

whereby the i_r is the interest rate in % and n is the depreciation period in years. To then get the specific CO₂ cost, the TAC is divided by the total annual CO₂ captured (M_{CO_2}):

$$LCO_2 = \frac{TAC}{M_{CO_2}} \quad 4$$

The economic parameters used for the techno-economic analysis are an investment period of 20 years and an interest rate of 6%, these are average values used in the Swiss Industry based on the evaluation of PA conducted. It is to note that, a general investment period and interest rate are used for comparison as the different industrial case studies have different values.



2.4.4. CO₂ transport and storage

DemoUpCARMA considered the overall CO₂ supply chain with CO₂ capture and liquefaction at the emitter's site, transport, and storage in geological storage in the Northern Lights storage hub in Norway, or in Icelandic basalts through the Carbfix technology (Becattini & Mazzotti, 2024). An algorithm is used to obtain the most economical transport pathways for the single source-single sink supply chains. The results presented in DemoUpCARMA provide an overview of the levelised costs of avoided carbon for the cost-effective supply chains reaching the geological storage sites in the near-term (early-movers) and dedicated vessels for the long-term solution. The near-time horizon expects that these supply chains will mostly rely on CO₂ transport on land by truck and train. As a result, transport costs constitute the largest share of up to 60% for early movers, as such multimodal transport solutions for long distances do not profit from economies of scale. Their costs are however expected to decrease significantly in the long term with more efficient solutions, e.g., a pipeline network, the levelised costs of transport would almost be halved with the use of dedicated transport options, however reconditioning costs, which are not considered, might be significant.

In this study, the analysis for transport and storage are not considered but derived from the report of DemoUpCARMA (Becattini & Mazzotti, 2024). The costs for the “Early Movers Solution” and the “Dedicated Vessels” correspond to Solution 1 and Solution 5 in the report for transportation to and storage in Norway (Northern Lights) (Becattini & Mazzotti, 2024).

2.5. Energy System Modelling

CO₂ capture from large point sources is a key element of a net-zero future in Switzerland. Its effects can be investigated using an energy system model, especially for the heat and electricity demand of the capture process.

The present report uses the Swiss Energyscope model (Marcucci et al, 2021), which was developed at ETH Zurich based on the original model from EPFL (Moret, 2017). SES-ETH is a linear optimization model of the energy system. It determines the investment and operation strategies to minimise the total annual cost of the energy system, given the end-use energy demand, the efficiency and costs of the conversion technologies, and the availability and costs of the energy resources.

SES-ETH represents the main end use demands: electricity, heat and mobility (Figure 9). It is a snapshot model, i.e., it models the energy system in a target year, but it does not make any statements on the trajectory to reach this future state. The original SES included monthly periods that could capture the seasonal aspects of generation, demand, and storage. The model was further developed to include an hourly resolution that allows it to represent the intra-day variations in the energy demands and resources available. Note that the heat required for the CO₂ capture process is listed separately on the demand side (Figure 9).

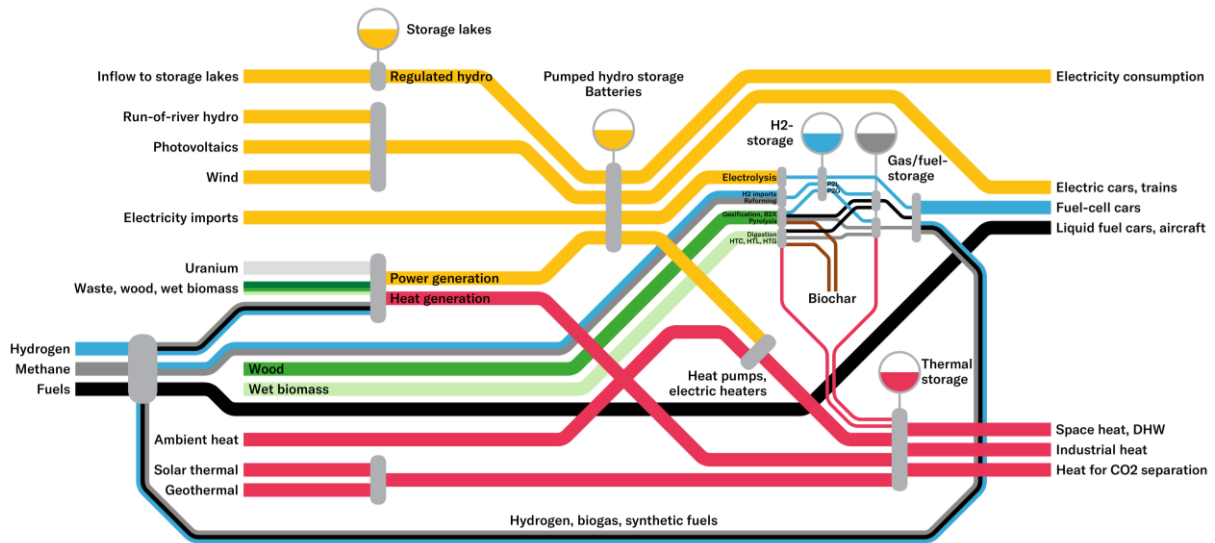


Figure 9: Schematic representation of the energy system as modelled in SES-ETH, adapted from SWEET-CROSS (2024).

The scenarios that are analysed in PICC have been defined within the SWEET-CROSS project (Marcucci et al, 2023). These are generated along two axes: climate policy and energy market integration. Another dimension was added by defining a technology conservative and a technology innovative variant, as well as a stricter climate goal (see Figure 10).

- Climate policy: “Net-zero GHG domestic” is net zero including hard to avoid emissions from agriculture but excluding aviation. “Net-zero GHG – carbon removal abroad” considers the option to balance up to 6 Mt/a of CO₂-equivalent emissions outside Switzerland. We added a third variant “Real zero” which also considers the emissions from aviation.
- Energy market integration: SES-ETH does not explicitly model the energy system outside Switzerland. Energy carriers like electricity, methane or hydrogen can be imported at a certain price. The two variants “high integration” and “low integration” are considered.
- Technology innovative/conservative: These variants are distinguished by the willingness to adopt new technologies or to find compromises with other public goods such as landscape preservation. Examples are alpine photovoltaics, the increase of hydro reservoir volumes or geothermal energy.

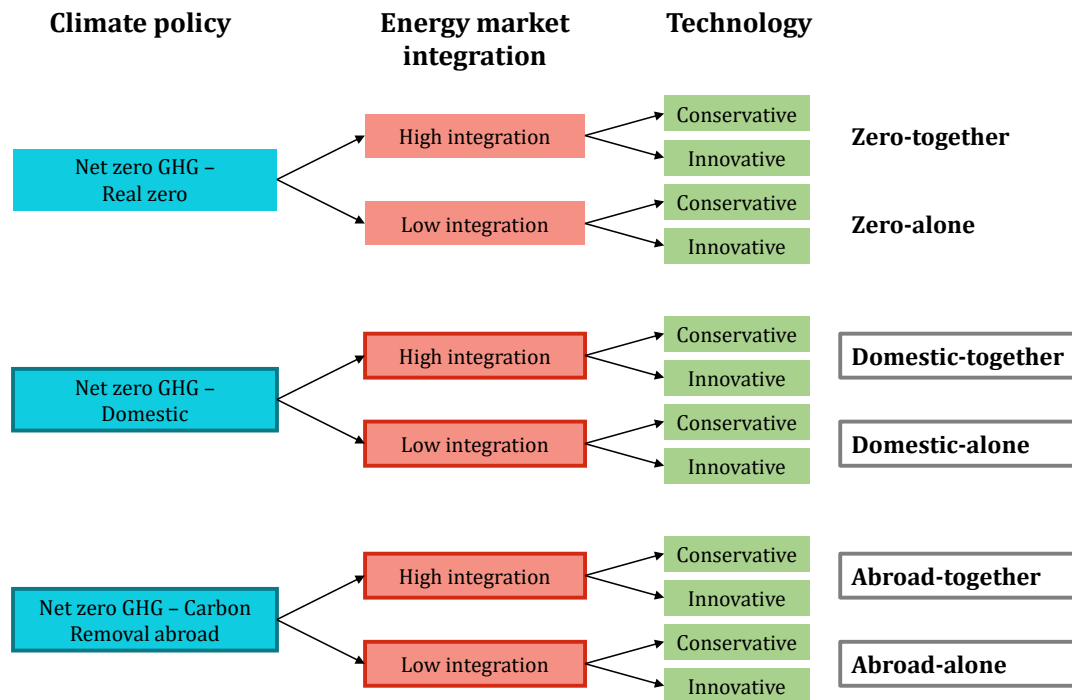


Figure 10: Basic CROSS scenarios.

Note that all inputs and results in this report refer to the target year 2050.

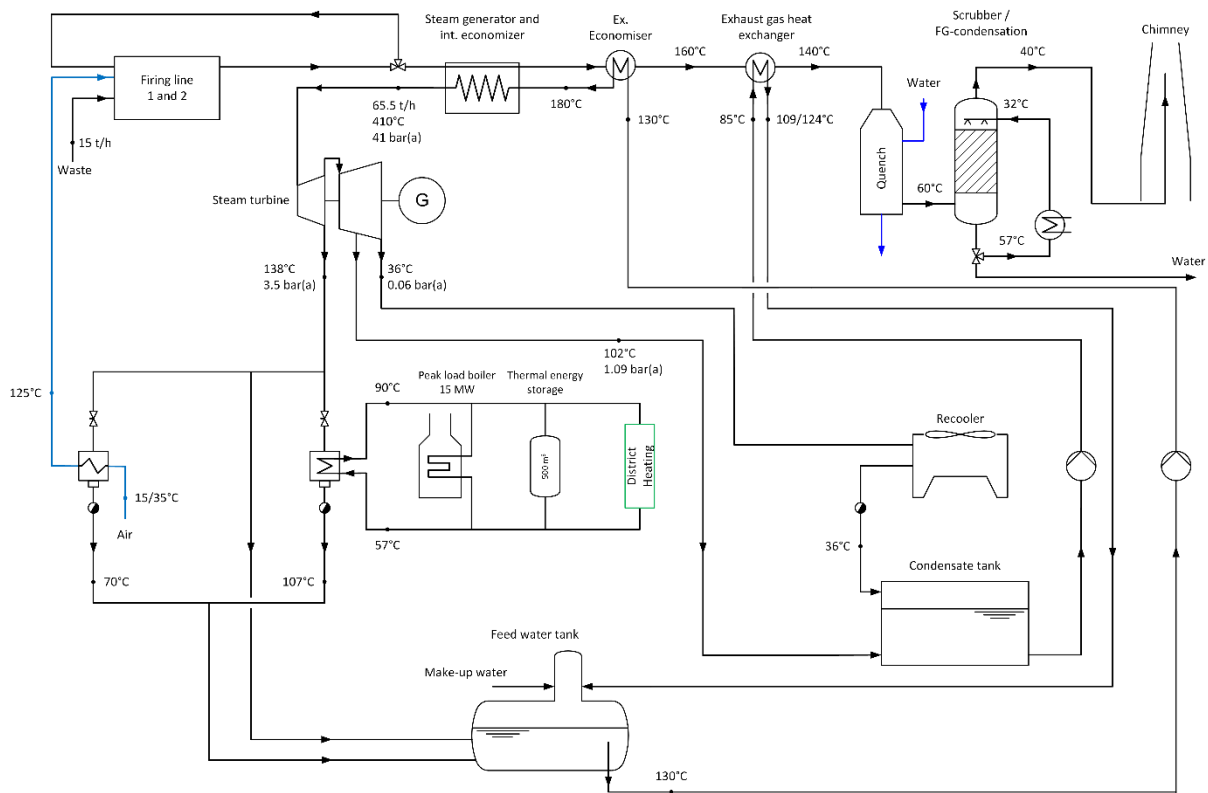
3 Description of case studies

Three case studies from different industrial processes are analysed to demonstrate the application of the proposed methodology. This chapter provides detailed descriptions of the three industrial processes and outlines their key characteristics. A comparative analysis highlights the critical aspects of each process. Additionally, this section covers the base case of the CO₂ capture plant. CO₂ capture plant in this study includes the CO₂ absorption, compression, and liquefaction steps, providing insights of the plant before their integration within the industrial systems.

3.1. KVA Linth

KVA Linth operates a waste incineration plant in Niederurnen and is the largest of the three CO₂ point sources analysed in this project. The plant processes waste that is approximately 52% biogenic fuel, with a waste throughput of about 15 t/h maintained constantly throughout the year, resulting in annual CO₂ emissions of approximately 133'600 tons.

The plant utilises two moving grate furnaces that vaporise feed water and heat it to 410°C at a pressure of 41 bar. The steam is then expanded in a two-stage steam turbine equipped with the steam extracted (bled-off) at the medium pressure level of 3.5 bar (between the first and second stages). This extracted steam is used to meet various heating demands, including preheating of the air, a DH network (T. B. F. Partner AG, 2022a) and other process requirements within the waste incineration plant. The exhaust steam is expanded to 0.06 bar at 36°C. The plant generates 15 MW of electricity. Figure 11 provides a simplified process flow diagram of KVA Linth.



In this project, the scenario considered for KVA Linth involves the maximum expansion of the DH network to 59.4 MW_{th}. The quench and flue gas (FG) condensation scrubber, as shown in Figure 11, are incorporated into the considered scenario for KVA Linth. Despite these additions, the waste volume remains constant at 15 t/h.

The annual load profile is calculated using the design reference year data from the Meteonorm database (Meteotest AG, 2023) for Niederurnen. Due to the significant inertia of DH systems (including storage, pipe volume and heat consumers' inertia), a rolling-mean filter with a four-hour averaging window is applied. Figure 12 shows the heating demand relative to ambient temperature, presented as the heat load curve and the resulting hourly profile, which serves as input to the integrated system model. This profile has been verified and validated by the industrial partner.

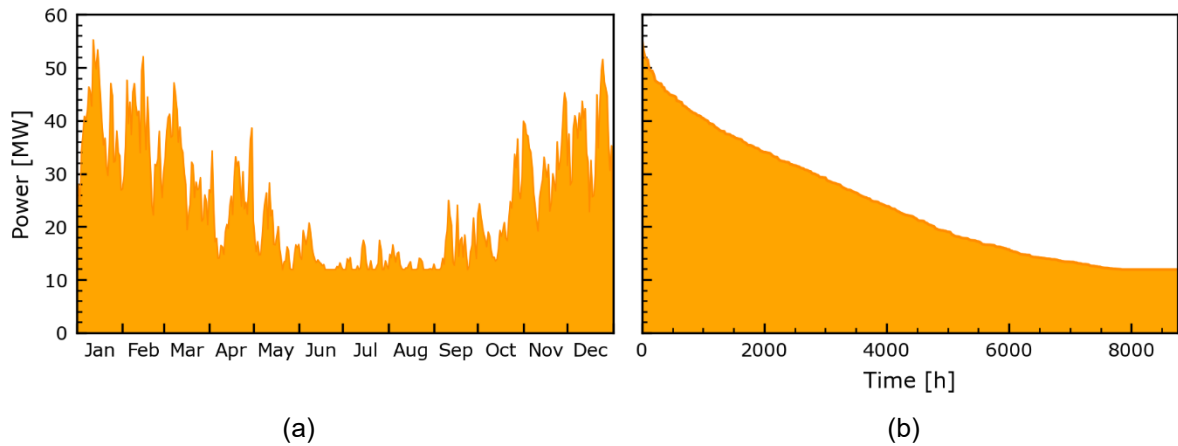


Figure 12: (a) Annual load profile of the district heating network and (b) the cumulative load profile with a total demand of 227.3 GWh/a.

In this expansion scenario, the constant waste volume is insufficient to fully supply the total DH demand. Therefore, a peak load boiler is added to the system, covering approximately 16.9 GWh per year of the total load.

3.2. KSV Werdhölzli

The Werdhölzli wastewater treatment plant operates a sewage sludge incineration facility that serves as a key CO₂ point source in the project. The plant processes sewage sludge collected from the entire canton of Zurich, handling approximately 90'000 tons annually. The incinerated sludge is used as fuel to generate heat and electricity, emitting around 22'000 tons of CO₂ each year annually (T. B. F. Partner AG, 2022b). This plant, which operates continuously with two shutdowns of about two weeks each, is the smallest CO₂ point source considered in this study.

The plant (Figure 13) utilises a fluidised bed furnace to vaporise and heat feed water to 420°C at a pressure of 64 bar. The steam generated is expanded in a backpressure steam turbine down to 5.7 bar, producing approximately 875 kW of power (Outotec Oyj, 2015). A significant portion of the generated thermal and electrical energy is consumed within the sewage sludge incineration process and the adjacent wastewater treatment plant. Additional excess heat is sold to secondary consumers, including a biogas treatment plant (GTP) and the local DH network.

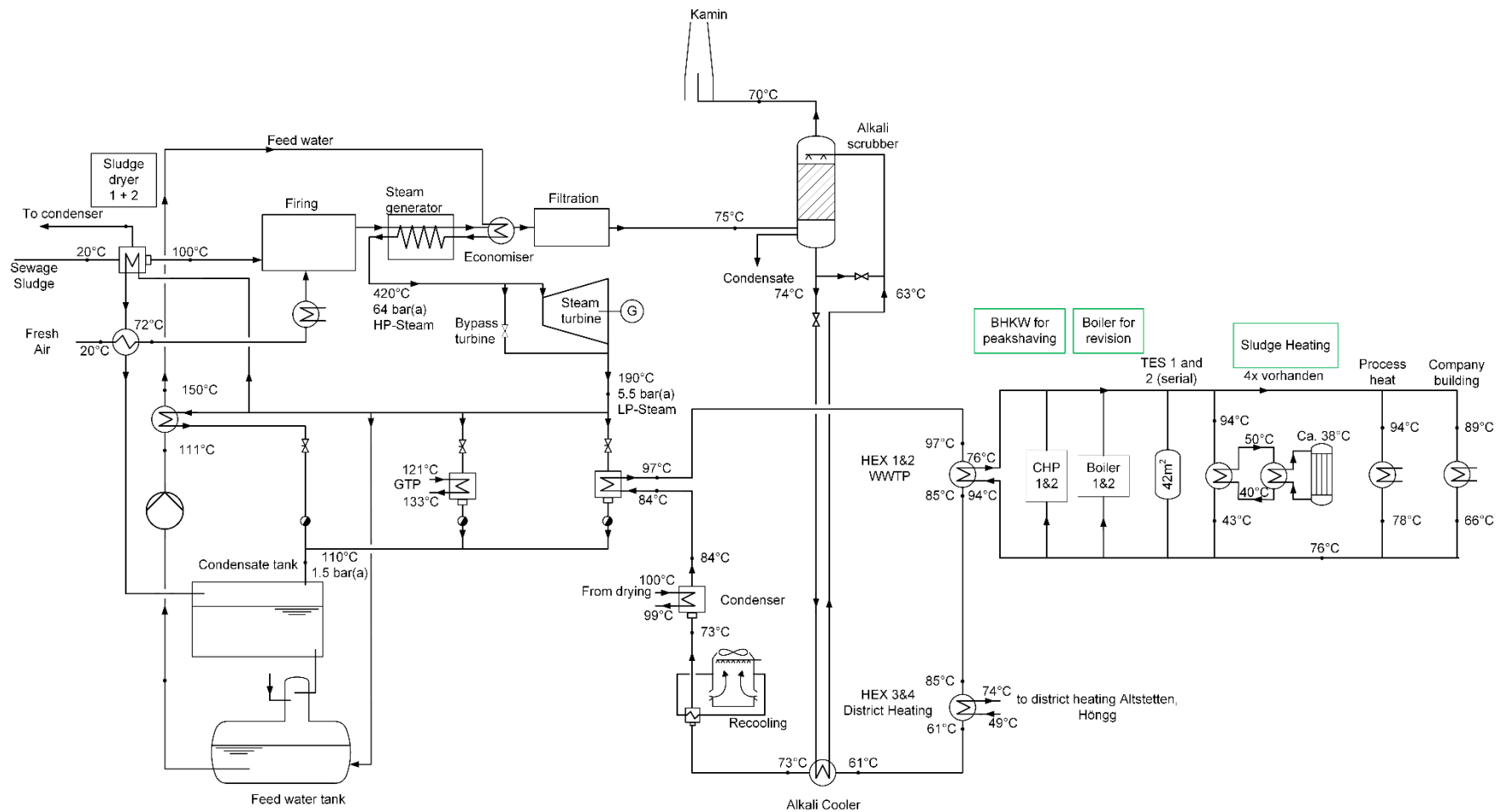


Figure 13: Simplified process flow diagram of KSV Werdhölzli.



The process heating demands for the sewage sludge incineration plant and the GTP remain constant throughout the year. However, the heating requirements of the wastewater treatment plant fluctuate with ambient temperature changes. Figure 14 shows the real hourly data of process heating demands for the wastewater treatment plant (WWTP) from the year of 2022.

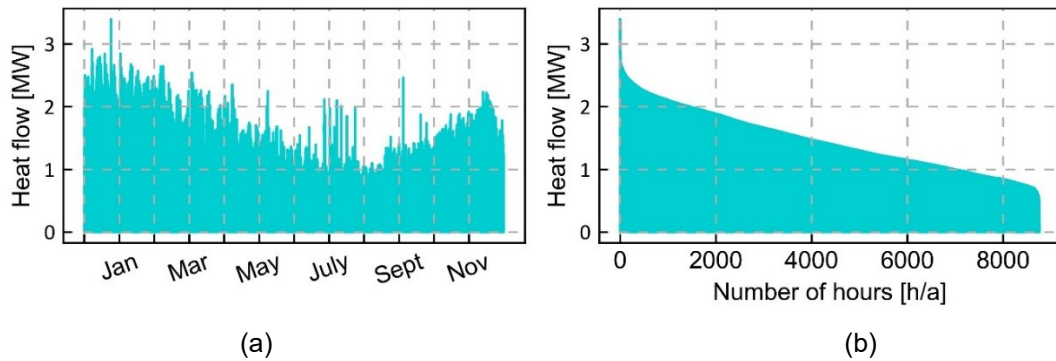


Figure 14: (a) Annual load profile of the hourly process demand and (b) the cumulative load profile of the WWTP.

Figure 15, developed using the same method as described in Section 3.1, shows the heating demand of the DH related to the design reference year of the city of Zurich.

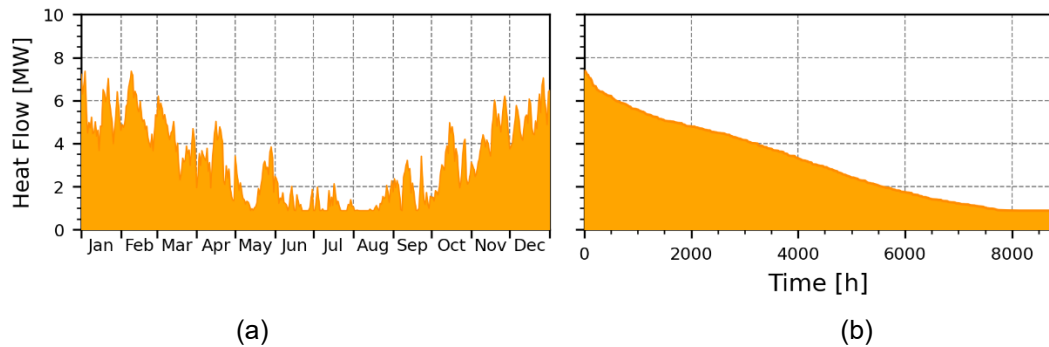


Figure 15: (a) Annual load profile of the district heating network and (b) the cumulative load profile with a total demand of 27.6 GWh/a.

3.3. HHKW Galgenen

Energie Ausserschwyz AG operates a wood-fired power plant in Galgenen (Figure 16) utilising a mix of waste wood (70%) and wood chips (30%) as fuel, emitting approximately 46'200 tons of CO₂ annually (Sulzer, 2022). The plant features a feed grate furnace that vaporises feed water, heating it to 420°C at a pressure of 60 bar. The resulting steam is expanded through a turbine to 2.5 bar and is extracted to supply a DH network, which is currently under expansion (E-Axiom GmbH, 2020). The scenario considered in this study is based on the planned DH network expansion for 2026. The exhaust steam is further expanded to 0.1 bar, corresponding to a temperature of 45.8°C, generating between 4.6 and 6.2 MW of electric power. Unlike the other plants analysed, HHKW Galgenen adjusts its operation based on the seasonal heat demand of the DH network, making it unique among the case studies.

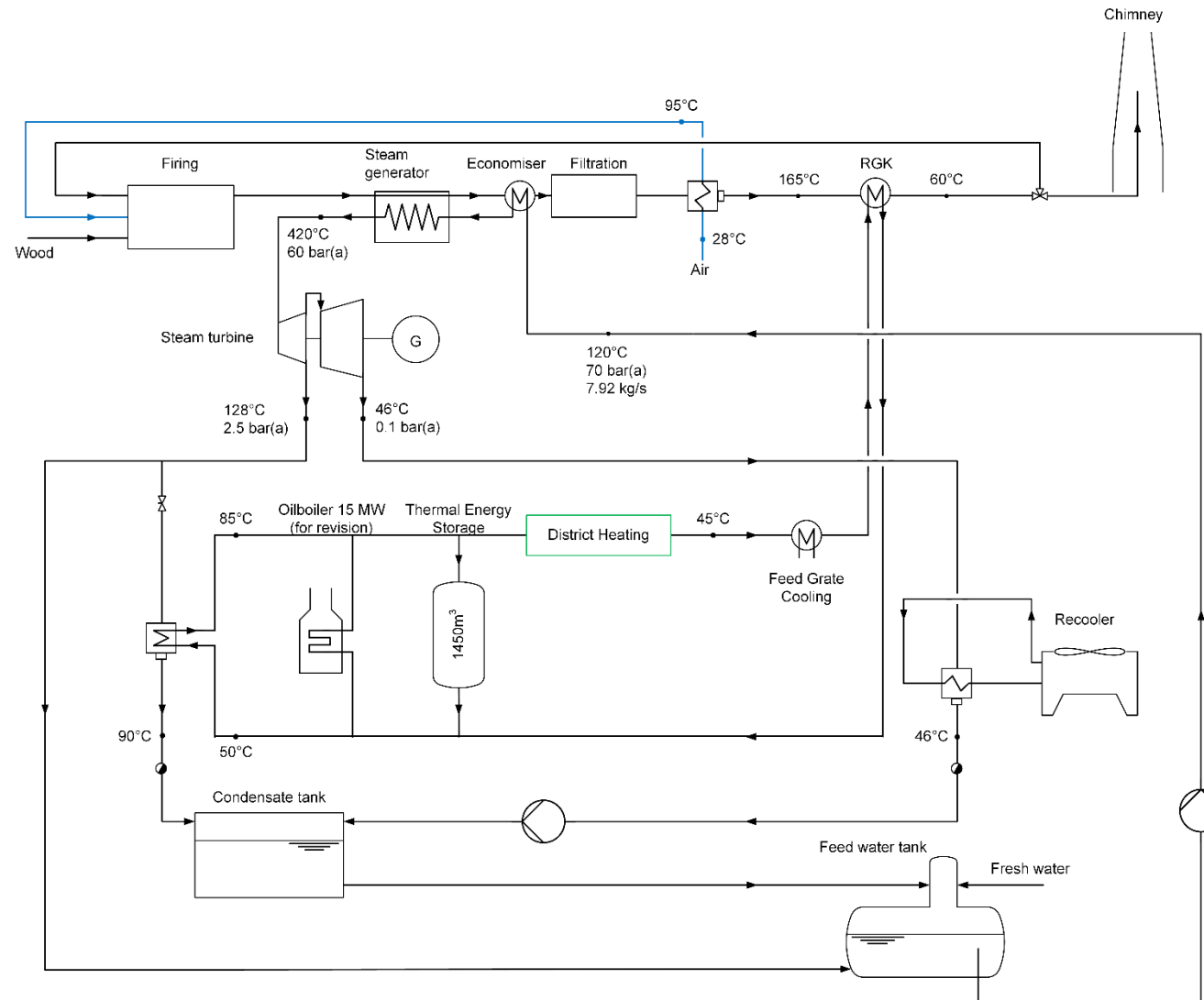


Figure 16: Simplified process flow diagram of HHKW Galgenen.



Figure 17, using the same methodology outlined in Section 3.1, shows the heating demand of the DH in relation to the design reference year for the city of Niederurnen, projected for 2026.

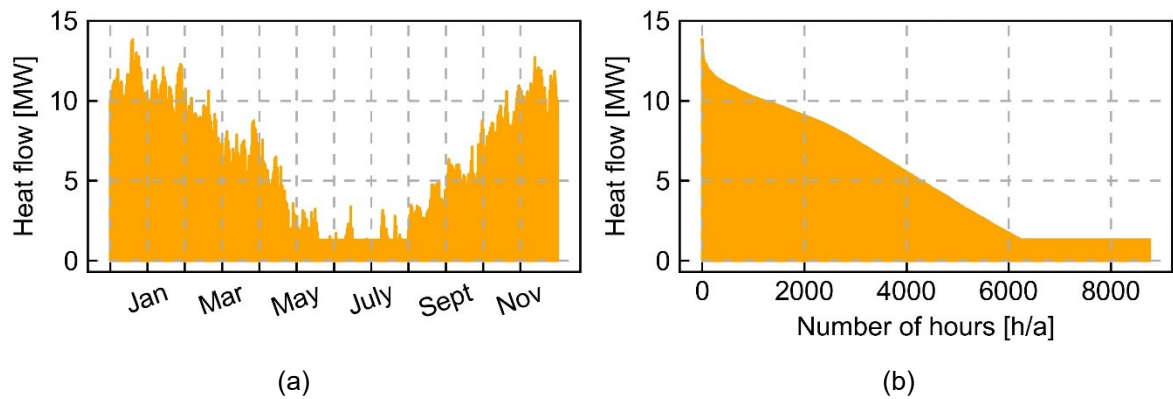


Figure 17: (a) Annual load profile of the DH network and (b) the cumulative load, total demand of 46 GWh/a.

3.4. Comparison of case studies

Table 2 summarises and compares the three different processes.

Table 2: Comparison of the processes.

	KVA Linth	KSV-Werdhölzli	HHKW-Galgenen
Fuel	Waste	Sewage sludge	Waste wood and wood chips
Key task	Waste disposal in the Linth region	Disposal of sewage sludge from the Canton of Zurich	Generation and sale of electrical and thermal energy
CO₂ emissions [t CO₂/a]	ca. 133'600	ca. 22'000	ca. 46'200
Heat consumers	DH network, large consumers, process heating	Internal processes, GTP, DH	DH of households, few large consumers
Operating characteristics	Constant operation, variable DH demand	Constant operation, variable process and DH heating demands	Partial load operation based on seasonality, variable DH demand
Scenario Considered	Expansion of DH estimated at 59.4 MW connected load	Current state where el. and th. energy almost fully utilised	Expansion of DH for 2026 estimated at 16.3 MW connected load
Heating cost [CHF/MWh]		65	65
Electricity cost [CHF/MWh]		80	140
			130



All three processes have an associated DH network. In the case of KVA Linth and HHKW Galgenen, the DH networks are the primary heat consumer. At KSV Werdhölzli, the thermal and electricity energy are primarily for internal process use and in the wastewater treatment plant.

The KVA Linth and the HHKW Galgenen have a multi-stage steam turbine with an exhaust steam pressure of 0.06 bar (a) and 0.1 bar (a), and a corresponding re-cooling system. The KSV Werdhölzli has only one decoupling stage of 5.7 bar (a) 180°C and a direct use of this stage. This reduces the power production and requires cooling capacity but increases the thermal energy demand.

3.5. CO₂ capture plant

The primary absorption capture process consists of two columns. The flue gas stream to be cleaned enters the absorber column above the sump. There, the CO₂ in the flue gas stream is absorbed by the MEA-solvent by chemical absorption, which is introduced in the upper part of the absorber. The lean CO₂-lean flue gas stream is then discharged at the top of the absorber. The higher the purity of this lean CO₂ gas stream, the more stages/pack height in the absorber is needed. The CO₂-rich solvent is then fed to the desorber and allowed to enter in its upper section. In the desorber, the CO₂-rich solvent is heated so that the CO₂ can be expelled more effectively. The condenser in the head section then separates the condensing water and the gaseous CO₂. The CO₂ is now extracted out of the system and can be further processed, e.g., liquefaction process. The regenerated and CO₂-lean solvent is discharged in the sump of the desorber before being cooled and fed back to the absorber. To cool the CO₂-lean solvent before it enters the absorber and to make the heating of the CO₂-rich solvent in the desorber more energy-efficient, heat transfer takes place between these mass flows. In the absorber and desorber, the mass and heat transfers are improved using trays and column packing. This improves the separation efficiency and the reaction surface (Rieder, 2016). There are different heating and cooling requirements. The goal is to integrate this process optimally, for example, by using existing excess heat. Furthermore, optimal heat extraction and injection should take place, which is suitable for the different operating cases. Figure 18 shows the simplified process flow diagram of a standard CO₂ capture process.

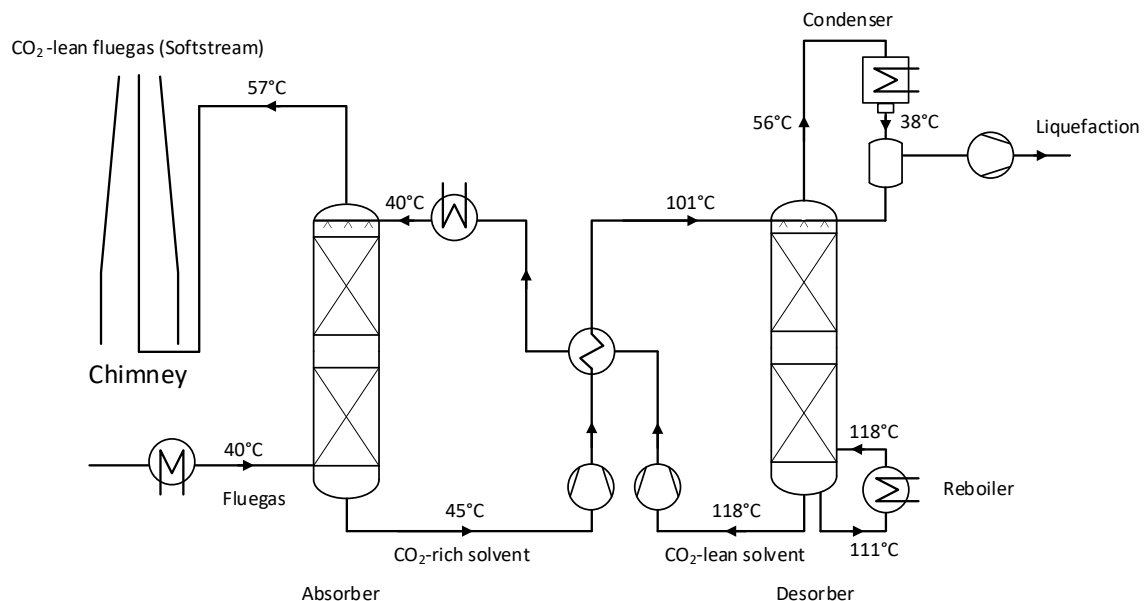


Figure 18: Simplified process flow diagram of a standard CO₂ capture process.



In addition, this project considers the liquefaction and storage of the captured CO_2 . For the CO_2 to be transported, it must be compressed and liquefied, as shown in Figure 19. Parameters that influence the liquefaction process are the liquefaction temperature and pressure, and the different process configurations. However, this work is not primarily about evaluating the most efficient liquefaction system but evaluating under the assumption of a "practical" system in which excess heat (from between the compression stages) utilization can be made on this system and which thermal and electrical consumption the system has. In the compression section, the CO_2 exiting the desorber is compressed from around 38°C and a pressure of 1.6 bar (a) to 18 bar (a) and cooled to 30°C . In addition, the remaining water, which is in the pure CO_2 stream, is condensed out using a 2-bed adsorption drying system. However, this system is not modelled in the CHEMCAD. The required electrical and thermal energy demand of the system is relatively small compared to the total energy demand; therefore it is estimated using an assumption from Sulzer CED. The compressed CO_2 stream is liquefied by cooling it to -28°C . This is achieved with a closed multi-stage cooling circuit using the coolant R290 (Chen & Morosuk, 2021), which is represented as a cold utility in this project.

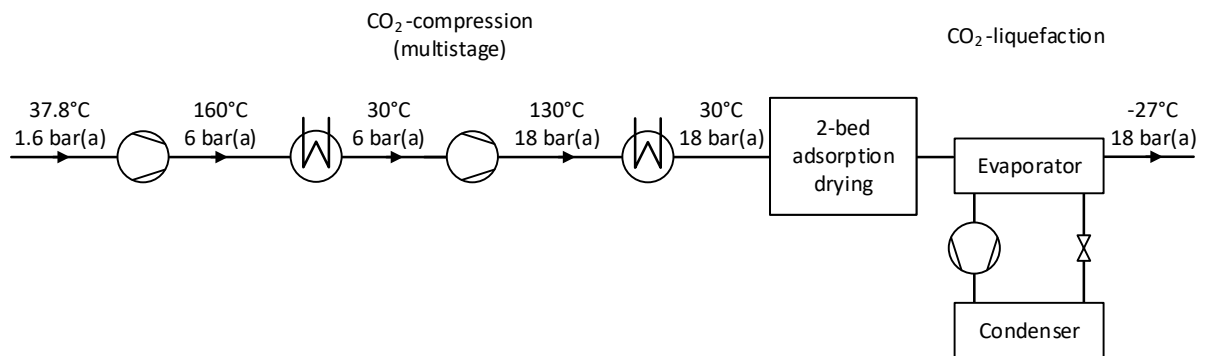


Figure 19: Simplified process flow diagram of CO_2 liquefaction process.

In this project, a closed system with a refrigerant is considered. This consideration is based on Chen and Morosuk (2021) and a conceptual engineering design (CED) from Sulzer (2022). They assumed an optimal pressure of 15 bar and a temperature of -28°C , while the CED by Sulzer assumes 16.1 bar and -27°C . The paper compared different refrigerants and systems. It is concluded that a closed system with the R290 refrigerant was the best. Therefore, in this study this refrigerant is also used, and the according system modelled. The entire system is modelled in CHEMCAD as a 2-stage compression system with a subsequent condensing stage.

4 Results and discussion

This section presents the results on the process simulation of the CO_2 capture plant and its integration with the industrial processes. The following terms and their definitions are used:

- CO_2 capture plant includes CO_2 absorption, compression, and liquefaction processes.
- Integrated system: integration of CO_2 capture plant with industrial process
- Integration concept (IC) 1: integrated system
- Integration concept 2: includes integrated system with HP
- Integration concept 3: includes integrated system with AHP



4.1. CO₂ capture plant

This subchapter discusses the implementation of the CO₂ capture and liquefaction process in the CHEMCAD simulation software. This includes the component selection, the definition of the thermodynamic models, and the definition of the boundary conditions. The essential operation of CO₂ capture by the amine process is similar in all three processes. A flue gas with a high CO₂ concentration is present in all three plants. About 90% of the CO₂ is then captured from the flue gas by the CO₂ capture process, liquefied, transported, and stored. However, the three processes differ in the concentration of CO₂ in the flue gas, the flue gas volume flow, and the energy source available to operate the reboiler. This changes the specific energy required to capture the CO₂. Also, the specific plant costs for the possible realization of the plants differ depending on the size of the plants. All these points will be compared and analysed.

4.1.1. Components and model selection

Two phases are involved in the first part of the absorption process. One is the gaseous incoming flue gas stream, which is composed of nitrogen (N), oxygen (O), water vapor (H₂O), and carbon dioxide (CO₂). The liquid phase flows in the top of the absorber. The components are CO₂, H₂O, and MEA. After selecting the components, one can choose between different modelling approaches for the phase/reaction equations and the enthalpy models. The CHEMCAD program provides the K-model "amines" for CO₂ capture with amine solvents. This is based on the Kent-Eisenberg model (Kent & Eisenberg, 1976), which is a semi-empirical model. The Kent-Eisenberg model neglects the non-ideal processes in the vapor and liquid phases, and the accuracy of the equilibrium values is achieved by a fit using experimental data. In simulating CO₂ compression and liquefaction, the Peng Robinson model is used, which is typically recommended for such applications (Jackson & Brodal, 2018).

4.1.2. Solvent

MEA is the most tested and researched solvent available for this application and is often considered a benchmark process. Therefore, this solvent is implemented in the CHEMCAD simulation for this project to ensure that validation of the obtained simulation data can thus take place easily.

4.1.3. Validation

The base model is validated according to various criteria before being supplemented with extended process optimizations. The criteria that are considered are the loadings and temperatures in the absorber and desorber, the specific energy to capture 1 ton of CO₂, and the loadings in the CO₂-rich and lean solvent. A validation approach by Gervasi et al. (2014) is comparing the thermal energy required per ton CO₂ captured for the reboiler. Typical values for a 90% CO₂ capture and a mass fraction of 30% MEA in the scrubber are 1.03 – 1.11 MWh/t CO₂ (Knudsen et al., 2009b) (Knudsen et al., 2009a), (Pasini et al., 2011).

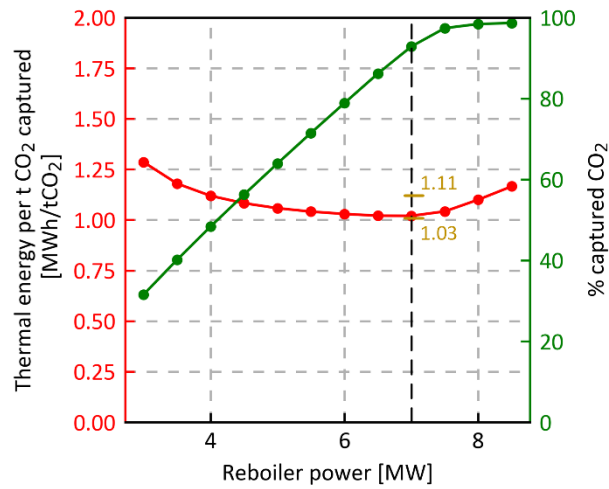


Figure 20: Flowrate: 40'823 kg CO₂/h, Composition Vol %: CO₂: 11.7%, H₂O: 16.7%, O₂: 5.8%, N₂: 65.8%, No process optimization and optimised control strategy (i.e. by-pass)

The compression and liquefaction system is validated according to the data from Chen and Morosuk (2021) and the CED by Sulzer. The performance of the compressors and the HEXs are also compared.

4.1.4. Process optimizations

In this project, the development of generic guidelines for designing and integrating a CO₂ capture plant should correspond to the current state of CO₂ capture plants. In the CED by Sulzer two process optimizations were considered. These process optimizations are **absorber intercooling (AIC)** and **rich stream splitting (RSS)**, see Figure 21.

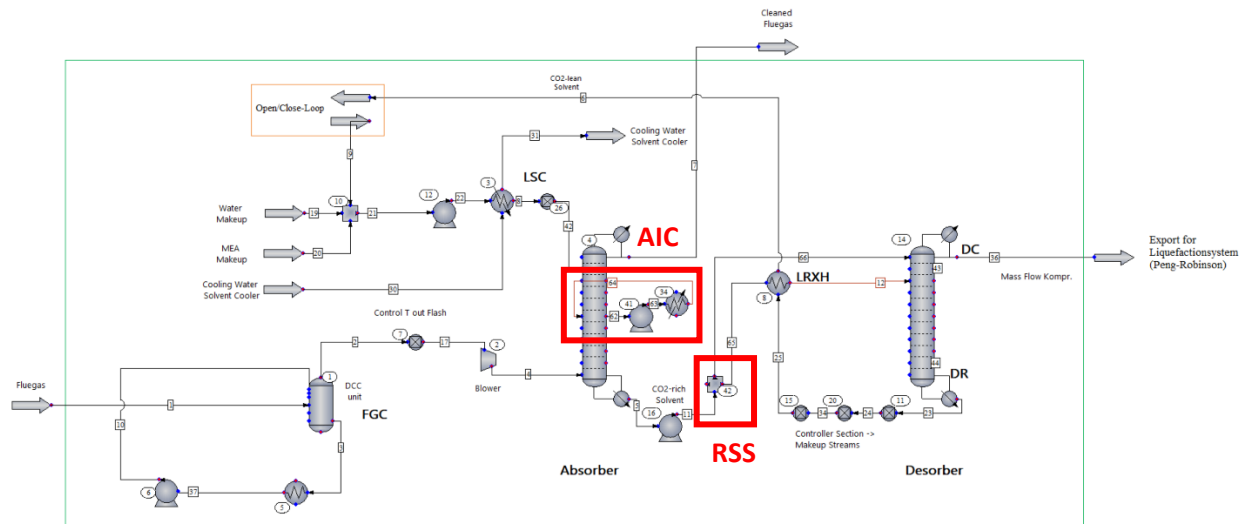


Figure 21: Simplified process flow diagram from CHEMCAD of CO₂ absorption process with process optimizations.

To operate the CO₂ capture process more efficiently, the optimizations of AIC and RSS are tested and their influence is explained.



Absorber-Intercooler

The optimal integration of the AIC is an extensive task. The aim is to understand at which stage of the absorber should the intercooler be integrated and the implications on the specific energy demand of the entire plant as well as the quality and quantity of the heat source from the intercooler. The system is modelled in accordance to (Cousins et al., 2011). In this model, the total amount of liquid (liquid ratio 1) is cooled with the AIC and the solvent is coupled and decoupled at the same stage. It is shown that implementing the AIC reduces the thermal energy required to capture 1 ton of CO₂ by 2 - 4%. The Tarong report achieves a saving up to 6.4% in the specific thermal energy demand for solvent regeneration (Cousins et al., 2011). In addition, the heat source of the AIC can be determined from the simulation data, which may be used for other purposes.

Rich Stream Split

The RSS is another process optimization considered in the Sulzer CED. In this configuration, a portion of the CO₂-rich solvent stream bypasses the rich/lean HEX and is fed directly into the upper section of the desorber. This reduces the thermal energy required for solvent regeneration, thereby lowering the specific energy demand per ton of CO₂ captured. In this study, the maximum energy savings achieved through RSS is approximately 8% at an optimal split ratio of 27.5%. These results align well with the findings of Cousins et al. (2012), who reported savings of around 7.1% at a 30% split ratio. Given this close agreement, the RSS optimization applied in our simulations is considered validated and suitable for further detailed assessments in system integration studies.

Total savings of around 13.6% occur around the 90% capture rate when implementing AIC and RSS. Thanks to the process optimizations, the plant runs more efficiently over the entire operating range.

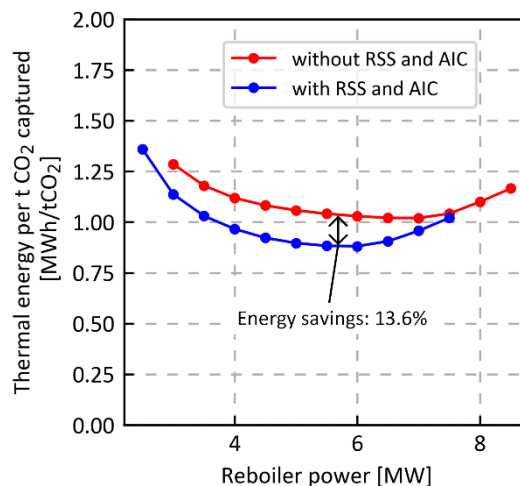


Figure 22: Comparison Base Case with and without Process optimization: Flowrate: 40'823 kg CO₂/h, Composition Vol %: CO₂: 11.7%, H₂O: 16.7%, O₂: 5.8%, N₂: 65.8%, 90 % CO₂-capture, Integrated AI.

The CHEMCAD simulation for the CO₂ capture plant is used as a base model to integrate the three processes. The inputs from the different processes are used as flow into the models. This sub-chapter lists and compares the differing input parameters and results.



4.1.5. Input parameters

The flue gas flowrates and compositions of all three processes are shown in Table 3. These data, provided by the industrial partners, serve as input parameters for modelling the flue gas stream in the CHEMCAD simulation.

Table 3: Flue gas compositions of the three case studies.

Flue gas Composition	KVA Linth		KSV Werdhölzli		HHKW Galgenen	
	Mass flow (kg/h)	wt%	Mass flow (kg/h)	wt%	Mass flow (kg/h)	wt%
CO ₂	16'700	11.4	2'800	10.3	9'000	13.2
H ₂ O	3'500	5.9	850	7.7	1'800	6.3
O ₂	6'500	6.0	1'300	6.6	3'200	6.5
N ₂	71'600	76.7	13'000	75.4	32'200	74.1
Total	98'200		17'900		46'200	

4.1.6. Pinch analysis of carbon capture plant

Figure 23Figure 23 the effect of implementing process optimizations on the heat integration potential of the CO₂ capture process. In subfigure (a), prior to applying the AIC and RSS, there is an overlap between the hot and cold CCs indicating available potential for internal heat recovery. After applying these optimizations (b), this heat recovery potential is fully exploited, as shown by the increased overlap of the composite curves. No further internal heat recovery can be achieved beyond this point, demonstrating the effectiveness of the applied process improvements.

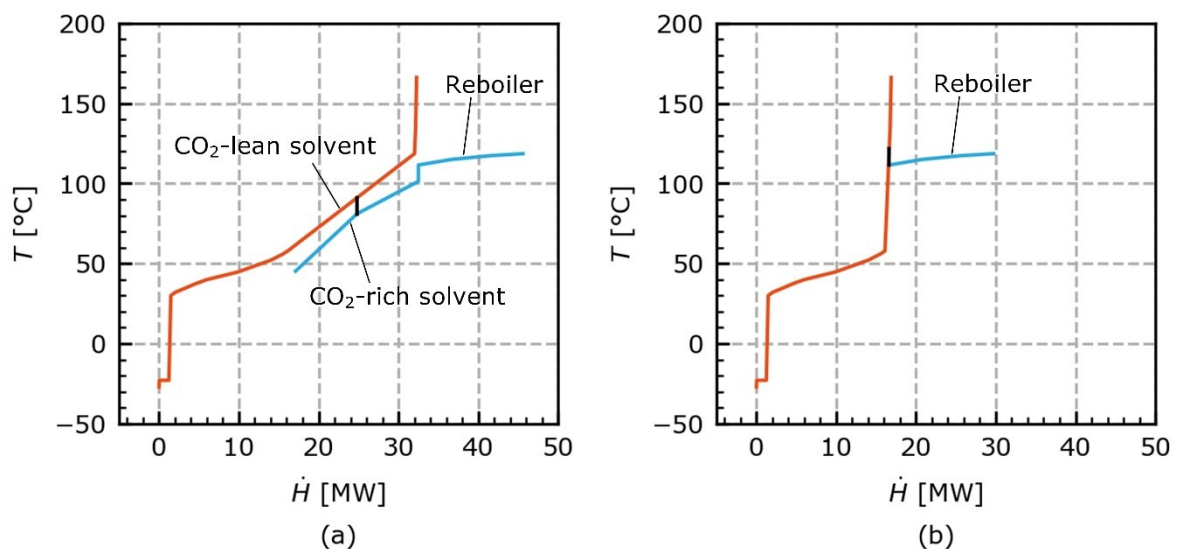


Figure 23: CCs of the CO₂ capture plant (a) before and (b) after implementation of process optimization of AIC and RSS.



4.1.7. Evaluation and results

One of the essential comparison values between the processes is the specific energy required to capture 1 ton of CO₂. This value provides information on how efficiently the process is operated. The comparison of the specific electrical demand is also relevant. Figure 24 shows that the specific demands for the processes are approximately the same at average of 0.88 MWh/t CO₂ (b). The specific electrical energy demands are also almost identical for all case studies, with a value of 0.12 MWh/t CO₂ (c) for the CO₂ absorption process. This is due to the very similar flue gas composition and the fact that identical base model is used for all the processes.

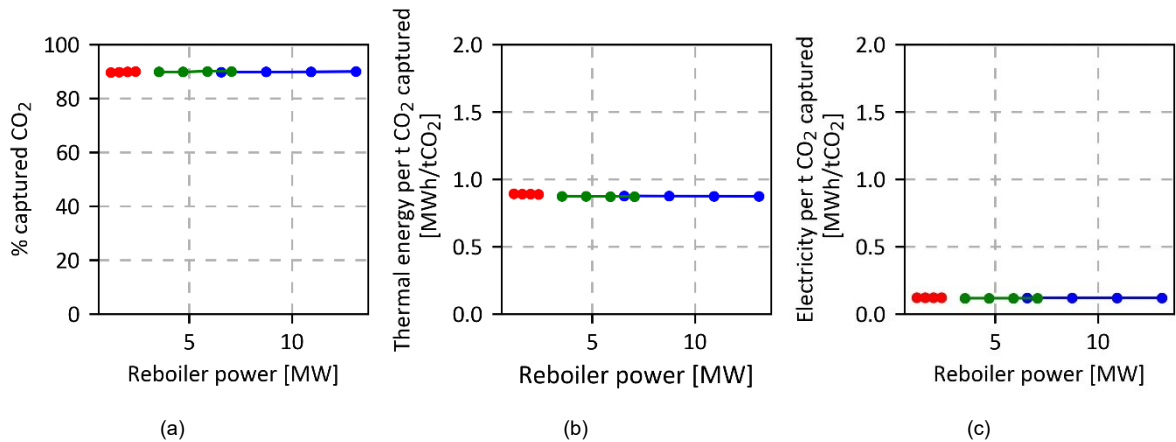


Figure 24: Evaluation of the partial load operation of the three case studies, KVA Linth (blue), KSV Werdhölzli (red), HHKW Galgenen (green) depending on reboiler power for (a) percent CO₂ captured, (b) thermal energy per ton of CO₂ captured and (c) electricity per ton of CO₂ captured.

4.1.8. Available excess heat from the CO₂ capture process

Figure 25 shows the reboiler energy for the cooling requirements (LSC) of the process. The results show that the cooling demand is linear with the reboiler capacity. Since the flue gas temperature of the Werdhölzli wastewater treatment plant is higher before entering the CO₂ capture plant, the specific cooling requirement is also about 10% higher.

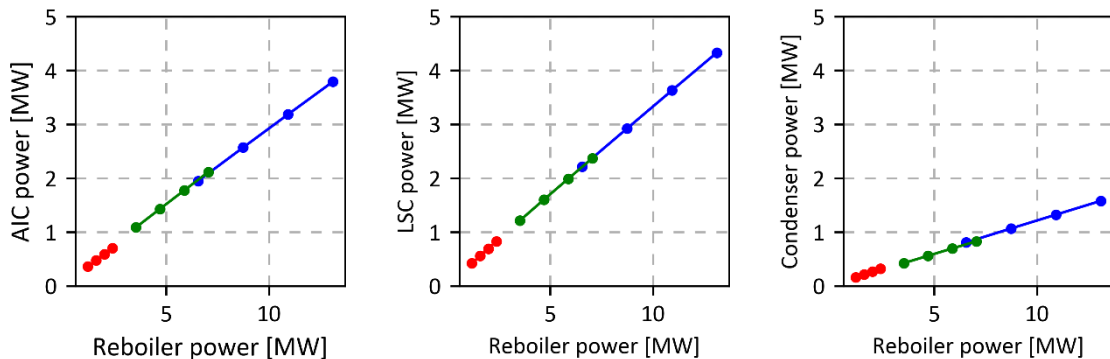


Figure 25: Evaluation of excess heat for the three case studies, KVA Linth (blue), KSV Werdhölzli (red), HHKW Galgenen (green).



Table 4: Compilation of the results from CHEMCAD

	KVA Linth	KSV Werdhölzli	HHKW Galgenen
Flue gas CO ₂ flowrate (kg CO ₂ /h)	16'700	2'800	9'000
Reboiler at 90% capacity (MW)	13.2	2.4	7.1
Specific thermal energy (MWh/t CO ₂)	0.88	0.89	0.87
Specific electrical power (MWh/t CO ₂)*	0.12	0.12	0.12
Specific cooling capacity (MWh/t CO ₂)	3.18	3.90	3.21

*for CO₂ absorption process only

4.2. KVA Linth

4.2.1. Pinch Analysis of processes

KVA Linth

KVA Linth operates a waste incineration plant in Niederurnen, utilising approximately 52% biogenic fuel. The plant's primary heat consumer is the DH network; in addition, electricity is generated by a turbine. Given that the primary business focus is on supplying heat to the DH network, a detailed understanding of the hot and cold utility demands of both the plant and the DH network is crucial for the successful implementation of the CO₂ capture plant. The process stream data for KVA Linth (detailed in the appendix) are provided by KVA Linth and used to generate the corresponding CCs and GCC, where the DH is scaled up to reflect the planned expansion of the plant during typical winter operations, as shown in Figure 26. These graphical tools are essential for identifying the critical hot and cold utility demands, which are crucial for the effective integration and implementation of the carbon capture plant.

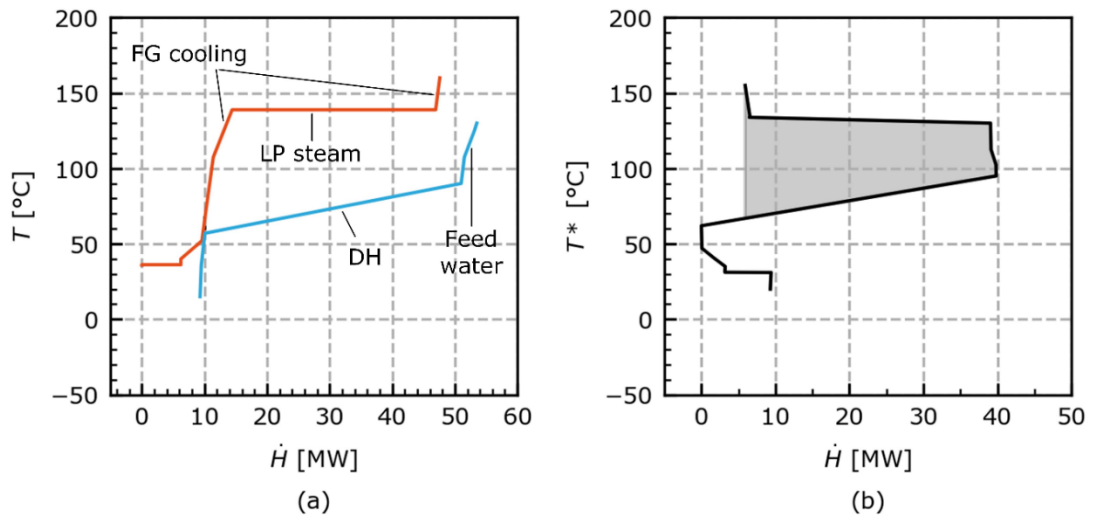


Figure 26: (a) CCs and (b) GCC of KVA Linth for a typical winter operating case.

From the CCs and GCC in Figure 26, the minimum specific HU and CU demands, and the maximum potential heat recovery of the processes are identified. In this case, the low pressure (LP) steam extracted from the turbine is defined as a process requirement, even though it is a utility. With this, any additional heat demand (district heating) that exceeds the plant's capacity is supplemented by peak load boilers. Figure 26 illustrates that the dominant heat demand arises from the DH network, with the remaining process requirements supporting the waste incineration operations. The resulting PA and the annual load profile (Figure 26Figure 12 (a)) were subsequently modelled in Modelica, providing a



detailed representation of the plant's thermal performance and integration potential. Figure 27 shows the stack plot of KVA Linth, depicting the operational dynamics.

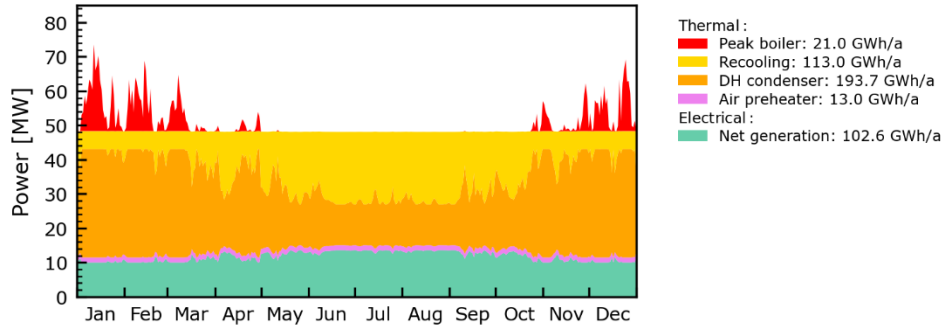


Figure 27: Annual stack plot of extracted heat flow rates and electric power from the case study.

It is evident from the analysis, that with the planned expansion, the existing LP steam capacity is insufficient to meet the peak heating demand of the DH network without the CO₂ capture plant. This excess demand is currently addressed by the peak load boiler for the expansion scenario. Figure 27 details the contributions of the various components under consideration, with electricity and heat extracted from the process summed in the vertical axis of the stack plot to provide an overview of the distribution of the different energy shares over time. A significant opportunity exists for using the recooling capacity throughout the year together with the CO₂ capture plant, enhancing overall system efficiency and reducing reliance on supplementary heating.

CO₂ capture plant

Figure 28 shows the CCs and GCC for the CO₂ capture plant, derived from the flue gas composition detailed in Table 3. The process requirements considered for the CO₂ capture are outlined in the appendix (Table 12).

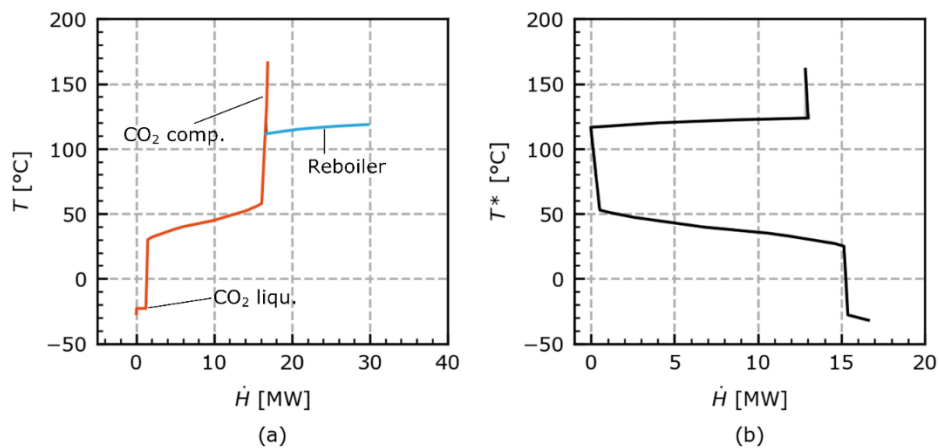


Figure 28: (a) CCs and (b) GCC of the CO₂ Capture Process with flowrates from KVA Linth at 90 % capture rate on an average winter day.



The CCs and GCC of the CO₂ capture plant have a pinch temperature of 86 °C. The curves depicted in Figure 28 refers to the CO₂ capture rate of 90% for the flue gas of KVA Linth. Since the base model is the same for all case studies, the CCs and GCC of the plants differ only in the absolute values, since different amounts of reboilers capacities are required due to the changing amount of CO₂, including the operation of reboilers.

4.2.2. Integration concepts

For KVA Linth, 3 integration concepts are evaluated to integrate the CO₂ capture plant.

- Integration concept 1 – Integrated system
- Integration concept 2 – Integrated system with HP
- Integration concept 3 – Integrated system with AHP

Figure 29 and Figure 30 show the possible integration.

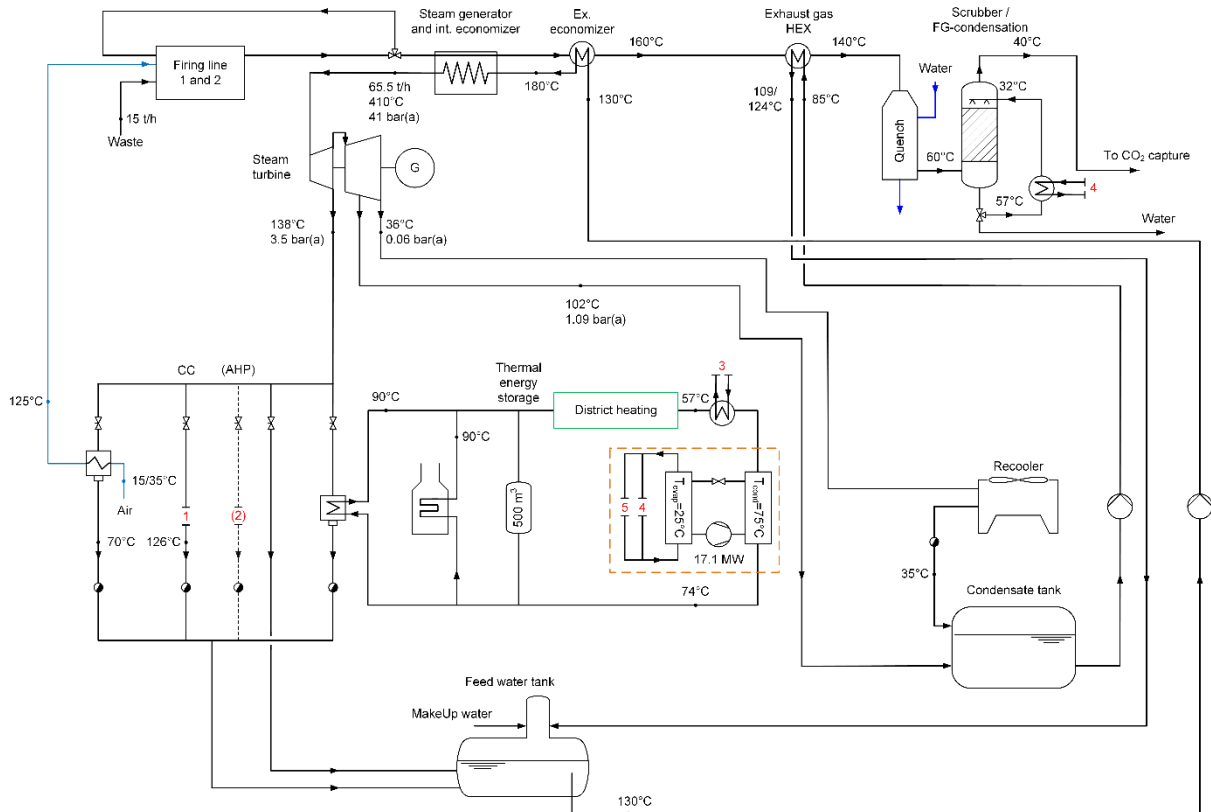


Figure 29: Integration concepts of KVA Linth and CO₂ capture plant for all ICs, where the dotted lines represent IC2 and 3.

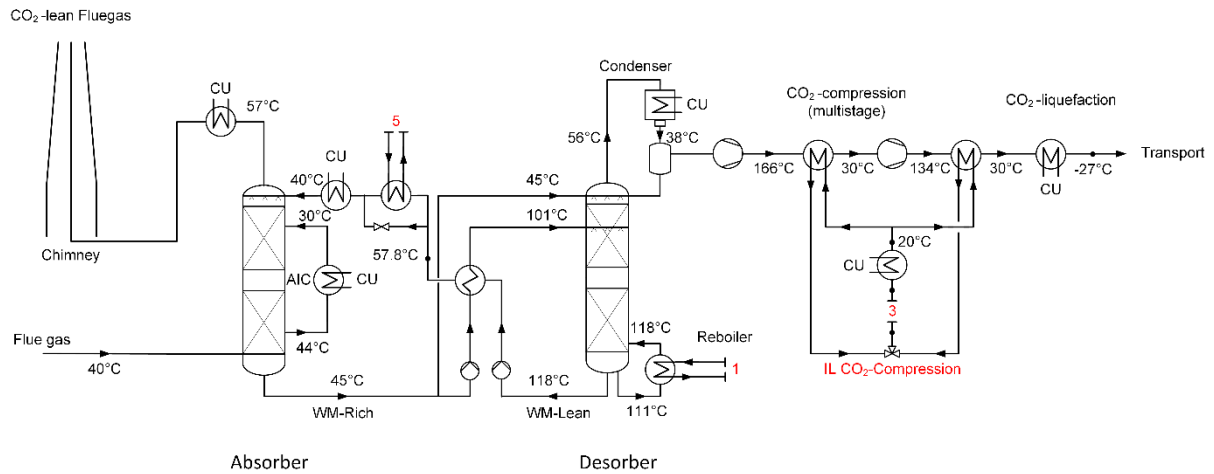


Figure 30: Integration concepts of KVA Linth and CO₂ capture process.

Integration concept 1 – Integrated system

IC1 involves evaluating the integration between the CO₂ capture plant and KVA Linth. The CCs and GCC of the integrated system are shown in Figure 31.

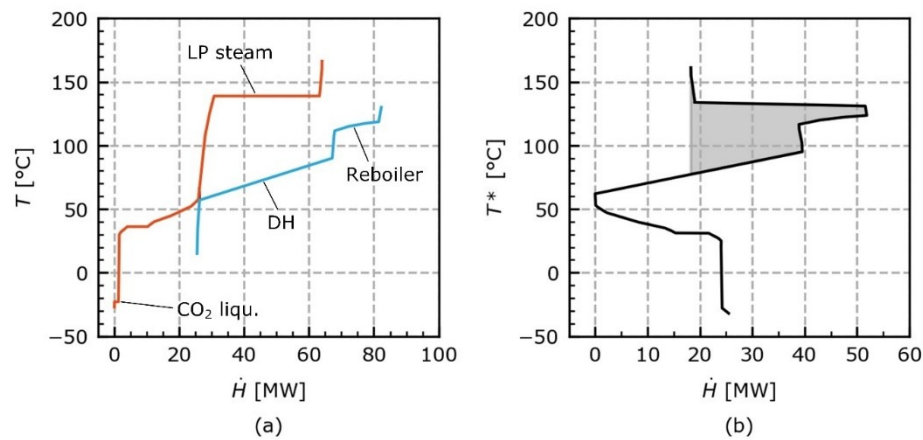


Figure 31: CCs and GCCs of the integrated CO₂ capture process with KVA Linth, on an average winter day at a 90% CO₂ capture, DH KVA Linth.

In the integrated process for KVA Linth, a significant heat deficit is evident, as depicted in Figure 31. The LP steam, which is typically used for DH, is now redirected to heat the reboiler of the CO₂ capture plant (Figure 31 (b)). Figure 32 illustrates the impact on the heat sources on the DH network when the CO₂ capture plant is integrated. Based on PA, a heat recovery measure can be implemented at the CO₂ compression stages to the DH network. In this case, it is implemented through an intermediate loop, as shown in Figure 29 and Figure 30. Using an intermediate loop provides a safer, more controllable and efficient method for heat recovery in CO₂ compression stages, addressing the challenges of direct heat recovery from high pressure CO₂-rich streams.

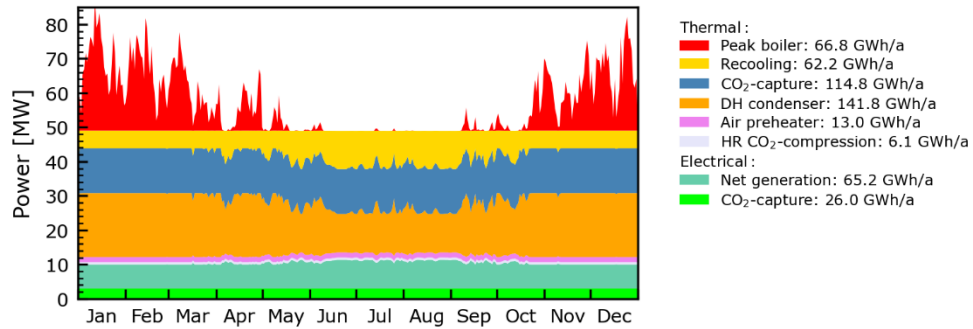


Figure 32: Annual stack plot of extracted heat flow rates and electric power of Integration Concept 1 (IC1).

With a constant CO₂ capture operation, the heat load for KVA Linth is splitted between DH and the CO₂ capture process. Compared to the KVA Linth depicted in Figure 27, the peak load boiler capacity increases from 21.0 GWh/a to 66.8 GWh/a. Due to the higher steam flow decoupled after the first stage, the total electricity generated in the system as a whole is reduced. Therefore, net electricity generation decreases from 102.6 GWh/a to 65.2 GWh/a and 26.0 GWh/a used for the CO₂ capture plant.

As shown in Figure 32Figure 31, with the planned DH expansion and CO₂ capture plant integration, there is a deficit of 18.9 MW at the KVA Linth in the average winter case. With the pinch point of 60°C, the excess heat can be valorised through upgrading technologies such as HP and/or AHP.

Integration concept 2 – Integrated system with compression heat pump

Figure 33Figure 33 shows the CCs and GCC of the integrated system with a HP.

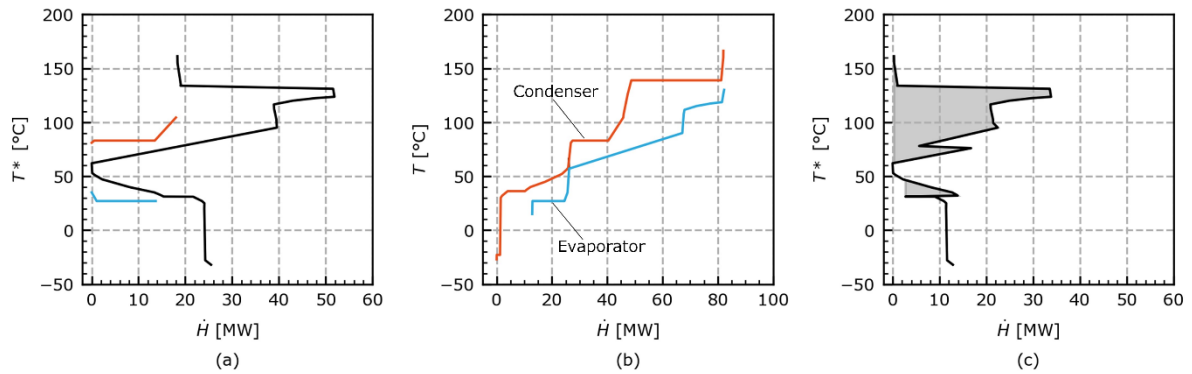


Figure 33: Variant 1 – (a) GCC of KVA Linth with potential HP, and (b) CCs and (c) GCC of KVA Linth with integrated HP on an average winter day

Figure 33Figure 33 shows the integration of a HP into the system, effectively addressing the deficit of 18.9 MW in the DH network. To optimise both cost and operational parameters, various HP capacities are evaluated, resulting in the selection of a 17.1MW HP for KVA Linth. This HP utilises heat from the lean CO₂ stream from the CO₂ capture plant (point 5 in Figure 30) and waste heat from the flue gas scrubber, as depicted in Figure 29Figure 29. Under these conditions, the HP achieves a COP of 3.8. The Modelica simulation results of the HP are shown in Figure 34Figure 34.

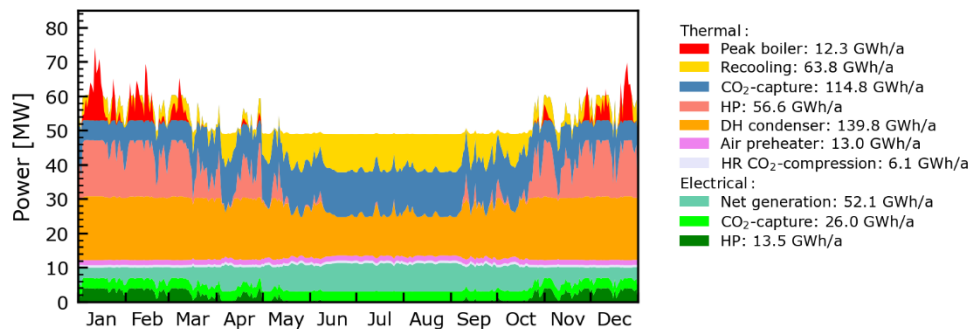


Figure 34: Annual stack plot of extracted heat flow rates and electric power of integration concept 2 (IC2).

During summer operations, the IC2 eliminates the heat deficit entirely. The peak load boiler requirement decreases significantly to 12.3 GWh/a due to the heat pump's contribution. Although the net electricity available for sale is reduced by 13.1 GWh/a due to the power consumption of the HP, this is compensated by the substantial reduction in peak load boiler operation and enhanced system efficiency.

Integration concept 3 – Integrated system with absorption heat pump

The integration of an AHP offers several advantages, primarily by reducing the extraction of LP steam from the turbine. The AHP condenser transfers energy from both the LP steam (high-temperature) and the evaporator (low-temperature) to the DH network. This configuration enables the delivery of higher power to the DH network with the same amount of steam or reduces the amount of LP steam required to achieve the same power output. For KVA Linth, the planned DH extension includes the integration of a 20 MW AHP, with its annual performance represented in the stack plot shown in Figure 35.

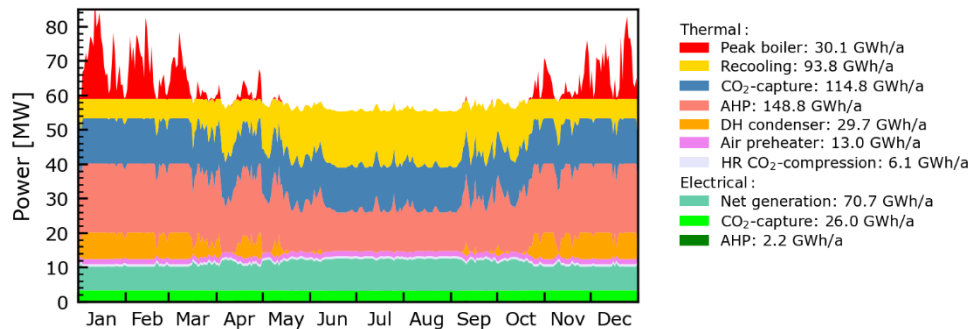


Figure 35: Annual stack plot of extracted heat flow rates and electric power of 20 MW AHP.

Compared to IC2, IC3 has an increase in the peak boiler load by 17.8 GWh/a. The fact that less LP steam is decoupled also increases the power production of the system. As the CO₂ capture plant is integrated, sufficient excess heat is available at a lower-temperature level. Moreover, according to PA, a AHP of 33 MW is possible. Figure 36 shows the CCs and GCC of the case study with an AHP.

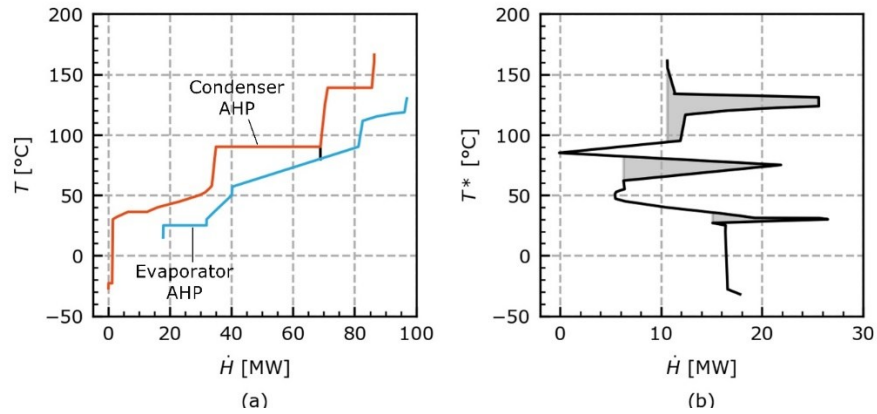


Figure 36: (a) CCs and (b) GCC of KVA Linth with integrated AHP on an average winter day with constant CO_2 capturing rate.

Even with the AHP, the winter DH demand cannot be fully met, leaving a 4.4 MW deficit. This shortfall is due to the output limitations of LP steam, which is constrained by the maximum decoupling capacity. The Modelica simulation of the AHP shows in Figure 37 further details of the operational dynamics.

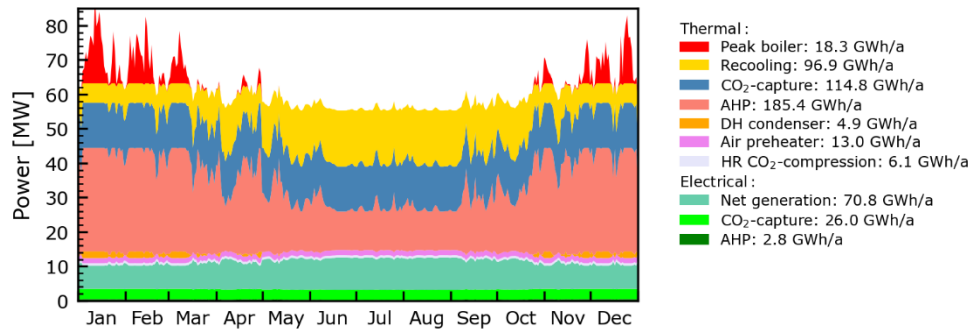


Figure 37: Annual stack plot of extracted heat flow rates and electric power of 30 MW AHP.

The integration of the AHP results in increased electricity production throughout the year, with the AHP supplying approximately two-third of the heat demand for the DH network. The schematic in Figure 38 illustrates the AHP configuration, replacing the HP within the dotted box from Figure 29.

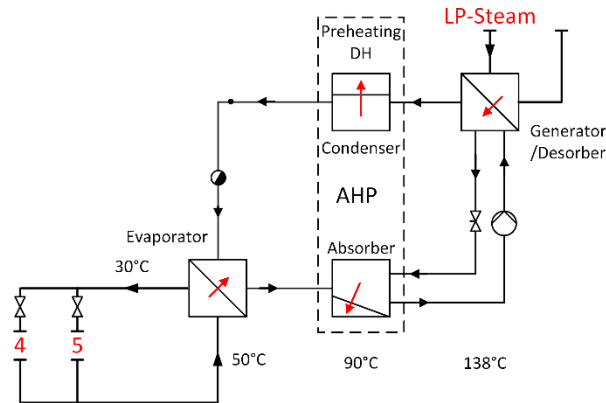


Figure 38: Schematics of the AHP.

The planned 20 MW AHP configuration utilises waste heat from the flue gas (FG) scrubber (Stream 4) and, for the 30 MW configuration, additionally leverages heat from the CO₂ lean stream. However, according to the European Commission report (2017) on large-scale heating and cooling, the largest currently installed AHP in the EU is of only 12 MW. Therefore, this integration concept only considers a 10 MW AHP, which solely uses the heat source from Stream 5 in Figure 30. Based on the cost assumptions for the AHP, the 10 MW configuration emerges as the most economical option among the three evaluated sizes.

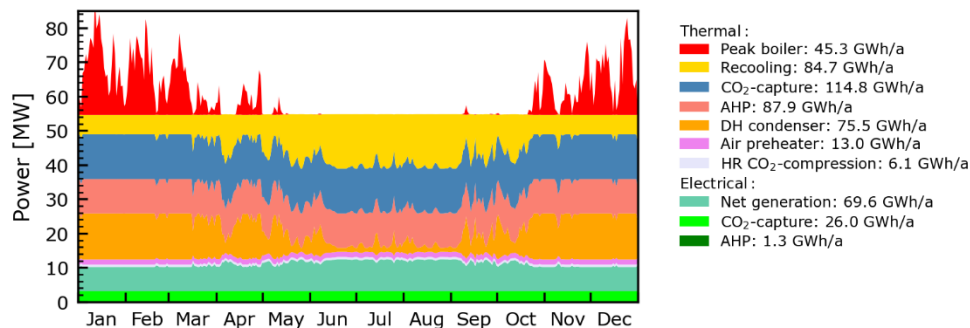


Figure 39: Annual stack plot of extracted heat flow rates and electric power of Integration Concept 3 (IC3) with a 10 MW AHP.

4.2.3. Techno-economic analysis

Key assumptions for the economic assessment are listed in Section 2.4. **Erreur ! Source du renvoi introuvable.** CO₂ capture processes are capital-intensive projects that involve technologies that have limited historical data. This introduces considerable business risks to the technological implementation. In the column of IC2 (+50%), the capital cost of the CO₂ capture plant is assumed to be 50% higher than the cost used for the other analysis. In capital cost estimation, the cost usually has an error of 30%, 50% is used instead as it is to reflect the worst-case scenario. Based on the techno-economic analysis, it is evident in KVA Linth that the integrated system with HP (IC2) has the lowest cost due to the reduction in the peak load boiler compared to the other integration concepts. In the PA, the 18.9 MW HP is the maximum capacity of the HP to be integrated. However, the operation of HP at that capacity only allows a full capacity operation of 1'026 hours. By reducing it to 17.1 MW, the HP can operate full load at 2'096 hours.



In addition, the HP emerges as the preferred integration solution for KVA Linth due to its superior performance in meeting the heat demand while optimising operational costs. The HP not only effectively covers the DH deficit but offers also a high COP of 3.8, ensuring efficient energy use. Additionally, the HP integration minimises reliance on the peak load boiler, significantly lowering operational costs associated with fuel consumption and emissions. While there is a trade-off in reduced electricity sales, the overall cost savings and enhanced system performance position the HP as the most viable and sustainable solution among the integration concepts evaluated.

While the AHP integration provides significant operational benefits by increasing electricity production and reducing LP steam decoupling, it is constrained by current technological limitations and market availability, making the proposed 10 MW AHP the most viable and cost-effective solution within these boundaries. However, the inability to fully cover the winter heating demand suggests that, despite the advantages, AHP alone may not sufficiently meeting the peak demands of the DH network in its expanded state. Consequently, this integration concept must be weighed against the HP alternative, which fully addresses the DH deficit with a higher COP and less dependence on LP steam.

Table 5 shows the techno-economic assessment concepts for KVA Linth.

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Table 5: Comparison of techno-economic analysis of the different integration concepts.

	Units	IC1	IC2	IC3	IC2 (+50%)
Total CO₂ captured	t CO ₂ /a	120'000	120'000	120'000	120'000
HP capacity	MW	-	17.1	20.0	17.1
Capital cost					



Investment cost of CO₂ capture	mil. CHF	86.0	86.0	86.0	119.2
Annualised investment cost of CO₂ capture	mil. CHF/a	7.5	7.5	7.5	11.0
Investment cost of EEMs*	mil. CHF	0.8	19.6	44.3	19.6
Annualised investment cost of EEMs*	mil. CHF/a	0.07	1.7	3.9	1.7
Operating cost					
Fixed operating	mil. CHF/a	2.9	3.1	3.5	4.1
Peak load boiler**	mil. CHF/a	3.0	-0.6	0.6	-0.6
Electricity generation losses**	mil. CHF/a	3.0	4.0	2.5	4.0
Other variable OM	mil. CHF/a	0.3	0.3	0.3	0.3
Total annual Cost	mil. CHF/a	16.8	16.1	18.3	20.8
Levelised CO₂ captured cost	CHF/t CO ₂	140.1	129.7	152.2	170.7
With early movers solution	CHF/t CO ₂	660.1	649.7	672.2	690.7
With dedicated vessels	CHF/t CO ₂	500.1	489.7	512.2	530.7

*EEMs include HP/AHP and HEN.

**operating cost is compared to the expansion scenario with no CO₂ capture plant.



KSV Werdhölzli

4.2.4. Pinch Analysis of processes

KSV Werdhölzli

KSV Werdhölzli operates a sewage sludge incineration plant with internal process requirements for sewage treatment, including sludge heating and drying. Remaining heat is supplied to external consumers, DH network and GTP. The process stream data, provided by the industrial partner, are used to generate the CCs and GCC, which represent typical winter operations for internal heat use (Figure 40).

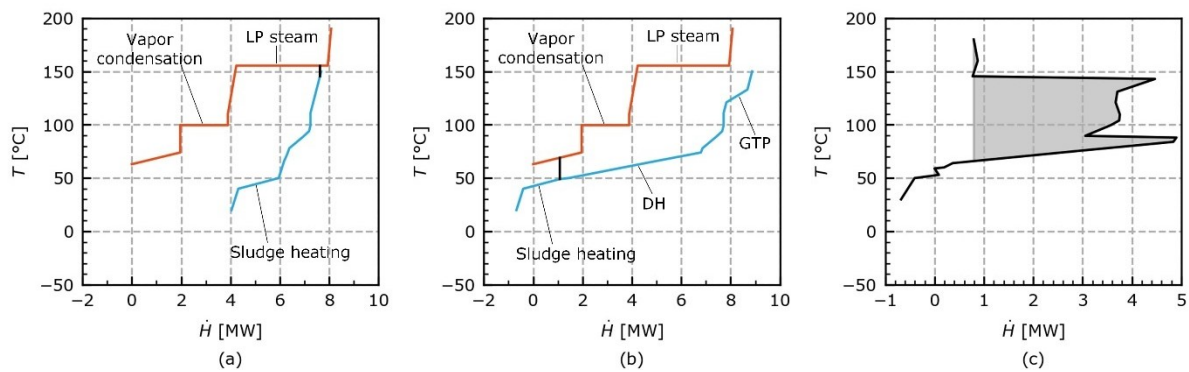


Figure 40: (a) CCs without DH and GTP, and (b) CCs and (c) GCC with DH from the KSV Werdhölzli.

Figure 40(a) illustrates the CCs for the internal processes, highlighting the minimum specific HU and CU demands, as well as the maximum potential for heat recovery within the plant. In contrast, Figure 40 (b) and (c) display the CCs and GCC with external consumers. The analysis shows that, in the current state, not all process requirements are met with the available LP steam, necessitating supplementary heating from external peak load boilers for the DH network. Notably, some process requirements at KSV Werdhölzli operate at lower temperature levels compared to KVA Linth. The stack plot in Figure 41, generated using input from Figure 14 and Figure 15, provides an overview of heat demands across the various processes over the year.

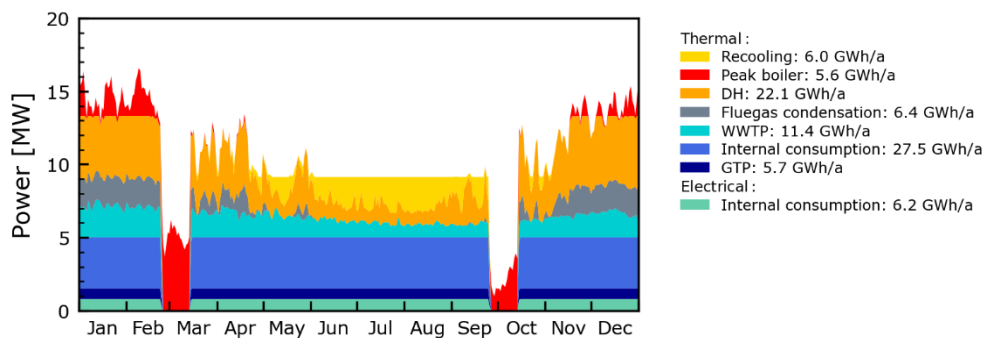


Figure 41: Annual stack plot of extracted heat flow rates and electric power from KSV Werdhölzli.

All electricity generated is consumed within the process. An external heating of 5.6 GWh/a is needed for the DH. In this study, two shutdowns are considered for an average of two weeks. LP steam is needed during this period to provide heat to the WWTP and to start up the processes.





CO₂ Capture Process

Figure 42 shows the CCs and GCC for the CO₂ capture plant, derived from the flue gas composition detailed in Table 3. The process requirements considered for the CO₂ capture are outlined in the appendix (Table 14).

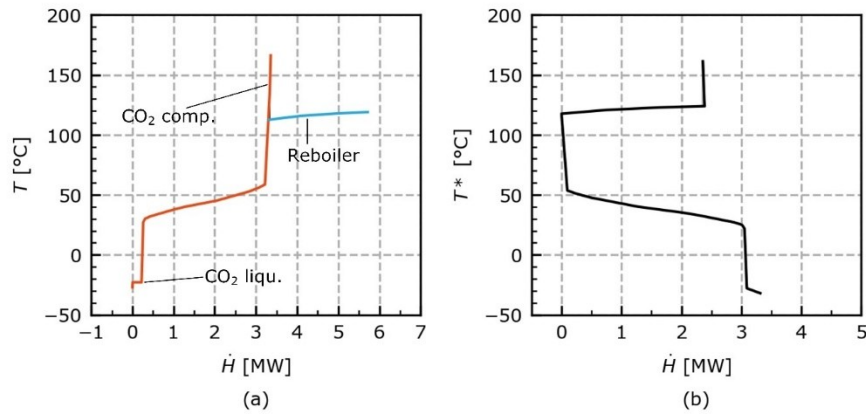


Figure 42: (a) CC and (b) GCC of the CO₂ capture plant for KSV Werdhölzli

The figure shown here refers to the CO₂ capture process for the KSV Werdhölzli at 90% capture of the flue gas. Since the base model is the same for all case studies, the CCs and GCC of the plants differ only in the absolute values, since different amounts of reboilers capacities are required due to the changing amount of CO₂, including the operation of reboilers.

4.2.5. Integration concepts

For KSV Werdhölzli, two integration concepts are evaluated to integrate CO₂ capture plant, based on the current operations:

- Integration concept 1 – Integrated system
- Integration concept 2 – Integrated system with HP

Figure 44 and Figure 43 show the integration between KSV Werdhölzli and the CO₂ capture plant. AHP is not considered for this case because there is insufficient steam for the case.

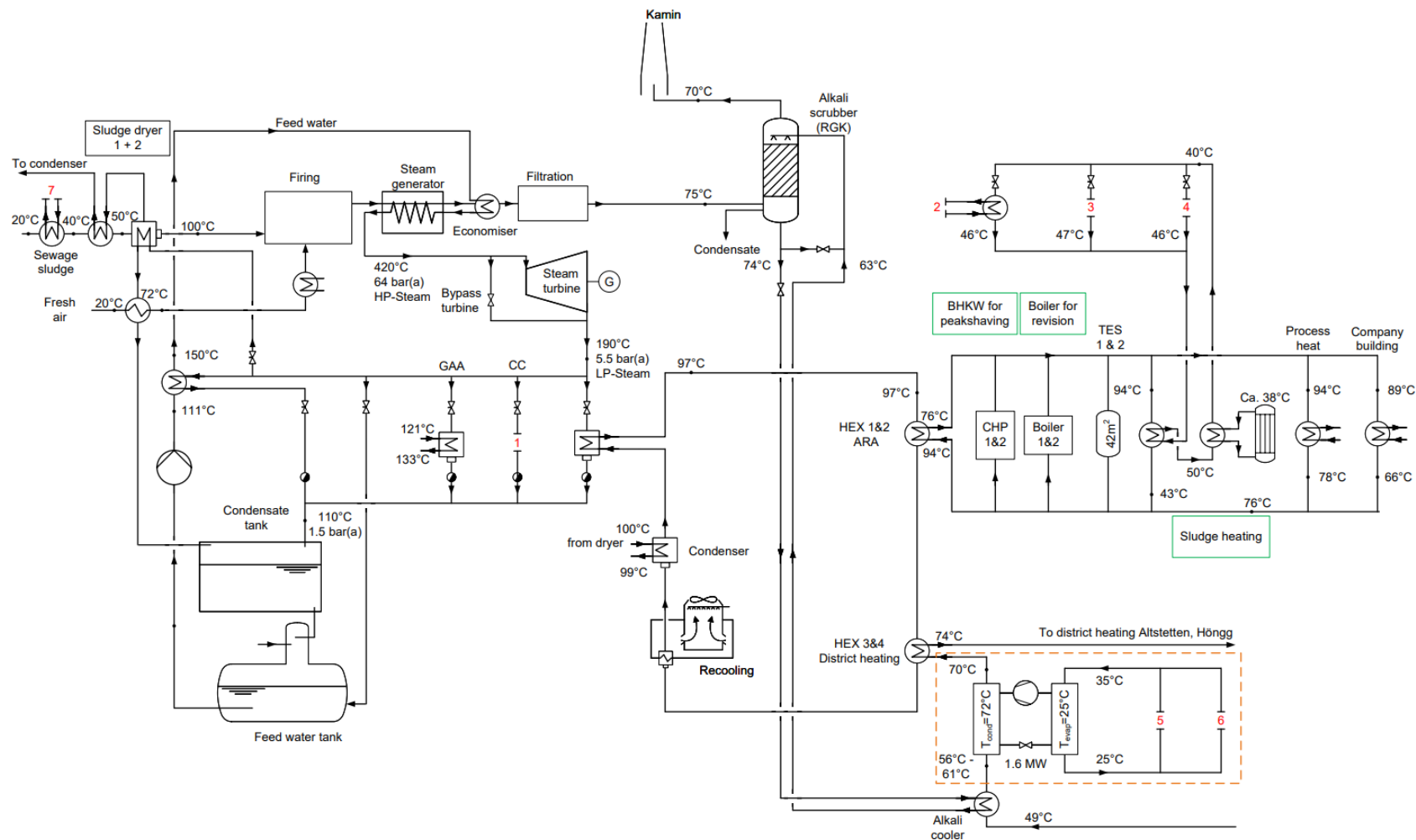


Figure 43: Integration concepts of KSV Werdhölzli and CO₂ capture process for all ICs, where the orange dotted box refers for only IC2.

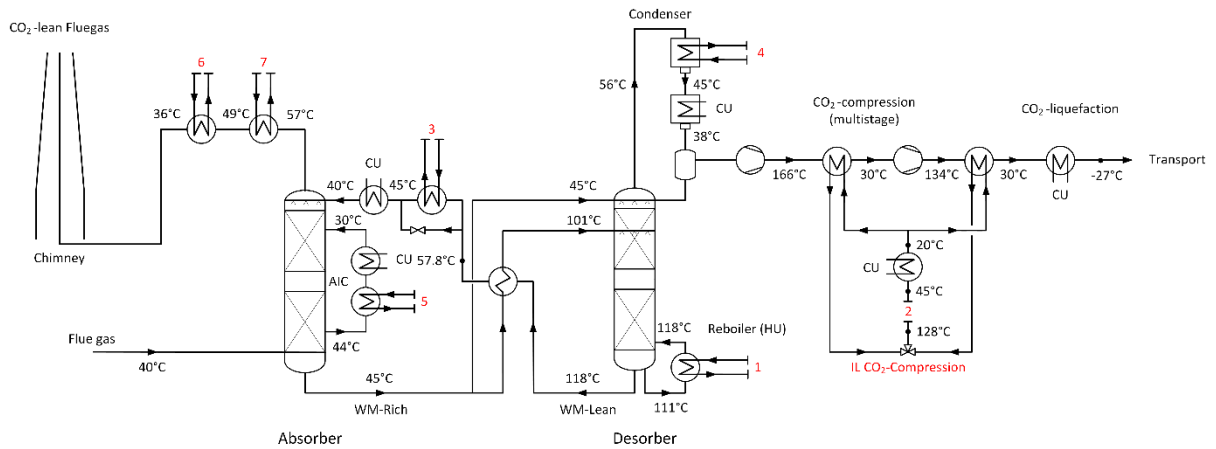


Figure 44: Integration concepts of KSV Werdhölzli and CO₂ capture process.

Integration concept 1 – Integrated system

IC1 involves evaluating the integration between the CO₂ capture plant and KSV Werdhölzli. Figure 45 shows the CCs and GCC of the integrated system.

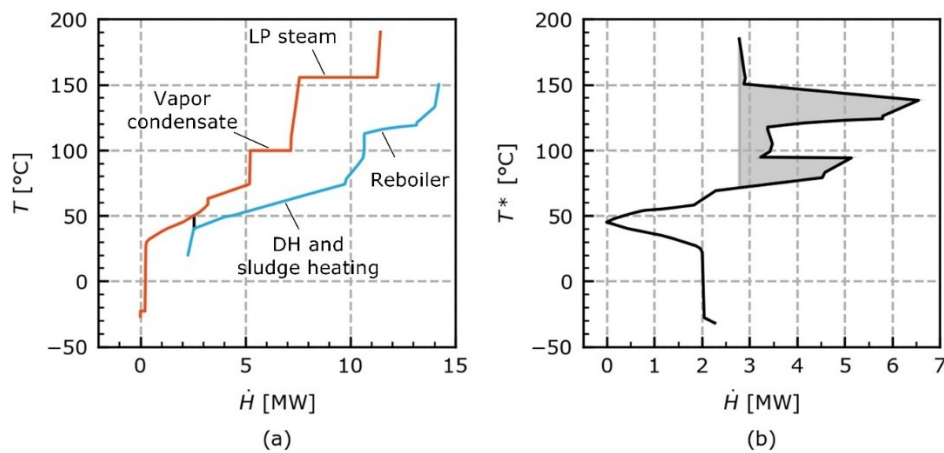


Figure 45: (a) CCs and (b) GCCs of the integrated CO₂ capture process with KSV Werdhölzli, on an average winter day at a 90% CO₂ capture.

IC1 leads to a deficit of 2.1 MW in the DH network during the average winter case, as shown in Figure 45. The LP steam, which typically supplies the DH network, is redirected to heat the reboiler of the CO₂ capture plant, causing the DH supply deficit. Currently, there are no binding contracts with external heat consumers, allowing for flexibility in heat allocation.

Based on PA, a heat recovery measure can be implemented with multiple streams from the CO₂ capture plant to Werdhölzli. A large heat consumer of the Werdhölzli sewage treatment plant is the process requirement of the sewage sludge heating. This process occurring at a temperature level of 38°C is currently supplied with thermal energy by the LP steam. Since the excess heat flows of the CO₂ capture plant exist on higher temperature levels, a utilization of the excess heat is possible (as shown in Figure 44 and Figure 43). The heat recovery implemented through an intermediate loop, as it provides a safer,



more controllable, and efficient method for heat recovery, addressing the challenges of direct heat recovery from high pressure CO₂-rich streams or to heat up sewage sludge streams.

A large part of the exhaust heat from the CO₂ capture plant can be integrated directly into the wastewater treatment plant process and direct heat recovery can take place in the sludge heating process. The alkali cooler is retrofitted for heat recovery to “pre-heat” the DH. Figure 46 shows the stack plot of the IC1. The annual simulations demonstrate how the changes in process requirements and peak load boiler can occur. From these evaluations, system characteristics such as district heat sold, and amount of CO₂ captured can then be seen more accurately.

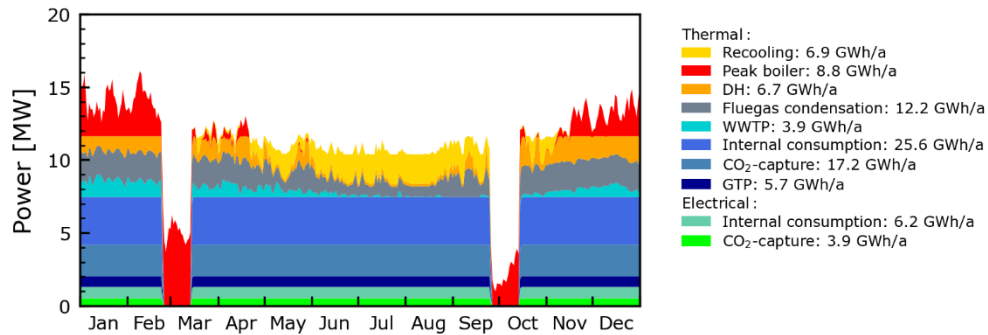


Figure 46: Annual stack plot of extracted heat flow rates and electric power of Integration Concept 1 (IC1).

The peak load boiler in Figure 46 shows that the amount of extra fuel needed to supplement the DH network is about 3.2 GWh/a. An additional of 3.9 GWh/a electricity is needed for the CO₂ capture plant, as all electricity generated is consumed internally.

Integration concept 2 – Integrated system with compression heat pump

To address the DH deficit, Integration Concept 2 introduces a HP into the system (Figure 47).

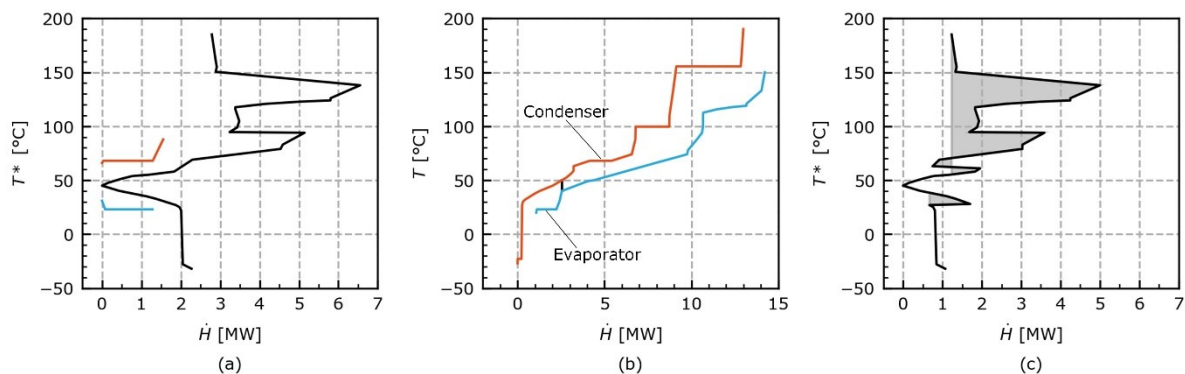


Figure 47: CCs and GCC from KSV Werdhölzli with integrated HP on a average winter day

Figure 47 shows the integration of a HP into the system, effectively addressing the deficit of 2.2 MW. To optimise both cost and operational parameters, various HP capacities are evaluated, resulting in the selection of a 1.6 MW HP. This HP uses excess heat from the AIC from the CO₂ capture plant and waste heat from the flue gas to stack, as depicted in in Figure 44 and Figure 43. Under these conditions, the HP achieves a COP of 4.0. The Modelica simulation of the HP is shown in Figure 48.

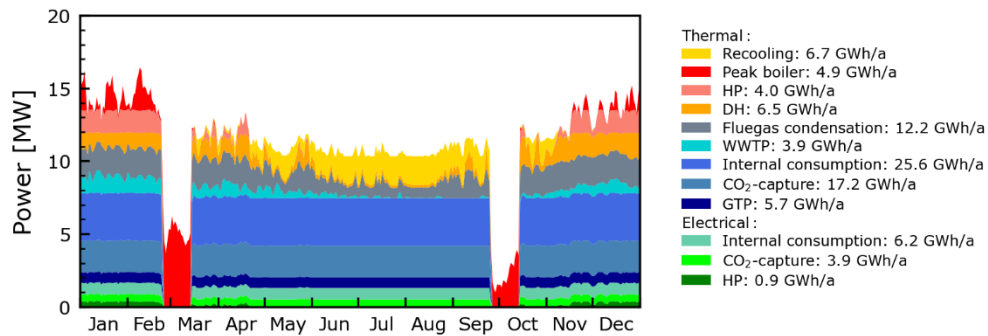


Figure 48: Annual stack plot of extracted heat flow rates and electric power of Integration Concept 2 (IC2).

By integrating a HP, the peak boiler is reduced to 4.9 GWh/a, which is 3.9 GWh/a less than IC1. Thanks to the COP of the HP, less than 1 GWh/a of electricity is needed to operate the HP.

4.2.6. Techno-economic analysis

Key assumptions for the economic assessment are listed in Section 2.4.

Table 6 shows the techno-economic assessment concepts for KSV Werdhölzli.

CO₂ capture plants are capital-intensive projects that involve technologies that have limited historical data. This introduces considerable business risks to the technological implementation. In the column of IC2 (+50%), the capital cost of the CO₂ capture plant is assumed to be 50% higher than the cost used for the other analysis. IC1 is more cost-effective, with a lower cost of 215 CHF/t CO₂ compared to 222 CHF/t CO₂ for IC2. This difference indicates that IC1 provides a more economical solution for integrating CO₂ capture into KSV Werdhölzli's existing operations. Although IC2 has a slightly higher cost, it offers operational advantages by incorporating a HP, which effectively addresses the DH network deficit and reduces the reliance on the peak load boilers. The HP also allows a better utilization of excess heat from the CO₂ capture plant, leading to a more balanced and energy-efficient operation. IC1 might be preferable from a purely cost perspective, especially when immediate cost savings are prioritised. However, IC2 provides long-term strategic benefits by enhancing operational efficiency which could translate to lower operating costs over time, increased resilience, and better alignment with energy sustainability goals.



Table 6: Comparison of techno-economic analysis of the different integration concepts.

	Units	IC1	IC2	IC2 (+50%)
Total CO₂ captured	t CO ₂ /a	19'800	19'800	19'800
HP capacity	MW	-	1.6	1.6
Capital cost				
Investment cost of CO₂ capture	mil. CHF	26.7	26.7	40.1
Annualised investment cost of CO₂ capture	mil. CHF/a	2.3	2.3	3.5
Investment cost of EEMs*	mil. CHF	0.6	2.8	2.8
Annualised investment cost of EEMs*	mil. CHF/a	0.05	0.2	0.2
Operating cost				
Fixed operating	mil. CHF/a	1.2	1.2	1.3
External heat needed for DH**	mil. CHF/a	0.1	-0.03	-0.03
Electricity generation losses**	mil. CHF/a	0.6	0.8	0.8
Other variable OM	mil. CHF/a	0.05	0.05	0.05
Total annual cost	mil. CHF/a	4.2	4.4	5.9
Levelised CO₂ captured cost	CHF/t CO ₂	215.0	222.1	294.6
With early movers solution	CHF/t CO ₂	735.0	742.1	816.6
With dedicated vessels	CHF/t CO ₂	575.0	582.1	656.6

*EEMs include HP and HEN.

**operating cost is compared to the expansion scenario with no CO₂ capture plant.



HHKW Galgenen

4.2.7. Pinch Analysis of processes

HHKW Galgenen

HHKW Galgenen is a wood-fired power plant located in Galgenen, using an average fuel mix of 70% waste wood and 30% wood chips. The plant operates with a feed grate furnace that produces steam, which is then expanded through a turbine to a pressure of 2.5 bar for supplying the DH network. HHKW Galgenen operates variably, depending on the DH demand. The plant is planned for an expansion in 2026. As detailed in Figure 49, the CCs and GCC shows the current heat integration scenario including the existing heat recovery measures from flue gas and feed grate.

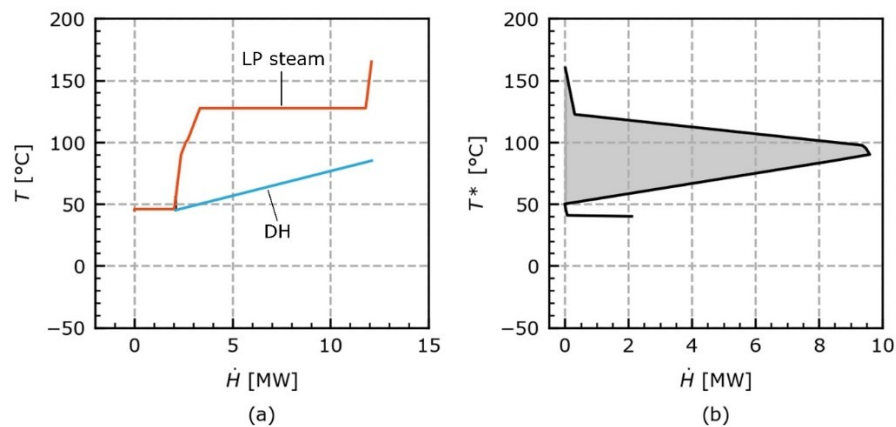


Figure 49: (a) CCs and (b) GCC of HHKW Galgenen for a typical winter operating case.

Figure 49 shows the full utilization of steam in HHKW Galgenen, indicating the plant operation, which is based on heat requirements. Heat is recovered from flue gas and feed grate to heat up the DH network. Internal processes utilise 8% of the total electricity generated, as shown in the stack plot (Figure 50).

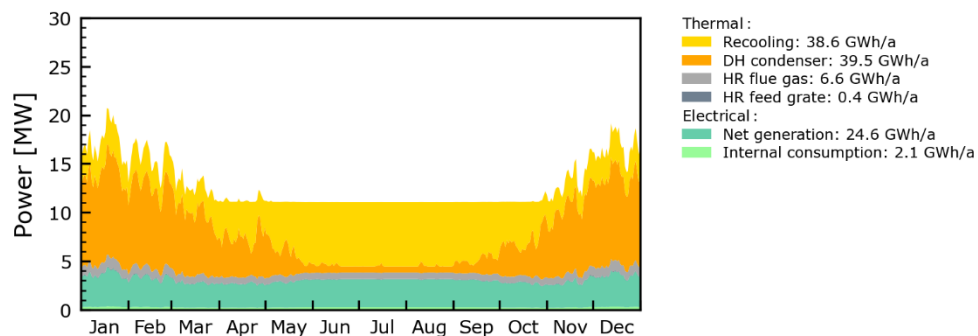


Figure 50: Annual stack plot of extracted heat flow rates and electric power from HHKW Galgenen.



CO₂ Capture Process

Figure 51 presents the CCs and GCC for the CO₂ capture process. They are based on the flue gas composition as shown in Table 3.

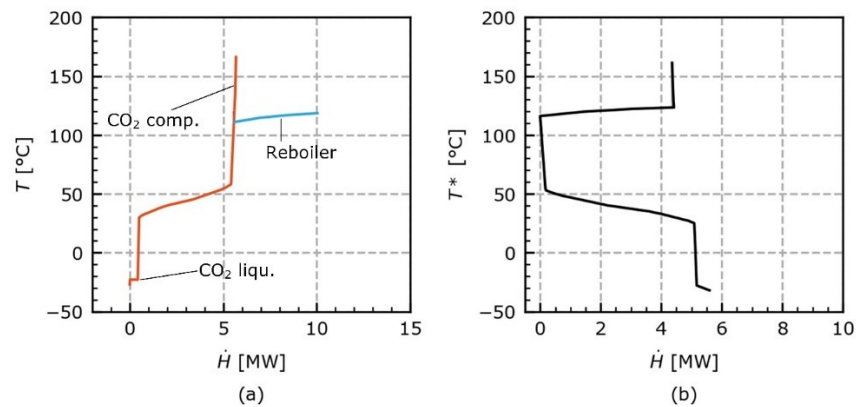


Figure 51: (a) CCs and (b) GCC of the CO₂ Capture Process with flowrates from HHKW Galgenen at 90 % capture rate on an average winter day.

4.2.8. Integration concepts

Two integration concepts are considered. The integration concepts explored for HHKW include:

- Integration concept 1 – Integrated system
- Integration concept 2 – Integrated system with HP

Integration concept of AHP is not considered for this case as the steam is produced on demand. Figure 52 and Figure 53 show the integration between HHKW Galgenen and the CO₂ capture process.

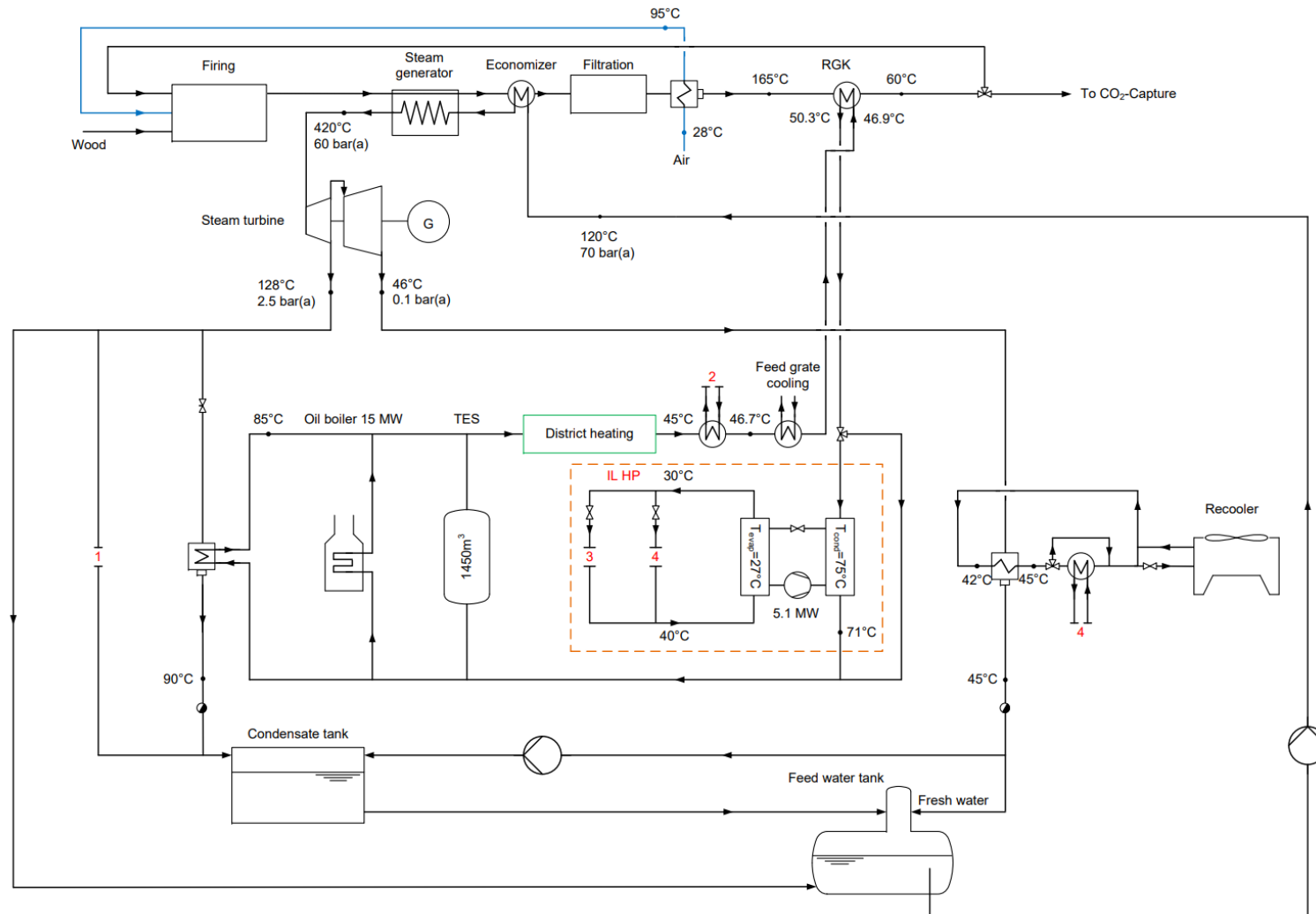


Figure 52. Integration concepts of HHKW Galgenen and CO₂ capture process, for all ICs, where the orange dotted box refers for only IC2.

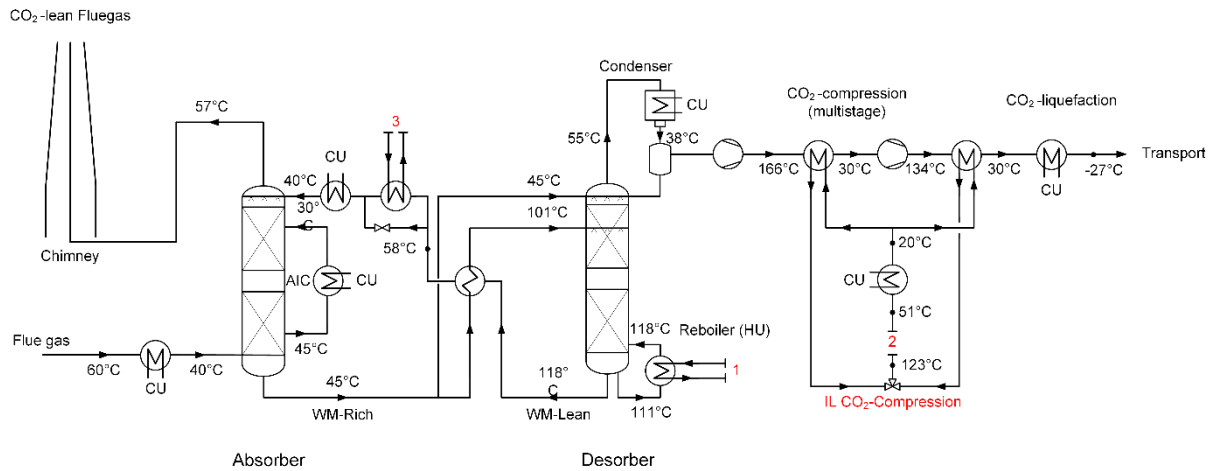


Figure 53: Integration concepts of HHKW Galgenen and CO₂ capture process.

Integration concept 1 – Integrated system

The first integration concept represents an integrated system between CO₂ capture plant and HHKW Galgenen. Since HHKW Galgenen only generates heat/steam to meet the requirements of the DH network, more wood is needed to generate more steam to meet the heat demands of the CO₂ capture plant. Figure 54 shows the CCs and GCC of the integrated system.

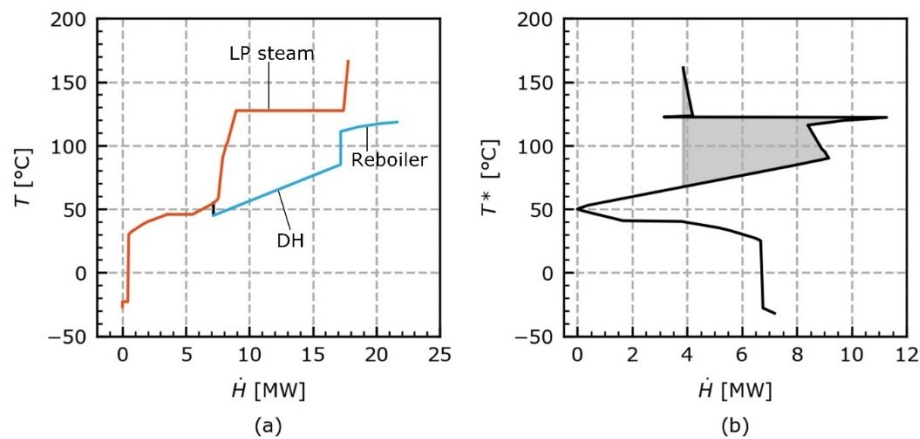


Figure 54: CCs and GCCs of the integrated CO₂ capture process with HHKW Galgenen, on an average winter day at a 90% CO₂ capture.

Figure 55 shows the effect of the system with the integrated CO₂ capture. It shows the stack plot to capture 72% of the total CO₂ emissions. This shortfall is due to the maximum heat generation capacity being reached at certain moment in the year, limiting the CO₂ capture rate. Despite the additional wood incineration required to supply heat for the CO₂ capture process, the net electricity generation of the plant remains relatively constant. This is because the increased steam production compensates for the steam extracted to supply the CO₂ capture plant, as illustrated with the same amount in Figure 50 and Figure 55.

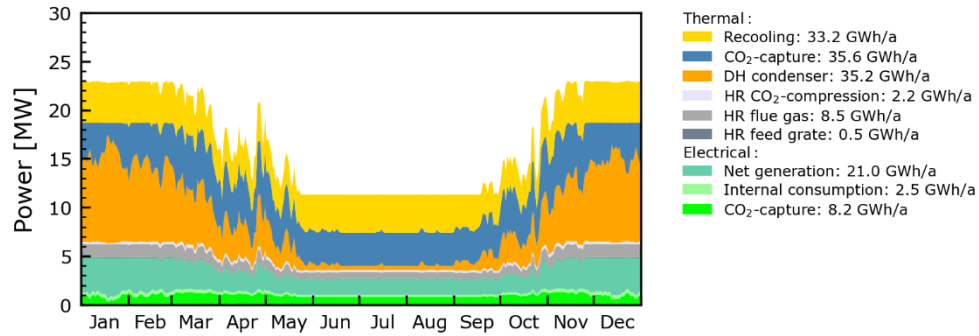


Figure 55: Annual stack plot of extracted heat flow rates and electric power of Integration Concept 1 (IC1).

Integration concept 2 – Integrated system with compression heat pump, Scenario 1 (demand driven operation)

Figure 56 shows the CCs and GCC of the integrated system with a HP.

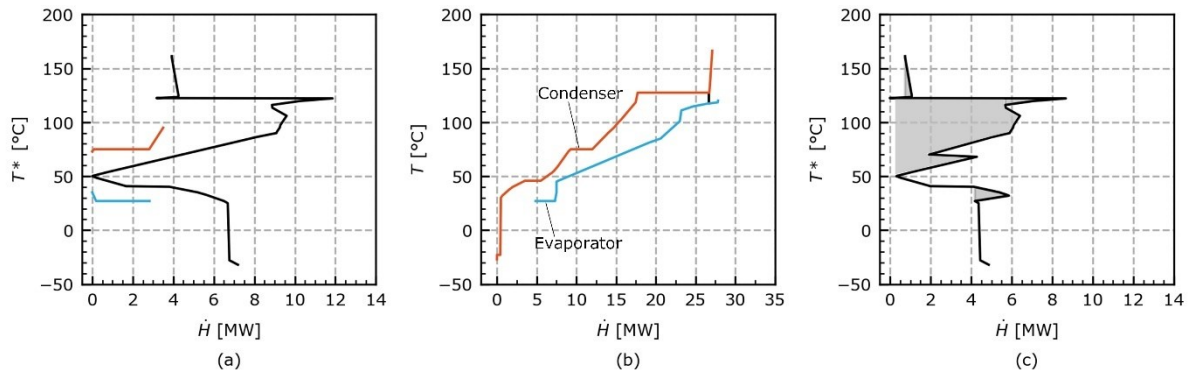


Figure 56: (a) GCC of HHKW Galgenen with potential HP, and (b) CCs and (c) GCC of HHKW with integrated HP on an average winter day, Integration Concept 2 Scenario 1 (IC2, S1).

Figure 56 shows the potential integration of a HP with 6.2 MW condenser capacity. However, an optimization based on cost and operational parameters led to the selection of a 5.1 MW HP condenser capacity. This HP utilises excess heat from the CO₂ lean stream from the CO₂ capture plant and recooling waste heat, as shown in Figure 52 and Figure 53. The Modelica simulation in Figure 57 demonstrates that this system captures 90% of the total annual CO₂, with similar wood usage as the current operations without CO₂ capture. This is possible because the DH network at HHKW Galgenen operates at a lower supply temperature compared to KVA Linth, allowing the HP to efficiently valorise waste heat from the CO₂ capture process to meet the additional heating demand without requiring significant extra wood combustion.

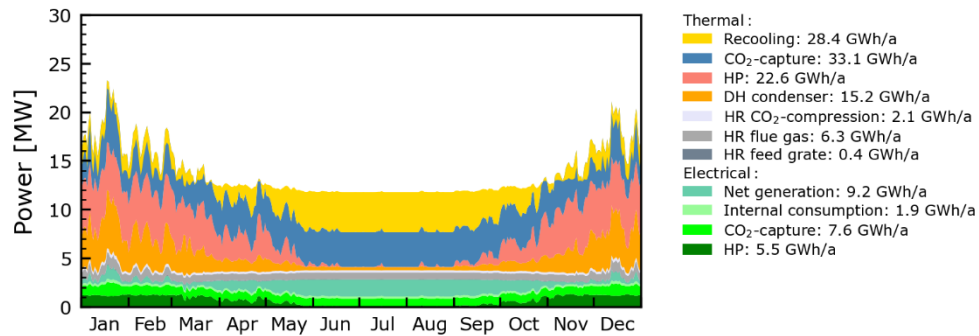


Figure 57: Annual stack plot of extracted heat flow rates and electric power of integration concept 2 scenario 1 (IC2, S1).

Integration concept 2 – Integrated system with compression heat pump, Scenario 2 (at fixed firing rate)

A scenario was evaluated where HHKW operates its boiler at full firing capacity (100%) during winter, transitions at 75% firing capacity, and operates at 50% firing capacity in summer. According to the industrial partner, there is available excess wood for this scenario. Figure 58 presents the impact of this operation on the recool capacity, highlighting a significant increase in capacity compared to Scenario 1 due to the rejection of excess heat not utilised by the DH network or CO₂ capture process.

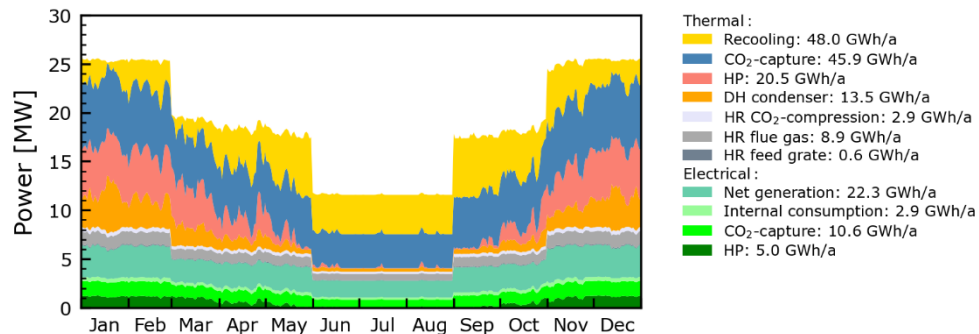


Figure 58: Annual stack plot of extracted heat flow rates and electric power of integration concept 2 scenario 2 (IC2 S2).

The integration of CO₂ capture with HHKW Galgenen reveals that the HP integrated system (IC2) provides a more comprehensive CO₂ capture solution, achieving 90% capture with efficient heat utilisation. While IC1 meets operational requirements, the CO₂ capture is lower due to inherent capacity limits. The lower DH supply temperature at HHKW Galgenen improves the HP's efficiency (higher COP), allowing more waste heat to be valorised. This makes the HP-integrated system (IC2) the preferred option for maximising CO₂ capture and enhancing the overall operational efficiency of the plant.



4.2.9. Techno-economic analysis

Key assumptions for the economic assessment are listed in Section 2.4. Table 7 shows the techno-economic assessment concepts for HHKW Galgenen.

Table 7: Comparison of techno-economic analysis of the different integration concepts.

	Units	IC1	IC2 S1	IC2 S2	IC2 S1 (+50%)
Total CO₂ generated	t CO ₂ /a	56'800	42'300	58'600	42'300
Total CO₂ captured	t CO ₂ /a	40'900	38'000	52'800	38'000
Percentage of total CO₂ captured	%	72	90	90	90
HP capacity	MW	-	5.1	5.1	5.1
Capital cost					
Investment cost of CO₂ capture	mil. CHF	48.1	46.2	53.5	69.4
Annualised cost of CO₂ capture	mil. CHF/a	4.2	4.0	4.7	6.1
Investment cost of EEMs*	mil. CHF	0.5	6.0	6.1	6.0
Annualised cost of EEMs*	mil. CHF/a	0.04	0.5	0.5	0.5
Operating cost					
Fixed operating	mil. CHF/a	1.5	1.5	1.6	2.0
Wood cost**	mil. CHF/a	1.2	-0.2	1.5	-0.2
Electricity generation losses**	mil. CHF/a	0.5	2.0	0.3	2.0
Other variable OM	mil. CHF/a	0.1	0.1	0.1	0.1
Total annual cost	mil. CHF/a	7.5	8.1	8.8	10.5
Levelised CO₂ captured cost	CHF/t CO ₂	183.5	211.9	166.7	278.3
With early movers solution	CHF/t CO ₂	703.5	731.9	686.7	798.3
With dedicated vessels	CHF/t CO ₂	543.5	571.9	526.7	638.3

*EEMs include HP and HEN.

**operating cost is compared to the expansion scenario with no CO₂ capture plant.

Table 7 show that IC1 has the lowest specific CO₂ capture cost among the different integration concepts. Although IC1 is lower in cost per ton of CO₂ captured, it only captures 72% of the total CO₂ emissions. In contrast, IC2 captures 90% of the total CO₂ emissions, which aligns better with higher CO₂ reduction targets and environmental regulations. This higher capture efficiency, however, comes at a higher cost. If the objective is to maximise CO₂ capture, then IC2 would be the preferred choice, despite its higher cost. The investment in IC2 can be justified if long-term carbon pricing, regulatory incentives, or corporate sustainability goals value higher CO₂ capture rates.



4.3. Comparison of case studies

Table 8 compares the integration concept 2 of all case studies.

Table 8: Comparison between case studies for integration concept 2 (with HP).

	Units	KVA Linth	KSV Werdhözli	HHKW Galgenen (S1)
Total CO₂ captured	t CO ₂ /a	120'000	19'800	38'000
Annualised cost of CO₂ capture	mil. CHF/a	7.5	2.3	4.0
Electricity cost	CHF/MWh	80	140	130
DH return temperature	°C	57	66	45
DH supply temperature	°C	90	74	85
Levelised CO₂ captured cost	CHF/t CO ₂	129.7	222.1	211.9

The CO₂ capture plant size of KVA Linth is bigger in terms of capacity by 3 to 6 times compared to the other case studies. However, based on the generated cost function, the annualised cost of the CO₂ of KVA Linth is only double. Therefore, the smaller capacity CO₂ plant has higher investment cost.

The other aspect that affects the cost of the case studies are the temperatures of the DH network. The interplay between supply and return temperatures and heat pump integration efficiency is evident, with lower DH temperatures allowing better performance and cost efficiency for heat pump systems. However, at HHKW Galgenen, the integration of a heat pump increases the overall system costs compared to a configuration without a heat pump. This is primarily due to the high electricity prices, which offset the thermal efficiency gains achieved through heat pump integration.

IC2 shows varying cost efficiency across the three case studies, primarily driven by scale, electricity, prices, and DH temperature profiles. KVA Linth stands out as the most cost-effective and efficient integration, while KSV Werdhölzli faces the greatest challenges due to high electricity costs and less favourable thermal conditions. HHKW Galgenen benefits from a low DH supply temperature, which helps moderate its integration costs despite the variability in operation and moderate electricity costs.



4.4. Energy system modelling

The detailed modelling of the CO₂ capture system with integrated heat pumps was introduced in a simplified way into the SES-ETH model. Two options are available: (1) a mechanical-driven heat pump that uses electricity to convert the heat that is rejected by the capture process to the temperature level needed for a DH network, and (2) an absorption heat pump that achieves the same purpose using steam which is extracted from the water steam cycle. This section analyses the influence of these options on the overall energy system.

4.4.1. Cross scenarios

Four scenarios for a net-zero Switzerland in 2050 have been defined within the SWEET-CROSS project (Aramis, 2023). These are generated along two axis: climate policy and energy market integration. Another dimension was added by defining a conservative and an innovative variant, as well as a stricter climate goal (see Figure 10 and Table 9):

- Climate policy: “Net-zero GHG domestic” is net zero including hard to avoid emissions from agriculture but excluding aviation. “Net-zero GHG – carbon removal abroad” considers the option to balance up to 6 Mt/a of CO₂-equivalent emissions outside Switzerland. A third variant “Real zero” was added which considers also the emissions from aviation.
- Energy market integration: SES-ETH does not explicitly model the energy system outside Switzerland. Energy carriers like electricity, methane or hydrogen can be imported at a certain price. The two variants “High integration” and “Low integration” are defined.
- Technology innovative/conservative: These variants are distinguished by the willingness to adopt new technologies or to find compromises with other public goods such as landscape preservation. Examples are alpine photovoltaics, the increase of hydro reservoir volumes or geothermal energy. In the context of the present project, the integration of heat pumps in CO₂ separation processes were considered as available in the innovative scenario and not available in the conservative scenario.
- As Table 9 shows, there are actually 3 climate goals ranging from +12 MtCO₂/a down to 0 MtCO₂/a. These numbers include aviation which accounts for approx. 6 MtCO₂/a. The question remains, which is the “correct net-zero target”. The answer is not straightforward. The Real Zero scenario enforces either the production of sustainable aviation fuels (SAF) in Switzerland or at least the compensation by negative emissions. Recent results from the VADER project (Aramis, 2023) indicate that the first option is not realistic, simply because Switzerland lacks renewable resources (biomass, PV, wind) to produce SAF domestically. For the second option only direct air capture (DAC) is able to deliver the amount of negative emissions, all other biogenic options are already exhausted to get even down to +6 MtCO₂/a. Probably it is more reasonable to either import SAF or to -balance the use of fossil kerosene by DAC in locations that are more favourable than Switzerland. This could be especially in proximity of storage sites where ideally also low-grade heat is available for the DAC process. We therefore consider the Real Zero scenario as an extreme benchmark which may become relevant if emissions must go below zero in the second half of the 21st century.
- Following the argument that Switzerland may be able to import SAFs by the middle of the century, the Domestic climate scenario at +6 MtCO₂/a becomes actually the aforementioned “correct net-zero target”. The Abroad scenario assumes that 6 MtCO₂/a can be balanced abroad, allowing Switzerland to still emit +12 MtCO₂/a. We consider this scenario because it allows to better understand the steps necessary to reach the Domestic scenario. All assumptions on technology costs and efficiency, resource availability and demand have been documented in a recent study, they can be found in Section 2.5 of the final report (Aramis, 2023).



Table 9: Key numbers for scenario variants (CROSS scenario definition from (Marcucci et al., 2023))

Climate policy	Real zero	Domestic	Abroad
Target for SES-ETH	0 MtCO ₂ eq/a	+6 MtCO ₂ eq/a	+12 MtCO ₂ eq/a

Market integration	High integration	Low integration
Electricity imports	Unlimited at 100-200 CHF/MWh	None
Methane imports	Unlimited at 30-60 CHF/MWh	
Kerosene imports	Unlimited at 50-100 CHF/MWh	
Diesel imports	Unlimited at 50-100 CHF/MWh	
Hydrogen imports	< 40 PJ/a at 160 CHF/MWh	None
Biogas imports	< 44 PJ/a at 100 CHF/MWh	None
Biofuel imports	< 5 PJ/a at 200 CHF/MWh	None

Technology	Innovative	Conservative
Hydro power	< 37.1 TWh/a	< 33.6 TWh/a
Storage reservoirs	< 6.5 TWh	< 8.5 TWh
Wood resource	< 19.3 TWh/a	< 15.6 TWh/a
Wind power	< 2.14 GW	< 0.85 GW
Alpine photovoltaic	< 4 GW	No
Seasonal thermal energy storage	Yes	No
H ₂ cavern storage	Yes	No
Centralised wet biomass anaerobic digestion	Yes	No
Hydrothermal conversion of digestate	Yes	No
CO ₂ separation by membranes	Yes	No
CO₂ separation with integrated heat pumps	Yes	No
Conversion of waste/wood to gases/fuels	Yes	No
Low temperature convective space heat supply	Yes	No
Borehole regeneration	Yes	No
5th generation cooling/heating networks	Yes	No
Negative emissions by using wood as building material	Yes	No

4.4.2. System value of heat pumps integrated into CO₂ separation

In Table 9, innovative and conservative scenarios are defined in a way that they differ by a large number of options such as the availability of alpine PV, seasonal thermal energy storage, etc. One can assess the value of each technology by *adding* it to the conservative scenarios and by *removing* it from the innovative ones. It can be expected that this process is generally not symmetric, i.e. the disadvantage of not having one out of many innovative technologies is probably smaller than the benefit of having only this single one.

The heat pumps in CO₂ separation processes allow to increase the heat delivered to district heating networks by lifting the heat that is rejected by the process to the temperature level needed. It is therefore interesting to observe the mix of technologies that supply space heat and domestic hot water (DHW) and how it changes. Figure 59 shows the baseline scenarios (median in grey) where heat pumps are not available in the conservative case and are available in the innovative case.

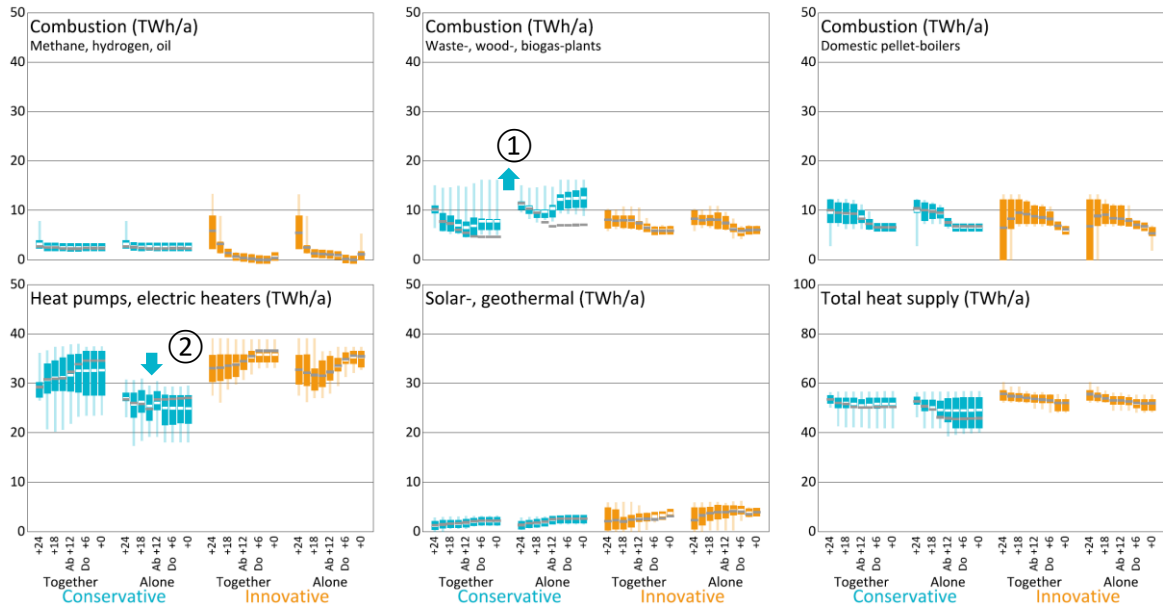


Figure 59: Space heating and DHW supply for base scenarios (median shown in grey) and new scenarios with/without heat pumps for CO₂ separation.

When heat pumps are made available in the conservative scenarios (blue), a number of shifts can be observed, the most important being an increase of heat supplied by combustion systems ① (mostly the waste-to-energy plants). This is exactly the desired effect, namely, to better utilise the energy in the waste for the purpose of heat supply.

A secondary effect is the reduction of heat supplied by heat pumps ②. This can also be seen in for the electricity consumption by heat pumps ③ in Figure 60. Finally, we directly compare the effect of having/not having heat pumps for CO₂ separation using two indicators, namely the overall energy imports and the total system costs. Figure 61 illustrates that the system costs decrease for the conservative scenarios. It is interesting to note that the overall imports increase. The reason is that the better utilization of waste as a resource in waste-to-energy plants leads to a shift from using waste for high temperature process heat to district heating networks. This is balanced by a slightly higher use of imported methane which can be seen in Figure 61.

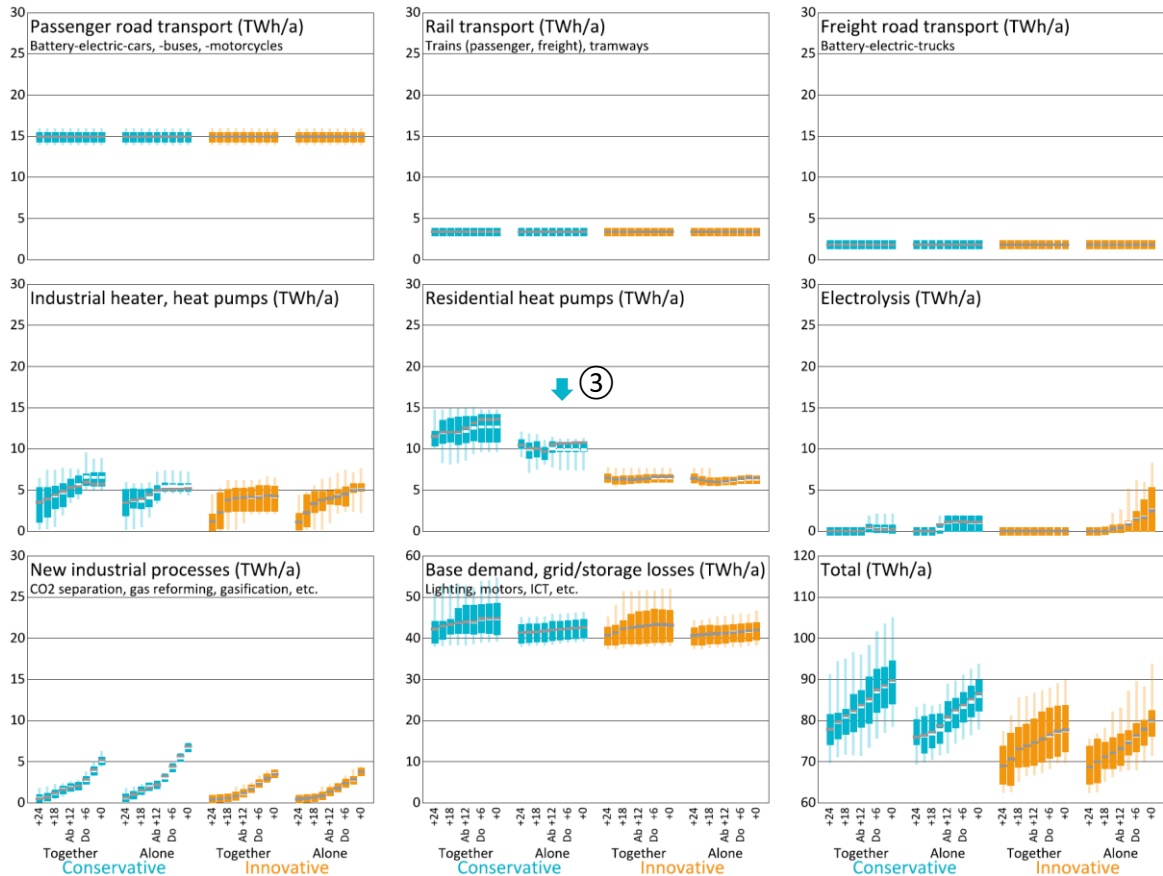


Figure 60: Electricity consumption for base scenarios (median shown in grey) and new scenarios with/without heat pumps for CO₂ separation.

The figure shows also that the effect of not having heat pumps for CO₂ separation available in the innovative scenarios is only marginal on all indicators. The most important reason is that waste is in any case better used in the innovative scenarios due to the availability of large scale seasonal thermal energy storage, e.g. in the form of a pit storage. According to the simulation results the volume of such storage could be in the order of 1-2 TWh. Therefore, the benefit of having heat pumps is less pronounced.

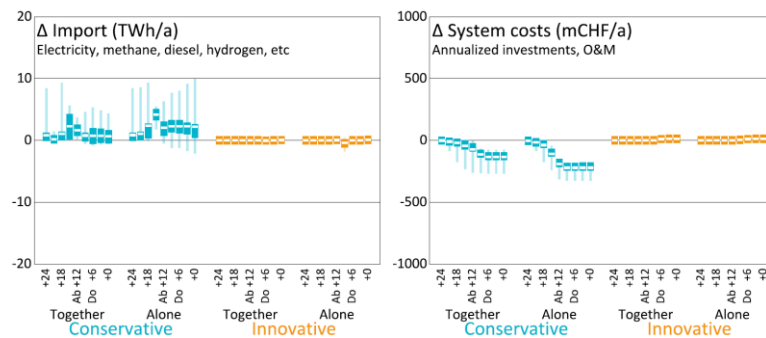


Figure 61: Variation of imports and total system costs of conservative/innovative scenarios with/without heat pumps for CO₂ separation with regards to baseline scenarios.

Figure 62 illustrates the time series during a year for a waste-to-energy plant for a typical scenario without (left) and with (right) heat pumps in the CO₂ separation process. The top row shows the energy balance for the plant. In both cases the same amount of waste is consumed (green). This waste is converted into electricity (yellow), heat at 80 °C for a district heating network (dark orange), heat at 130 °C for the CO₂ separation process (orange) and losses that are rejected to the environment (grey). It can immediately be seen that the availability of a heat pump reduces these losses.

The second row shows the energy balance for the heat at 130 °C. Most of it is consumed by the reboiler of the CO₂ separation plant. When heat pumps are available, part of the heat is used in an absorption heat pump.

The third row shows the heat that is rejected by the cooler of the CO₂ absorption process. When heat pumps are available, part of this heat can be recovered and made available for the district heating system (rose). This can be seen in the last row where the demand (black) is met by the heat extracted from the steam cycle (dark orange) and by the heat delivered by the heat pumps (rose).

The benefit of the heat pumps becomes evident when comparing the waste input (green) with the heat delivered (black). For the same waste input, the delivered heat increases significantly when heat pumps are integrated into the CO₂ capture process. Using this simple energy system model we therefore confirm the results which were obtained with the more detailed model in the previous sections.

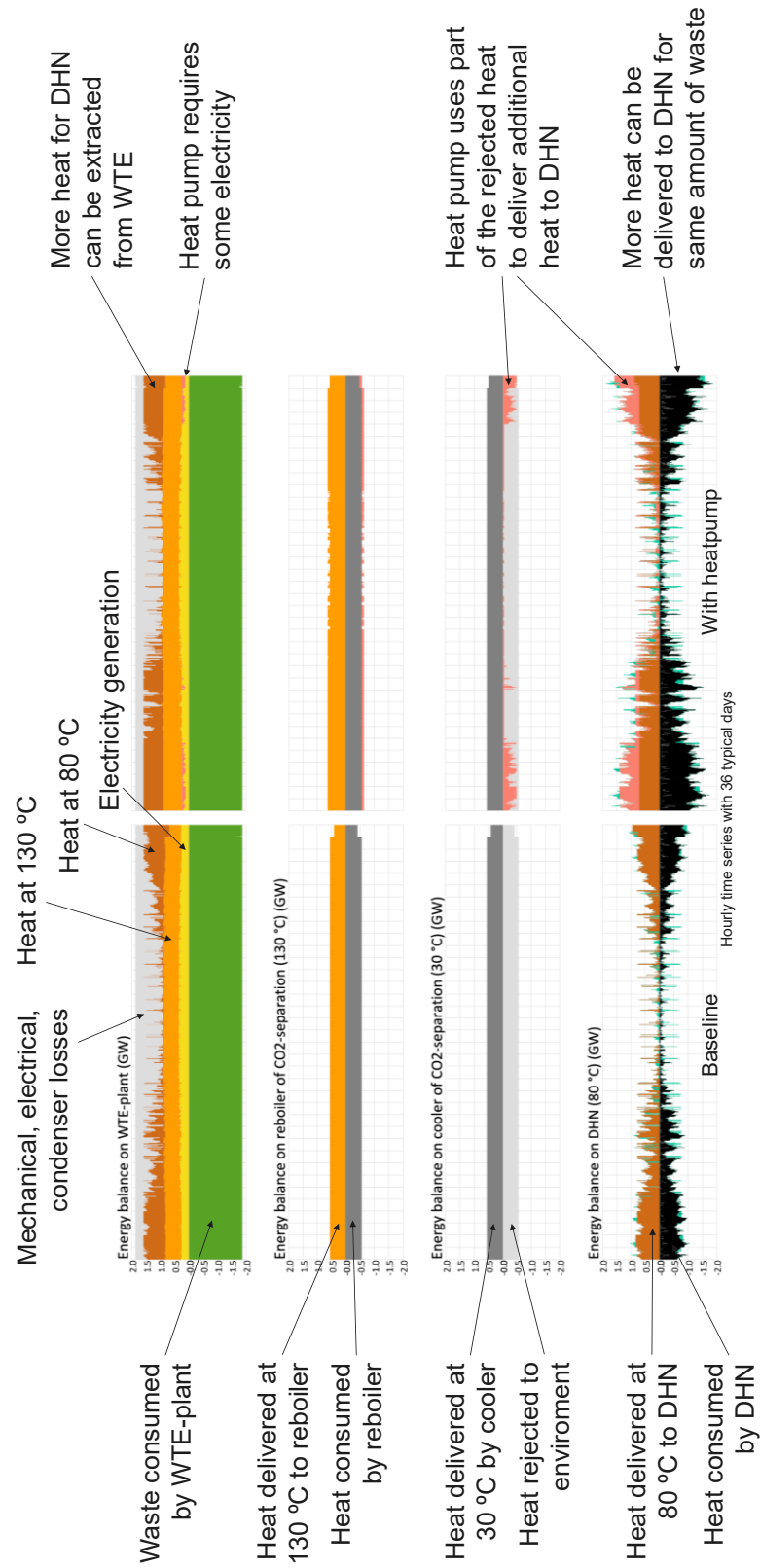


Figure 62: Time series of energy flows on base case (left) and variant with heat pumps available for CO₂ separation.



5 Outlook on carbon capture and utilization: Power-to-X

In exploring alternatives to CCS, the integration of Carbon Capture Utilization (CCU) with onsite Power-to-X (P2X) technologies offers a promising pathway for enhancing the value of captured CO₂. P2X technologies enable the conversion of surplus renewable electricity into various energy carriers and industrial feedstocks through electrochemical processes (Kober et al., 2019).

Selecting the appropriate P2X technology to integrate into an already complex system is a multi-criteria decision-making process. The primary feedstock for these pathways (captured CO₂) offers multiple potential uses, adding another layer of complexity in the selection process. It is crucial to evaluate which P2X technology would offer the greatest benefit when integrated with existing systems, considering factors such as process compatibility, economic viability, and system efficiency. The integration of P2X technologies can involve material and/or heat exchanges that optimise resource use and enhance the overall economics of the system. However, traditional engineering design methods typically focus on either site-wide material integration or heat integration, but not both simultaneously. For the optimal integration of P2X technologies, it is essential to consider both material and heat exchanges holistically, using the methodology outlined in PA.

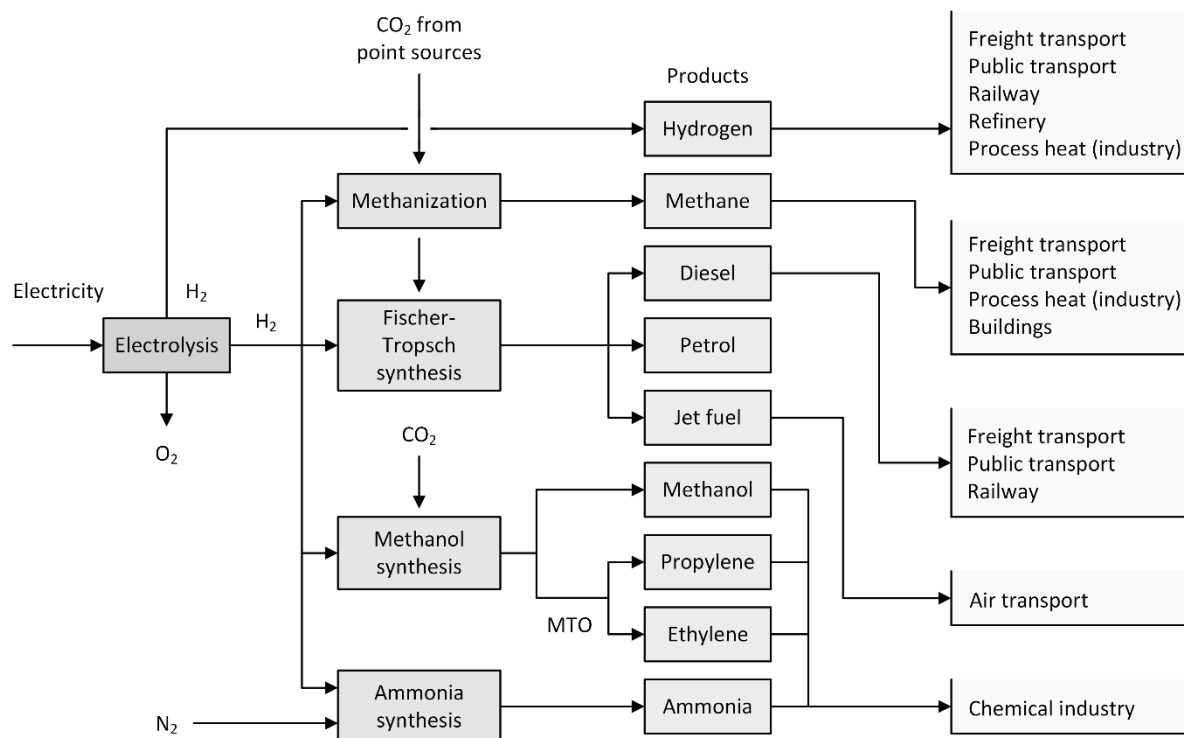


Figure 63: Potential process synthesis route for utilisation of CO₂.



Through strategic heat and material exchanges, the integrated system can achieve higher efficiency. For example, excess heat from P2X processes can be redirected to the other integrated system operations, reducing the need for additional heating resources and vice versa. Balancing Feedstock Needs: matching the CO₂ and hydrogen supply with the demand of P2X processes ensures that resources are used efficiently. This balance is critical in selecting the right P2X technology and optimising the overall system.

Figure 63 shows different potential routes for utilisation of the CO₂. This section considers Power-to-Hydrogen (P2H2) as a foundational P2X process, alongside Power-to-Methane (P2CH4) and Power-to-Methanol (P2CH3OH) pathways, to leverage both the net electricity surplus and captured CO₂ within the integrated system.

5.1. Power-to-Hydrogen (P2H2)

As the base process for other P2X pathways, P2H2 converts electricity into hydrogen through electrolysis. Green hydrogen, produced from water in an electrolyser using renewable electricity, can be used as a viable energy storage for surplus electricity. This hydrogen can be used directly or serve as a feedstock for further conversion processes. P2H2 integration focuses on aligning with existing hydrogen demand within the system or creating new applications for the generated hydrogen.

The water is split into its two components, hydrogen and oxygen, in the electrolyser with the addition of electricity according to the following endothermic reaction:



The reaction enthalpy amounts to -39.41 kWh/kg_{H2}. Based on a hydrogen production rate of 100 kg/h and a typical electrolyser efficiency of 0.7, the process has an electricity demand of 5.67 MWh and produces excess heat of 1.42 MWh at 70°C (Friedl et al., 2018).

5.2. Power-to-Methane (P2CH4)

This process combines captured CO₂ with hydrogen (from P2H2) to produce methane, which can be utilised as a clean fuel or injected into the natural gas grid. This process is known as Power-to-Gas, specifically Power-to-Methane when the final product is methane. The key to successfully integrate the P2CH4 is ensuring the availability of sufficient hydrogen and maintaining an optimal CO₂-to-hydrogen balance for the methanation process.

The conversion occurs via the exothermic Sabatier reaction:



The Sabatier reaction consists of two sequential steps:



The overall reaction is highly exothermic, with a reaction enthalpy of approximately -4.384 kWh/kg_{CH4}-, indicating a significant release of heat during the conversion to methane. For a methane production rate of 100 kg/h, the process requires approximately 70.9 kWh of electrical energy. The thermal process requirements and the heat integration potential of the P2CH4 process are shown in Figure 64.

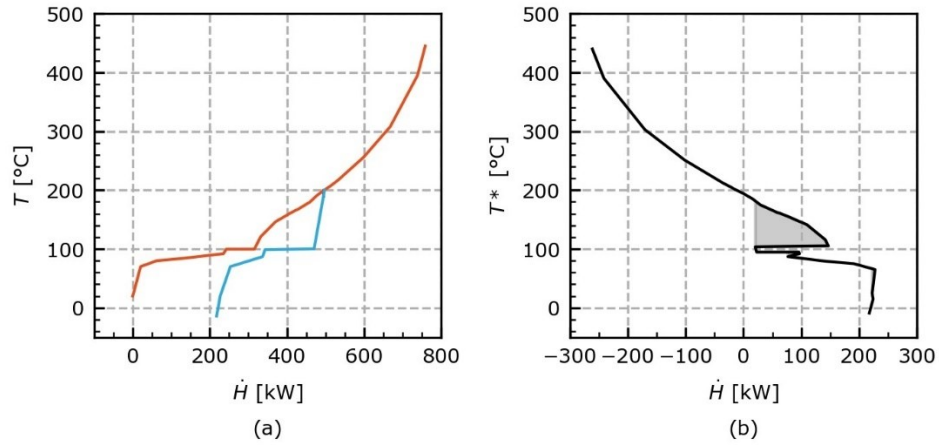
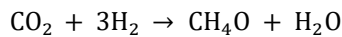


Figure 64: CCs and GCC of the methanization process based on methane production rate of 100 kg/h.

5.3. Power-to-Methanol (P2CH₃OH)

P2CH₃OH involves synthesising methanol from captured CO₂ and hydrogen produced through electrolysis. Methanol is a versatile product, serving as a fuel, a chemical feedstock and an energy carrier, making it a valuable component in various industrial applications. Integrating P2CH₃OH into the system requires a careful assessment of hydrogen availability, as well as optimising operational conditions such as temperature, pressure and catalyst performance to maximise methanol yield.

This process belongs to the broader category of Power-to-Liquid technologies, with methanol synthesis specifically referred to as Power-to-Methanol. The conversion takes place according to the following exothermic reaction:



9

Similar to methanation, this reaction produces water as a by-product. The reaction is exothermic, releasing energy with a reaction enthalpy of approximately $-0.4273 \text{ kWh/kg}_{\text{CH}_4\text{O}}$, indicating that heat is generated during methanol synthesis. For a methanol production rate of 100 kg/h, the process has an electrical demand of about 31.5 kWh. The thermal process requirements and integration opportunities for P2CH₃OH are shown in Figure 65.

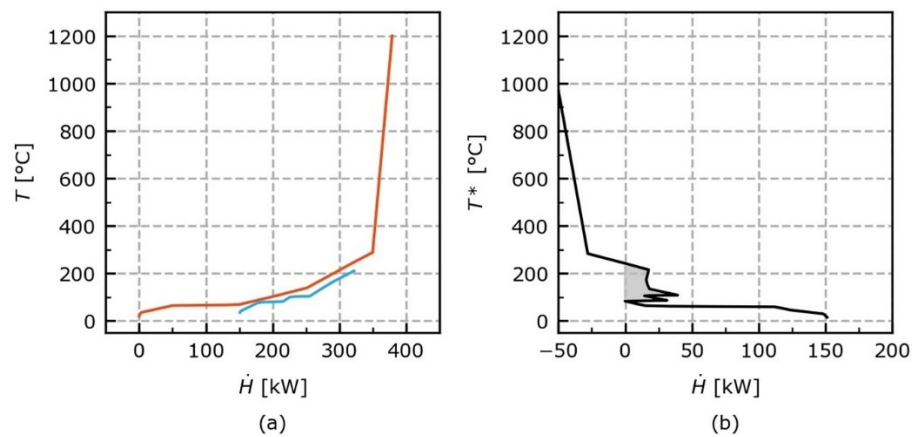


Figure 65: CCs and GCC of the methanol synthesis based on methanol production rate of 100 kg/h.



Given the exothermic nature of the methanol synthesis reaction, the excess heat generated could be repurposed for other processes, such as district heating or pre-heating reactants, thereby reducing the overall energy consumption of the plant.

5.4. Integration of Power-to-X technologies into KVA Linth

In this section, the thermal integration of the previously considered P2X technologies into the KVA Linth case study is examined.

5.4.1. Power-to-Hydrogen integration

Hydrogen electrolysis and the corresponding electricity demand primarily dictate the scale of the P2H₂ plant. Based on the net electricity surplus available, the maximum feasible hydrogen production is approximately 151 kg/h, utilising 80% of the average electricity output (10.7 MW) from the Linth waste incineration plant. The thermal requirements for the P2H₂ process introduce only a minor additional hot stream, which has a negligible impact on the overall process requirements, as shown in Figure 66.

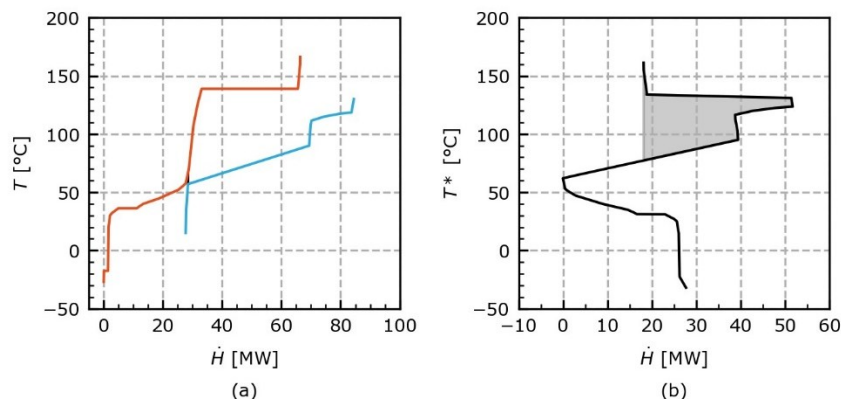


Figure 66: CCs and GCC for the integrated system including the P2H.

Figure 66 presents the CCs of the integrated system of KVA Linth with the integration of the P2H₂ plant. The addition of hydrogen electrolysis does not alter the previous pinch temperature of 62°. However, the introduction of a single hot stream from the P2H₂ waste heat causes a slight modification in the hot CC near the pinch point. This adjustment results in an increased CU demand of 27.7 MW, which is 2.0 MW higher than the original demand. The HU demand remains relatively unchanged at 18.2 MW.

This analysis highlights that while the integration of the P2H₂ plant slightly influences the thermal profile of the system, the overall utility requirements remain manageable, demonstrating the feasibility of incorporating hydrogen electrolysis into the existing infrastructure with minimal disruption to the plant's thermal balance.



5.4.2. Power-to-Methane integration

By using the hydrogen from the P2H₂ plant as a feed for a methanization plant, the net positive electricity needs to cover both processes. Hence, hydrogen production is reduced to 148 kg/h, which is reused directly together with 812 kg/h of the captured CO₂ for the production of 295 kg/h of methane. The plant is able to reuse around 5.5% of the captured CO₂ from the waste incineration plant directly. The rest has to be stored temporarily and transported. The thermal process requirements for the P2H₂ and P2CH₄ plant have only a minor influence on process requirements shown in Figure 67. **Erreur ! Source du renvoi introuvable.** The integration has no effect on the pinch temperature of 62°C for a $\Delta T_{\min}$ of 10 K. However, thus the GCC is sharper at the Pinch temperature, there is potential for a HP integration. The hot and CU demands are 16.72 MW and 27.64 MW respectively, where the HU reduces.

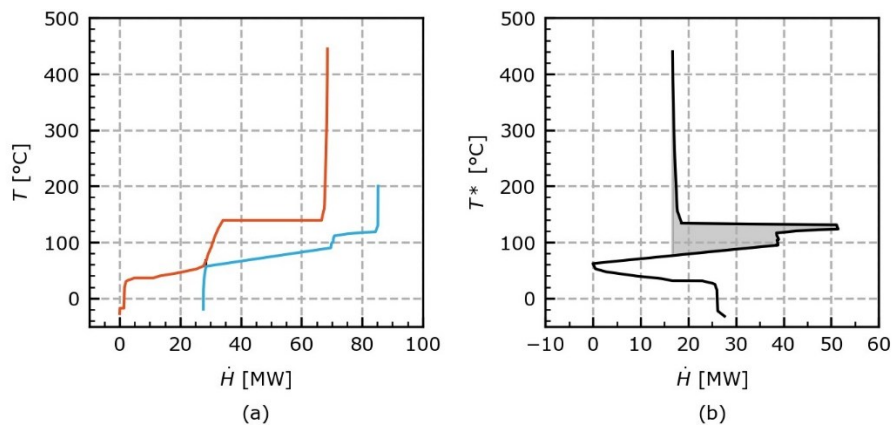


Figure 67: CCs and GCC for the integrated system including the P2H and P2CH₄ plants.

5.4.3. Power-to-Methanol integration

By using the hydrogen from the P2H₂ plant as a feed for a methanol synthesis, the net positive electricity needs to cover both processes. Hence, hydrogen production is reduced to 144 kg/h, which is reused directly together with 1'052 kg/h of the captured CO₂ for the production of 721 kg/h of methanol. The plant is able to reuse around 7.1% of the captured CO₂ from the waste incineration plant.

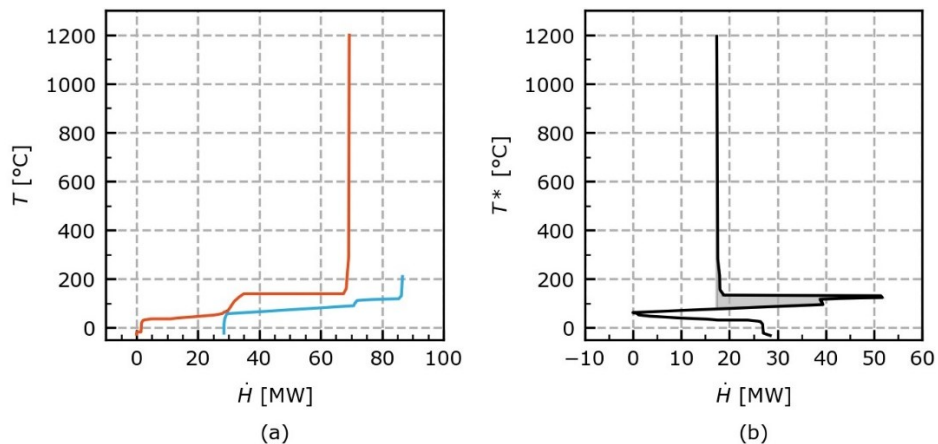


Figure 68: CCs and GCC for the integrated system including the P2H and P2CH₄O plants.



The thermal process requirements for the P2H2 and P2CH4O plant, have only a minor influence on process requirements shown in Figure 68. The integration has no effect on the pinch temperature of 62°C for a $\Delta T_{\min}$ of 10 K. However, thus the GCC is even sharper at the Pinch temperature, the potential for a heat pump integration is increased even further. The hot and CU demand are 17.32 MW and 28.48 MW respectively.

5.4.4. Economic analysis P2X integration

To complete the techno-economic analysis, a rough economic analysis has been performed. The cost functions are extracted from Belloti et al. (2022) and the results are shown in Table 10. In this case, the electricity is used for the P2X integration, and no electricity revenue is included.

Table 10: Economic comparison for the integrated Power-to-X plants.

	Units	P2H2	P2CH4	P2CH4O
Annual production	t/a	1'326	2'587	6'312
Annualised investment costs	mil. CHF/a	0.8	1.0	0.9
Operating costs	mil. CHF/a	6.3	5.2	5.5
Specific cost	CHF/t	4'091	1'800	790
Red.CO₂ emissions	kt/a	0	7.1	9.2
CO₂ abatement cost	CHF/a	0	1.7	2.2
Selling cost	CHF/t	1'070	1'023	525
Profit	CHF/t	-3'020	-118	84

The HR potential has a high impact on the profit for each plant. Due to the low increase of potential HR, the integration of the P2H2 plant is rather expensive and has with -3'020 CHF/t the highest loss (negative profit). By integrating the P2CH4 the HR potential is increased significantly and thus the loss can be reduced to -118 CHF/t. With the integration of the P2CH4O plant, the profit is only of 84 CHF/t. Two of the three integrated Power-to-X technology generate negative profit and are therefore, not economically viable. KVA Linth has the lowest selling prices for electricity of the case studies and thus, has the highest potential for a viable integration of Power-to-X technologies. Therefore, none of the other case studies need to be further analysed to conclude that Power-to-X technologies cannot be integrated to generate a profit.



5.4.5. Conclusions

Carbon utilization technologies encompass a range of applications, including enhanced oil and gas recovery, construction materials, chemicals and fuels and agriculture. In Switzerland, assessing the feasibility of carbon utilization technologies hinges on evaluating market capacity and scalability. This involves analysing the potential volume and market share of new products and their competitiveness with existing products in the same market niche. Understanding market size is crucial, particularly regarding the scale of carbon utilization from captured CO₂.

While carbon utilization is often promoted as a strategy to mitigate emissions by repurposing waste CO₂ within a circular carbon economy, not all utilization technologies will lead to significant greenhouse gas reductions or serve as net carbon sinks. Life-cycle assessment (LCA) is a valuable tool for assessing the environmental and energy impacts of these technologies. Different LCA approaches may be more suitable at various stages of technology development; for instance, attributional LCA provides a detailed accounting of energy and environmental impacts at earlier stages, while consequential LCA is useful later to evaluate how new technologies might alter material and energy flows on a larger scale. In both cases, it is essential to apply consistent and transparent assumptions, along with standard emissions factors, to accurately compare carbon utilization technologies against conventional processes.

One promising research area for Switzerland is exploring “end-storage” solutions for captured carbon within building materials. Such materials would need to maximise carbon storage capacity while maintaining essential structural characteristics and the durability of built infrastructure. In the concrete industry, potential applications include: (1) integrating CO₂ through carbonation reactions by injecting liquid CO₂ into fresh concrete during mixing (e.g., CarbonCure); (2) carbonating recycled concrete aggregates from demolition processes, using carbon-rich admixtures as an alternative to newly quarried aggregates; and (3) producing artificial aggregates in carbonated form from waste cement, steel slag and wood or paper ash. Further research to identify suitable materials for CO₂ storage would be beneficial. However, current challenges include the lack of comprehensive design guidelines, building codes and standards, which limit demand and large-scale application of CO₂-enriched building materials. Additionally, the long-term durability of such concrete, particularly concerning reinforcement corrosion and carbonation due to reduced alkali content, requires further investigation.



6 Conclusions and outlook

6.1. Conclusions

The Process Integrated Carbon Capture – Design and Evaluation project aims to integrate CO₂ capture plant with industrial processes, focusing on technical and economic feasibility. By studying 3 distinct case studies, KVA Linth, KSV Werdhölzli, and HHKW Galgenen, the project demonstrates the potential of integrated CO₂ capture systems in advancing Switzerland's net-zero carbon emissions goals. The PICC project incorporates 3 existing process engineering tools: (1) process simulation of mass and energy balances of the CO₂ capture process, (2) Pinch Analysis of the processes and (3) piecewise steady-state simulation of the integrated systems. The simulations identify the characteristics of thermal requirements and provide specific plant operating data, including the thermal and electrical energy demand to capture 1 ton of CO₂. By examining the plants various operations and demands throughout the operating year, the project evaluates changes resulting from CO₂ capture integration and assesses the effectiveness of process optimizations, allowing for detailed economic considerations.

A critical finding is the importance of analysing direct heat recovery potential, particularly in plants with a heat demand at lower temperature levels, as seen in KSV Werdhölzli. In scenarios where district heating is supplied directly with low-pressure steam and additional heat demand exists at low temperatures, integrating a conventional compression heat pump can enhance energy efficiency. However, this integration reduces the net electricity available for sale and the economic feasibility is influenced by electricity costs. The findings indicate that integrated CO₂ capture plants offer better energy efficiency compared to stand-alone systems, mainly due to the utilization of waste heat and the alignment with lower temperature heating requirements of industrial processes. Heat pumps emerged as critical components in balancing heat demands and enhancing overall system performance. However, the economic viability of CO₂ capture integration is highly dependent on site-specific conditions, such as energy prices and waste heat availability. The integration at KVA Linth demonstrated that, although its CO₂ capture plant has a higher capacity (120,000 t/a), 3 (38,000 t/a) to 6 (19,800 t/a) times than the one of the other case studies, its specific cost per ton of captured CO₂ is double, illustrating that smaller capacity CO₂ plants have higher investment costs per unit of CO₂ captured. The levelised CO₂ captured cost per ton ranges at 129.7, 222.1, and 211.9 CHF for KVA Linth, KSV Werdhölzli, and HHKW Galgenen, respectively with HPs.

Overall, the PICC project provides implementation-relevant insights into integrating CO₂ capture systems in industrial settings. Although there are similarities in all 3 case studies in terms of integration, there is still a necessity for tailored integration strategies that consider the unique characteristics of each industrial site, including the availability of resources and economic variables. These integrated approaches are crucial for achieving significant emissions reductions and aligning with Switzerland's broader environmental objectives.

The integration concept with HP was modelled into the energy system model to analyse multiple scenarios in 2050. The analysis across multiple scenarios demonstrates that the availability of heat pumps leads to better use of waste heat, reducing overall system costs and increasing heat supply to district heating networks. However, the impact varies with the extent of other available innovations; the benefits are most pronounced in conservative scenarios with fewer technological options, illustrating the reduced impact when multiple innovations are already in place. This underscores the importance of targeted integration strategies that align with broader energy and climate goals.



6.2. Outlook

The future of CO₂ capture requires a multidisciplinary approach that combines technological innovation, policy support and seamless integration into broader energy and industrial systems. Continued research and development are essential to address current limitations and establish CO₂ capture as a viable, large-scale solution for mitigating climate change. Key areas of focus include enhancing efficiency, reducing costs and increasing the scalability of CO₂ capture technologies.

In chemical absorption, current efforts are concentrated on identifying new solvents that can capture CO₂ more effectively and at lower costs. Researchers are exploring solvents with improved performance and reduced energy requirements. For instance, Li et al. (2023) reviewed the use of catalysts in the CO₂ desorption process, which lower the activation energy and allow the reaction to occur at lower temperatures. However, this work has only been conducted at the laboratory scale and scaling up to industrial levels is necessary to fully understand the characteristics and practical applications. Additionally, process modifications, such as reducing the pressure in the desorber to lower the solvent's boiling point and the required reboiler temperature, present further opportunities for improvement.

The PICC project has demonstrated that the overall energy efficiency of integrated systems can be significantly enhanced through direct heat recovery and heat pump integration. However, there remains unused potential in the low-grade excess heat from the CO₂ capture process, which is currently cooled using cold utilities. This presents an opportunity for the electrification of CO₂ capture processes. For example, Jensen et al. (2024) employed a two-stage heat pump system to fully electrify an amine-based CO₂ capture process, eliminating the need for thermal boilers by utilising low-temperature heat sources. Similarly, Li et al. (2022) developed configurations integrating mechanical vapor recompression (MVR) technology to reduce the MVR reboiler duty, further enhancing process efficiency.

Beyond optimising absorption processes, future work could involve comparing various CO₂ capture technologies to determine their suitability for different point sources and their potential for energy integration within industrial plants. While the PICC project has focused on the holistic integration of CO₂ capture with industrial processes, future research should expand this holistic perspective to include the retrofitting of district heating networks to optimise integration and maximise overall system efficiency. One of the future considerations is the clustering of CO₂ point sources, which could provide a pathway for more cost-effective integration.

By pursuing these paths, the field can progress towards more efficient, cost-effective and scalable CO₂ capture solutions that align with global climate goals.

7 Cooperation and publications

Throughout this project, the project collaborated with the three industrial partners, the results were presented to them as a whole group and individually. In addition, this research has been published in the following conference proceedings and subsequently presented in those conferences.

Benjamin H. Y. Ong, Andrin Duss, Jonas Grand, Raphael Agner, Beat Wellig. Design and Integration of a CO₂ Capture Plant using Piecewise Steady-State Simulation and Process Integration, Proceedings of the 26th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, 8 – 11 October 2023, Thessaloniki, Greece.

Raphael Agner, Jonas Grand, Andrin Duss, Beat Wellig. Piecewise Steady-State Modelica Simulation for the Conceptual Design Phase of Industrial Processes, Proceedings of the 15th International Modelica Conference, 9 – 11 October 2023, Aachen, Germany.



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9 Appendix

The appendix presents the process stream tables used to construct the CCs and GCCs in the project.

9.1. KVA Linth

Table 11: Process stream table for KVA Linth (expansion scenario) for an average winter day (residual).

Stream	Hot/ Cold	T _{in} [°C]	T _{out} [°C]	$\dot{m}$ [kg/s]	cp [kJ/kg K]	$\Delta\dot{H}$ [kW]
LP-Steam 3.5 bar for DH	Hot	139	108	14.7	-	33'334
Condensate Preheating from DH	Cold	108	130	14.7	4.2	1'402
LP-Steam 3.5 bar for Air Preheating	Hot	139	70	0.5	-	1'287
Condensate Preheating from Air Preheating	Cold	70	130	0.5	4.2	134
Condensate 0.06 bar	Hot	36.2	36	3.0	-	6'241
Condensate Preheat	Cold	36	130	3.0	4.2	1'174
Fluegas Cooling Line 1	Hot	160	140	11.0	1.1	243
Fluegas Cooling Line 2	Hot	160	140	16.9	1.1	379
Cooler Fluegaswasher Line 1	Hot	56	32	32.28	4.2	3'200
Cooler fluegaswasher Line 2	Hot	56	32	44.18	4.2	4'750
District Heating	Cold	57	90	289.1	4.2	40'000
Primary Air Preheating Line 2	Cold	15	125	9.3	1.0	1'032
Secondary Air Preheating Line 2	Cold	35	125	5.0	1.0	456

Table 12: Carbon capture plant for KVA Linth for capturing 120'000 t CO₂/a.

Stream	Hot/Cold	T _{in} [°C]	T _{out} [°C]	$\dot{m}$ [kg/s]	cp [kJ/kg K]	$\Delta\dot{H}$ [kW]
Reboiler	Cold	112	119	75.5	-	13'100
WM-Lean	Hot	58	40	71.5	3.5	4'502
CO ₂ -Lean Fluegas	Hot	58	32	24.4	-	4'421
Absorber Intercooler (AIC)	Hot	45	30	74.4	3.5	3'801
Condenser Desorber	Hot	56	38	13.3	6.6	1'579
CO ₂ -Liquefaction	Hot	30	-27	4.2	-	1'475
CO ₂ -Compression Stage 1	Hot	166	30	4.2	-	664
CO ₂ -Compression Stage 2	Hot	134	30	4.2	1.0	441



9.2. Werdhölzli KSV

Table 13: Process stream table for KSV Werdhölzli and their external consumers for an average winter day.

Stream	Hot/Cold	T _{in} [°C]	T _{out} [°C]	$\dot{m}$ [kg/s]	cp [kJ/kg K]	$\Delta\dot{H}$ [kW]
LP-Steam 5.5 bar	Hot	190	110	1.8	-	4'187
Vapor Condensation	Hot	99.6	99.6	0.9	-	1'930
Fluegas Condensation	Hot	74	63	42.4	4.2	1'960
Feedwater Preheating	Cold	111	150	2.6	4.2	434
Air preheating	Cold	20	72	3.7	1.0	192
Dryer Sewage Sludge	Cold	20	100	2.4	4.2	800
Process Heat	Cold	78	94	8.6	4.2	578
Company Building	Cold	66	89	1.3	4.2	129
Sludge Heating Digestion	Cold	40	50	35.7	4.2	1'500
Gas Treatment Plant	Cold	121	133	14.3	4.2	720
District Heating	Cold	49	74	49.5	4.2	5'197

Table 14: Carbon capture plant for KSV Werdhölzli for capturing 19'800 t CO₂/a

Stream	Hot/Cold	T _{in} [°C]	T _{out} [°C]	$\dot{m}$ [kg/s]	cp [kJ/kg K]	$\Delta\dot{H}$ [kW]
Reboiler	Cold	113	119	13.7	-	2'400
WM-Lean	Hot	59	40	12.9	3.5	853
CO ₂ -Lean Fluegas	Hot	59	32	4.5	-	843
Absorber Intercooler (AIC)	Hot	45	30	13.5	3.5	705
Condenser Desorber	Hot	56	38	2.7	6.4	322
CO ₂ -Liquefaction	Hot	30	-27	0.7	-	266
Fluegas Cooling (Fixed Match)	Hot	40	27	3.2	4.2	172
CO ₂ -Compression Stage 1	Hot	166	30	0.7	-	120
CO ₂ -Compression Stage 2	Hot	134	30	0.7	1	79



9.3. HHKW Galgenen

Table 15: Process stream table for HHKW Galgenen (Scenario 2026) for an average winter day.

Stream	Hot/Cold	T _{in} [°C]	T _{out} [°C]	$\dot{m}$ [kg/s]	cp [kJ/kg K]	$\Delta\dot{H}$ [kW]
LP-Steam 2.5 bar	Hots	128	90	3.9	-	9'065
Condensate 0.1 bar	Hot	46	45	0.8	-	2029
Fluegas Cooling	Hot	165	40	12.8	1.0	1'500
Feed Grate cooling	Hot	102	100	8.3	4.2	85
District Heating	Cold	45	85	59.7	4.2	10'000

Table 16: Carbon capture plant for HHKW Galgenen for capturing 38'200 t CO₂/a (IC2).

Stream	Hot/Cold	T _{in} [°C]	T _{out} [°C]	$\dot{m}$ [kg/s]	cp [kJ/kg K]	$\Delta\dot{H}$ [kW]
Reboiler	Cold	111	118	25.7	-	4'441
WM-Lean	Hot	58	40	34.4	3.5	1'538
CO ₂ -Lean Fluegas	Hot	59	32	7.0	-	1'405
Absorber Intercooler (AIC)	Hot	45	30	25.4	3.5	1'336
Condenser Desorber	Hot	55	38	4.5	6.5	523
CO ₂ -Liquefaction	Hot	30	-27	1.4	-	501
CO ₂ -Compression Stage 1	Hot	166	30	1.4	-	226
CO ₂ -Compression Stage 2	Hot	133	30	1.4	1.0	150