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PICC

Process Integrated Carbon Capture – Design and Evaluation (Guidelines)


KVA Linth


HHKW Galgenen


KSV Werdhölzli

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

Authors:
Dr. Benjamin Ong, HSLU, benjamin.ong@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 crucial 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 CO_2 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, optimize heat recovery, and reduce CO_2 emissions, thereby supporting Switzerland's net-zero targets.

The project investigates how integrating CO_2 capture processes with various industrial point sources influences the energy efficiency and techno-economic performance of the integrated designs. The approach combines process simulation, Pinch Analysis, and system performance analysis through piecewise steady-state simulations:

> **Process Simulation**: Using CHEMCAD, the CO_2 capture process 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), optimizing the integration of CO_2 capture processes with existing plant systems to maximize heat recovery and minimize 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.

This document aims to provide a framework for conducting process simulations of generic CO_2 capture technologies, ensuring that practitioners or researchers can systematically model, analyse, and optimize CO_2 capture processes.

Contents

1 Introduction

This document presents a guideline for the design and integration of CO_2 capture systems into existing industrial processes, based on the methodology developed in the Process Integrated Carbon Capture – Design and Evaluation (PICC) project, SI/502519[1]. The guideline provides a structured workflow for engineers, researchers, and practitioners to model, simulate, and optimize CO_2 capture processes and assess their integration into industrial sites.

The PICC project itself focused on the post-combustion CO_2 absorption process using monoethanolamine (MEA), applied to three representative industrial point sources in Switzerland:

- KVA Linth – Waste incineration plant.
- KSV Werdhölzli – Sewage sludge incineration plant.
- HHKW Galgenen – Wood-fired power plant.

While this guideline draws heavily from the experiences and results of these case studies, the step-by-step methodology is formulated in a way that can be transferred to similar industrial CO_2 capture projects, provided the user adapts the input data and boundary conditions to their specific case.

In this context, the term "generic" refers to the structured approach of the methodology itself, not to the specific capture technology or solvents. The guideline emphasizes a systematic integration process, including:

- Component-level process simulation for mass and energy balancing,
- Pinch Analysis for integration,
- System-level performance evaluation using piecewise steady-state simulations.

This document assumes that readers are familiar with process simulation tools (e.g., CHEMCAD, Aspen Plus), Pinch Analysis methodologies, and have basic knowledge of industrial energy systems.

Throughout this guideline, practical hints, modelling tips, and integration considerations are provided. For full details, specific results, and in-depth case analyses, readers are referred to the PICC project report.

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[1] The ARAMIS link of PICC: https://www.aramis.admin.ch/Grunddaten/?ProjectID=51491

2 Methodology

PICC uses a combination of existing frameworks and tools to design an integrated system (Figure 1). The methodology for the integrated process design incorporates process simulation, Pinch Analysis and heat exchanger network design, as well as piecewise steady state analysis of the integrated.

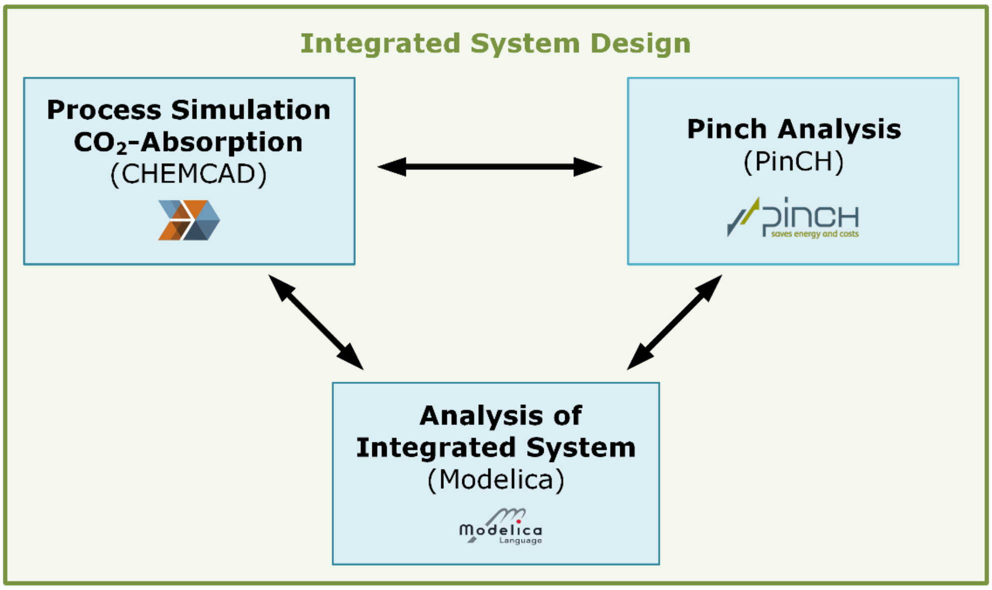

Figure 1: Integrated process design methodology of PICC.

Process Simulation: The first step involves simulating the CO_2 capture process using established engineering tools to calculate **mass and energy balances**. This provides specific operational data, such as thermal and electrical energy demands for capturing 1 ton of CO_2. Different process configurations and optimizations are explored to determine the most efficient setup for the capture plant. The initial Process Simulation step is conducted under steady-state conditions, focusing on defining mass and energy balances for the CO_2 capture process itself (e.g., absorber/desorber unit sizing, solvent flow rates, and energy consumption per ton CO_2 captured). This is standard practice for component-level design and allows for a robust baseline evaluation of process performance.

Pinch Analysis: Afterwards, a pinch analysis is conducted to identify opportunities for energy integration between the CO_2 capture plant and existing industrial processes. This analysis helps to optimize heat recovery and minimize the need for external energy inputs by matching heat sources and sinks within the system. It considers the entire operating year to assess the variability and efficiency gains from different process configurations.

Integrated System Analysis with Modelica: When integrating the CO_2 capture system into an existing industrial plant, the overall system behaviour exhibits variability, such as changes in heat demand, flue gas flow rates, and seasonal operational modes. To capture these system-level impacts, a piecewise steady-state approach is employed using Modelica. Instead of running fully dynamic transient simulations, several representative steady-state scenarios (e.g., summer low-load, winter full-load, transition periods) are simulated, which together approximate the system's annual performance.

Modelica is utilized for this integrated system analysis because of its object-oriented and acausal modeling capabilities, which simplify the connection of components like steam turbines, heat exchangers, and heat pumps, and facilitate scenario-based evaluations. This modular approach also ensures that models can be easily adapted for future case studies or different process configurations

2.1 Process Simulation

Process simulation has been used to develop flowsheets in the chemical engineering industry for the past decades. In PICC, the process simulation was used to evaluate process and its efficiency (mass balance), assessing energy consumption (energy balance), and optimizing the process flowsheet. To conduct the process simulation, the user needs to have the basics of chemical/process engineering. More information can be found user guides of the process simulators.

Objective:

- To model the CO_2 capture process to determine mass and energy balances and identify key process requirements.

Key Activities:

- Define the process boundaries and system components, including capture processes, absorption, and desorption units.
- Input accurate physical properties of CO_2, solvents, and other chemicals involved.
- Simulate steady-state operation to establish baseline energy and material flows.
- Calculate specific thermal and electrical energy requirements for capturing one ton of CO_2.

Important Variables and Key Results:

- Solvent selection and properties (e.g., capacity, reaction kinetics).
- Absorber and desorber operating conditions (e.g., temperature, pressure).
- Energy requirements for CO_2 separation and compression.

The appropriate process simulation software (e.g., CHEMCAD, Aspen Plus, HYSYS, etc.) should be chosen based on the specific requirements (e.g. adequate phase equilibrium model for the amine system) and the user's familiarity with the tool. The following steps are necessary to develop a process simulation model:

2.1.1.Selecting Physical Property Environment and Equation of State

Before constructing a flowsheet or running simulations, it is crucial to select a suitable property method for thermodynamic and physical property calculations. This choice directly impacts the accuracy of simulation results. Property methods define how key material properties are calculated within the simulation environment, including:

- Phase equilibria (vapor-liquid, liquid-liquid, solid-liquid, etc.)
- Heat capacities
- Vapor pressure
- Density
- Viscosity

Different methods offer varying levels of accuracy depending on the chemical system, operating conditions, and simulation objectives. Therefore, selecting an appropriate model (e.g., NRTL, UNIQUAC, Peng-Robinson) is essential to ensure realistic process predictions.

2.1.2. Process Simulation Steps

Step 1: Process Flow Diagram (PFD) Development

- Outline the process flow for the process, including key units such as absorbers, desorbers, heaters/coolers, and compressors and etc..
- Define boundaries and key streams, ensuring all inputs and outputs are clearly specified.

Figure 2 shows an example of a PFD of CO2 Capture using MEA.

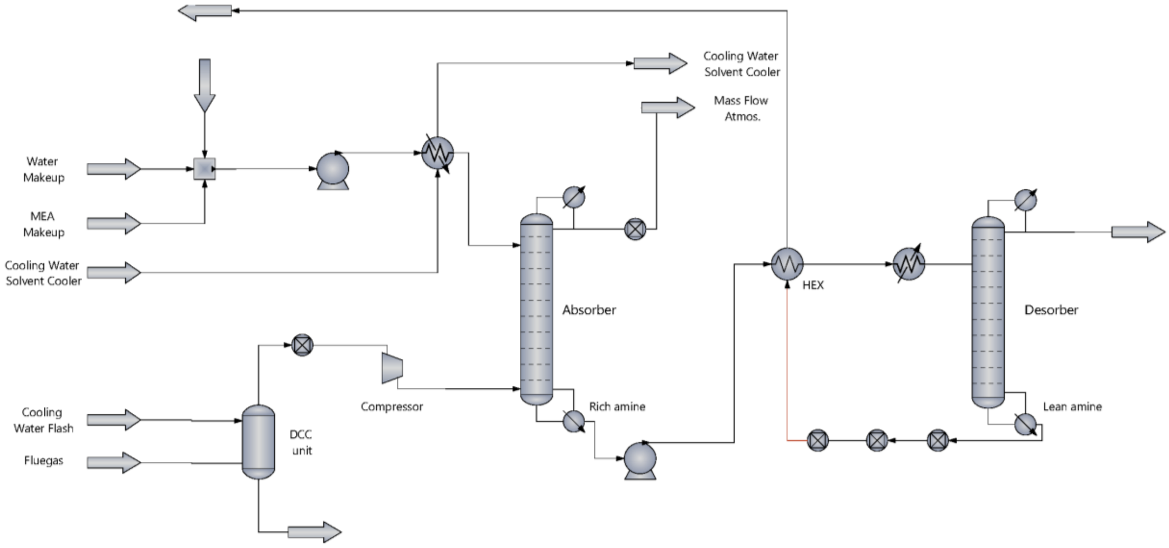

Figure 2: Example of CO_2 Capture Process from ChemCAD.

Step 2: Component and Stream Specifications

- Define all chemical components involved in the process. *In the example, this includes flue gas constituents, solvents (e.g., MEA), and utilities (e.g., steam, cooling water) for Figure 2*.
- Specify stream properties such as temperature, pressure, composition, and flow rates.
- Ensure utility streams are correctly defined to reflect their interactions with the CO_2 capture system.

Step 3: Unit Operation Model Configuration

- Configure each unit operations *(e.g., reactors, columns, heat exchangers, separators, pressure changers*) according to the process design.
- Select appropriate modelling approaches for critical units. For the example of Figure 2:
    - Absorbers/Desorbers: Kent-Eisenberg model, vapor-liquid equilibrium (VLE) approach, packed column mass transfer model, or tray-by-tray column model.
    - Reactors: Input reaction kinetics if chemical reactions are involved.
    - Heat Exchangers and Separators: Ensure correct heat and phase separation models are applied.

- Validate and reconcile the thermodynamic phase equilibrium model using literature data relevant to the operating region. This step is vital to ensure accurate phase behavior predictions, which form the foundation for reliable process design.

Step 4: Energy and Material Balance Calculations

- Simulate the process under steady-state conditions to calculate mass and energy balances.
- Verify that the simulation results conform to fundamental physical laws (mass and energy conservation).
- Extract key performance indicators (KPIs). For Figure 2, this includes:
    - CO_2 capture efficiency (wt%)
    - Thermal and electrical energy consumption (kW/kWh)
    - Solvent consumption rates

Step 5: Sensitivity Analysis

- Conduct sensitivity analysis on critical parameters (e.g., temperature, pressure, solvent flow rates) to understand their impact on system performance. For Figure 2, the variability of the mass flow of the flue gas on the impact of the CO_2 capture efficiency was studied.

2.1.3. Optimization and Validation

Step 1: Process Optimization

- Explore optimization opportunities such as heat integration (see Section 2.2), process modifications, and solvent selection to minimize energy use.
- Adjust operating conditions and configurations iteratively to improve overall system efficiency and reduce costs.

Step 2: Validation of Simulation Results

- Summarize key findings from the simulation, highlighting energy and material efficiencies, CO_2 capture rates, and any identified optimization pathways.
- Compare simulation results with experimental data, pilot plant results, or literature benchmarks to validate the model.

2.2 Pinch Analysis

This section outlines the systematic approach for performing Pinch Analysis (PA) aimed at integrating CO_2 capture plants with existing industrial processes by considering interactions and heat exchange opportunities between them. To conduct PA, the PinCH software[2] or other pinch analysis tools can be used.

Objectives:

- To optimize heat integration to maximize energy recovery and minimize external energy requirements of the plants individually.
- To integrate the two plants and develop a heat recovery/heat pump system for the integrated system.

Key Activities:

- Perform a detailed energy analysis for both the CO_2 capture plant and industrial processes.
- Identify heat sources (hot streams) and sinks (cold streams) within the process.
- Construct composite curves and identify the pinch point to guide heat exchanger network (HEN) design.
- Design HEN to optimize heat recovery and reduce additional energy input requirements.

Important Variables and Key Results:

- Temperature levels of heat sources and sinks.
- Heat exchanger effectiveness and configuration.
- Integration opportunities for low-grade heat recovery.

2.2.1. Data extraction

Collect data on all relevant process streams (hot and cold streams) from both the CO_2 capture and industrial plant, including:

- Stream temperatures: Supply and target temperatures[3].
- Heat capacities: Flow rates and specific heat capacities.
- Heat duties: The amount of heat to be transferred.
- Identify utility streams: Include steam, hot water, cooling water, and any other heating or cooling utilities.

Figure 3 are coloured with red and blue, which represent the hot and cold streams for data extraction.

Data extraction from the real processes should always be preferred. However, in the absence of real plant data, the aforementioned data can be obtained using the process simulation as demonstrated for the CO_2 *capture plant in the context of the PICC project or above. For industrial processes data in PICC, the data were extracted from the industrial plant for winter, summer, and transition periods.*

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[2] www.pinch.ch

[3] Supply and target temperatures refer to the temperatures of the inlet and outlet temperatures.

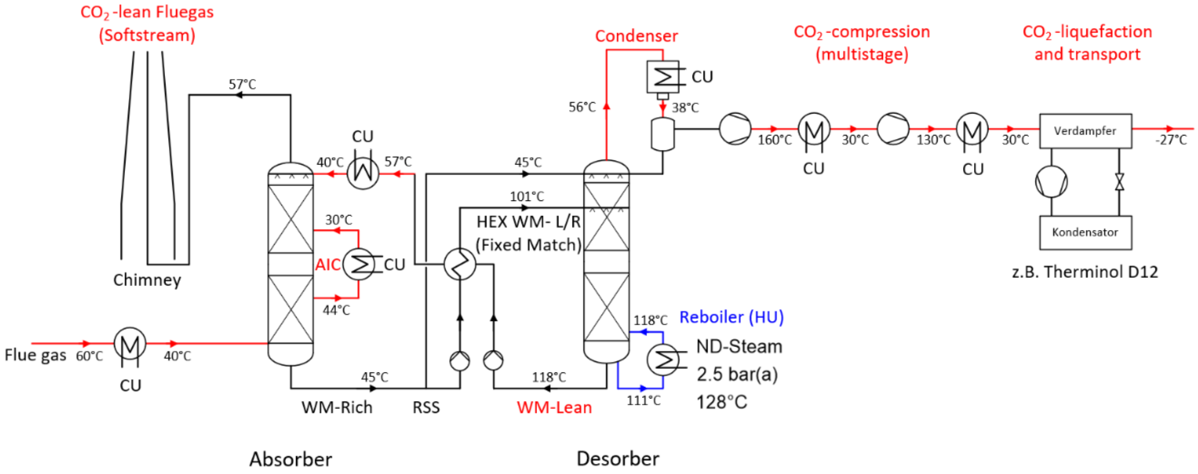

Figure 3: Simplified PFD of the CO_2 Capture Plant.

2.2.2. Performing Pinch Analysis[4]

Step 1: Construct Composite Curves (CCs)

- Create hot and cold CCs using stream data:
  - Hot CC: Represents all streams that need cooling (hot streams).
  - Cold CC: Represents all streams that need heating (cold streams).
- Plot the CCs on a temperature-enthalpy diagram (see Figure 4, left).

Step 2: Identify the Pinch Point

- Determine the Pinch Point: This is the point of closest approach between the hot and cold composite curves, representing the most constrained energy transfer point in the system.
- Calculate the minimum temperature difference (ΔT_{min}) at the Pinch Point, which is crucial for determining the feasibility and efficiency of heat recovery.
- Adjust ΔT_{min} and assess how changes affect the heating and cooling demands, and the overall integration feasibility, (see Figure 4, right).

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[4] The steps on how to conduct a Pinch Analysis can be found in the SFOE Handbook, https://www.pinch.ch/docs/PDFs-Research-Publications/Einfuehrung_in_die_Prozessintegration_2017.pdf

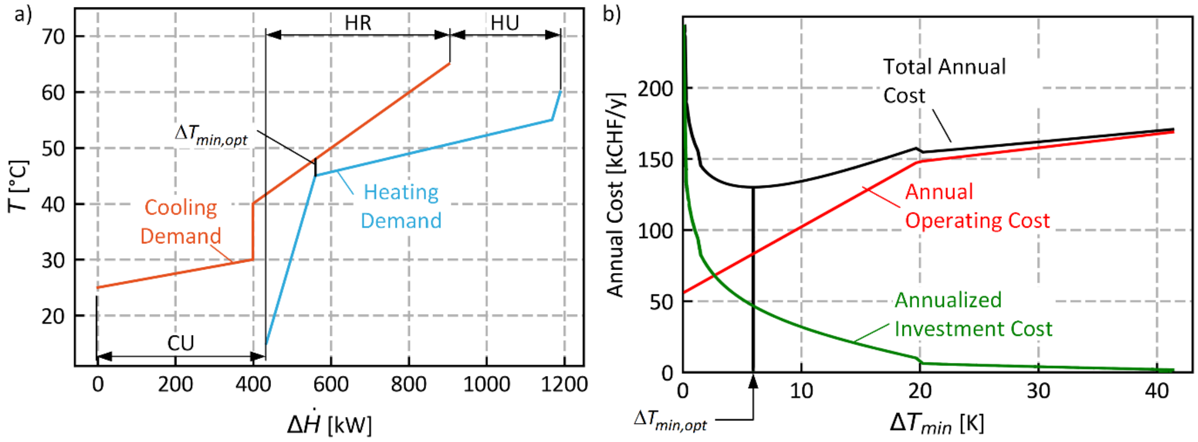

Figure 4: Exemplary CCs and cost curves. Left: CCs of the cooling (red curve) and heating (blue curve) demands showing the potential HR and HU and by the CU for the cost optimal temperature difference $\Delta T_{min,opt}$. Right: cost curves showing total annual cost (black curve), annual operating cost (red curve), and annualized investment cost (green curve). The optimal temperature difference $\Delta T_{min,opt}$ is found at the minimum of the total annual cost curve.

Step 3: Determine Energy Targets

Calculate minimum heating and cooling requirements with Grand Composite Curve (GCC):

- Above the Pinch: Focus on reducing the heating requirements.
- Below the Pinch: Focus on reducing the cooling requirements.
- Set energy targets to minimize external utility use (e.g. amount of HU/steam and CU/cooling water), as shown in Figure 5.

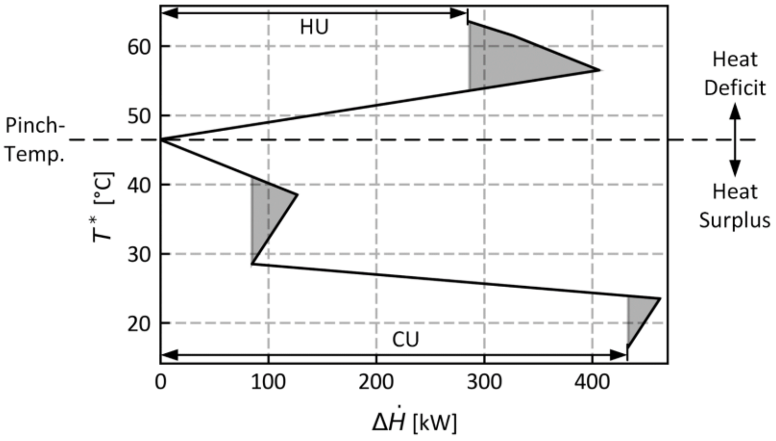

Figure 5: The exemplary GCC shows the heat deficit and surplus depending on the temperature level. Above the pinch there is a heat deficit and below a heat surplus.

2.2.3. Energy Efficiency Measures Design[5]

There are multiple energy efficiency measures that are available. In this document, only heat exchanger network (HEN) and heat pumps (HPs) are considered to explain the concept of EEM design.

Design of HEN

The HEN is designed to maximize internal heat recovery between process streams while adhering to the fundamental principles of Pinch Analysis. The objective is to minimize the need for external utilities (hot and cold) by strategically matching hot and cold process streams.

Key design principles include:

- Above the Pinch:
    - Do not use cold utilities (e.g., cooling water or air coolers).
    - Only recover heat internally by matching hot process streams with available cold streams.
- Below the Pinch:
    - Do not use hot utilities (e.g., steam or hot oil).
    - Maximize internal heat recovery by exchanging heat between cold and hot process streams.

These rules ensure that external utilities are only applied where thermodynamically necessary, avoiding inefficiencies caused by improper utility placement.

Integrating HPs

Integrating a HP across the pinch point is an effective strategy for enhancing heat recovery in industrial processes. In this configuration, the evaporator of the HP extracts heat from process streams below the pinch, thereby reducing the heat surplus. Simultaneously, the condenser releases heat to process streams above the pinch, offsetting the heat deficit (see Figure 6).

While this approach appears to violate the third principal rule of pinch analysis, which prohibits heat transfer across the pinch, the HP operates by actively upgrading heat from a lower temperature level to a higher one. As a result, the HP functions as a mechanical means of reversing heat flow direction, enabling additional heat recovery that would otherwise not be feasible through passive heat exchange.

Key effects of integrating a HP across the pinch:

- Below the Pinch (Evaporator side): Absorbs low-grade heat, reducing the thermal surplus.
- Above the Pinch (Condenser side): Delivers upgraded heat, mitigating the thermal deficit.
- Enhances overall process energy efficiency by utilizing excess low-temperature heat that would otherwise be wasted.
- Introduces an external work input (usually electrical), which should be evaluated against the energy savings achieved.

This method provides a practical solution for processes where direct heat integration is limited by pinch constraints, thus offering additional flexibility in process heat recovery strategies.

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[5] This should be~~is~~ conducted with the PinCH software, or any similar heat exchanger network design tool.

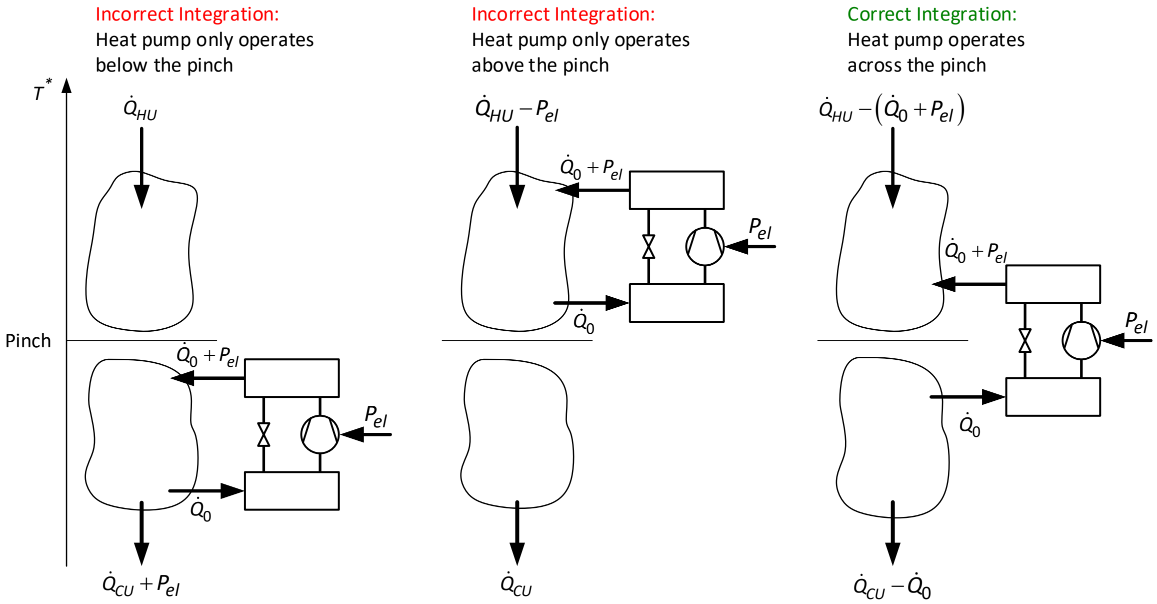

Figure 6: Correct and incorrect HP Integration into a continuous process.

2.2.4. Economic Evaluation

- Estimate costs and savings related to the integration:
  - Capital costs: New heat exchangers, heat pumps, or retrofits.
  - Operational savings: Reduced utility consumption, improved energy efficiency.
- Perform a cost-benefit analysis to determine the economic viability of the integration strategy.[6]

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[6] See appendix for formula.

2.3 System Analysis

To analyse the integrated system, Modelica[7] is recommended. Modelica enables users to create accurate models, perform comprehensive simulations, and optimize system performance for energy efficiency and emissions reduction. However, any similar dynamic simulation software (e.g., Simulink, Dymola) can be used for this purpose. To perform the system analysis as described in these guidelines effectively, the user should have a basic understanding of how to use Modelica[8].

Objective:

- To assess the performance of the integrated system under varying operating conditions and over a full operational year.

Key Activities:

- Develop a detailed model that includes CO_2 capture, heat recovery, and industrial processes.
- Conduct (piecewise steady state) simulations to account for seasonal variations and fluctuating operational conditions.
- Analyze the system's response to changes in demand and supply and identify optimized operating strategies.

Important Variables and Key Results:

- Seasonal variability in heat and power demand.
- Interaction between CO_2 capture and other industrial processes.
- Impact of heat pump integration and its operational flexibility.
- Explore scenarios for different configurations and retrofits to improve overall performance.

2.3.1.Model Setup and Component Selection

Step 1: Define System Boundaries and Objectives

- Define the scope of the system: identify which components and processes will be included in the model (e.g., Figure 7 shows the system boundary for a steam cycle of a combustion process).
- Set objectives for the analysis: determine the KPIs such as energy efficiency, and overall system performance.

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[7] Modelica is an object-oriented modeling language for modelling physical systems, more info at https://modelica.org/

[8] Introductory tutorials can be found at https://modelica.org/language/

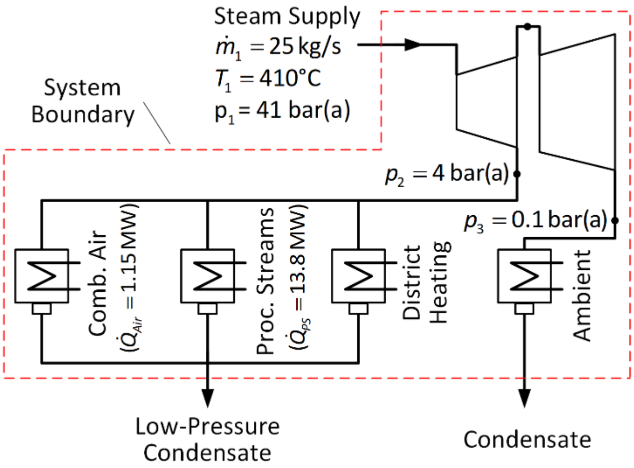

Figure 7: Steam cycle of a combustion process.

Step 2: Gather Data and Process Requirements

- Collect Component and Process Data: Gather comprehensive data for all relevant process components, including operational parameters such as temperatures, pressures, flow rates, and heat duties. Ensure that data is accurate and reflects typical operating conditions. An example of the required data structure is illustrated in Figure 8.
- Map Process Interconnections: Identify and document the interconnections between different process units, with particular focus on mass and energy flows. Understanding these relationships is essential for accurate simulation and effective heat integration.
- Define Variability for Piece-Wise Steady-State Modelling: If the process involves operational variations (e.g., batch operations, load changes), incorporate these variations into the simulation setup as piece-wise steady-state scenarios. This enables the model to represent different operating points and enhances its predictive capability under varying conditions.

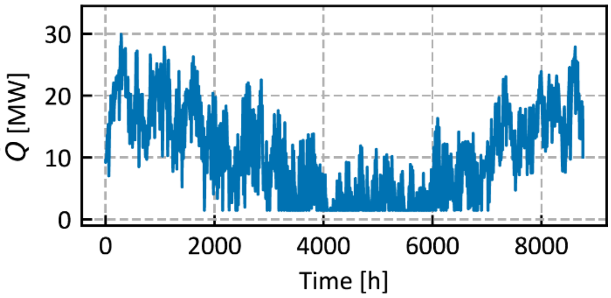

Figure 8: Hourly district heading load profile, calculated based on design reference year data of Meteonorm database that is imported into Modelica.

Step 3: Select and Define Model Components

Component Selection: Based on the specific processes in your integrated system, select appropriate and pre-defined Modelica components such as:

- Steam Turbine
- Generator
- Condenser
- Liquid Heater/Cooler
- Heat Pumps/Absorption Heat Pumps
- Mixing Tanks
- Pumps
- Heat Exchangers

Customization: Adapt standard components to reflect the specific characteristics of your system, using the object-oriented and acausal nature of Modelica to easily modify and reuse components. e.g., the steam turbine stage is modelled based on typically available design parameters like the outlet pressure, isentropic efficiency, and combined mechanical and electrical efficiency.

Step 4: Develop System Model

Build the system based on the real site topology with the selected components (Figure 9).

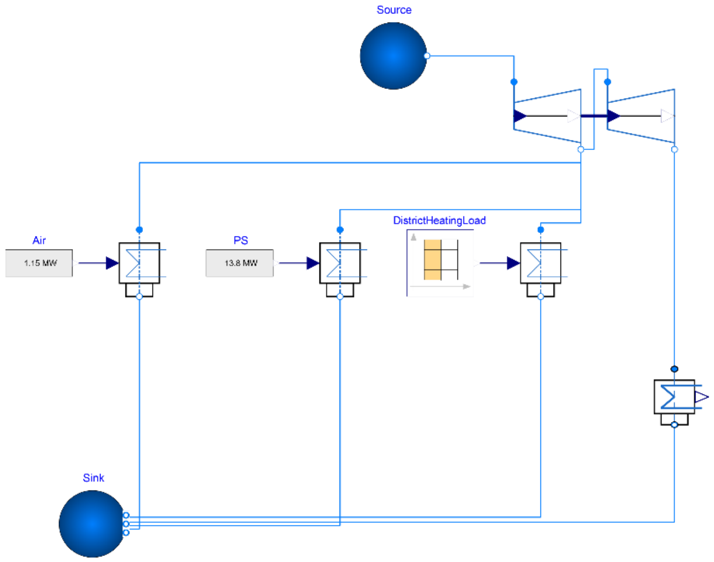

Figure 9: Modelica model of the system boundary.

Step 5: Run Simulations

Use Modelicas equation solver to set up and solve the equations for the desired simulation time.

- Annual system simulations were performed on the system of Figure 9 to evaluate the functionality and performance of the described modelling approach. The steady-state solution of each timestep (in this case, one hour) is computed by the Modelica solver (Dassl®).
- The calculated steady-state solutions for each hour of operation are then analyzed to create an overview of the resulting operating points of the eventual system. Figure 10 shows the duties of the different components under consideration. Electricity and heat extracted from the process are added up in the vertical of the stack plot to give an overview of the shares of the different quantities over time.

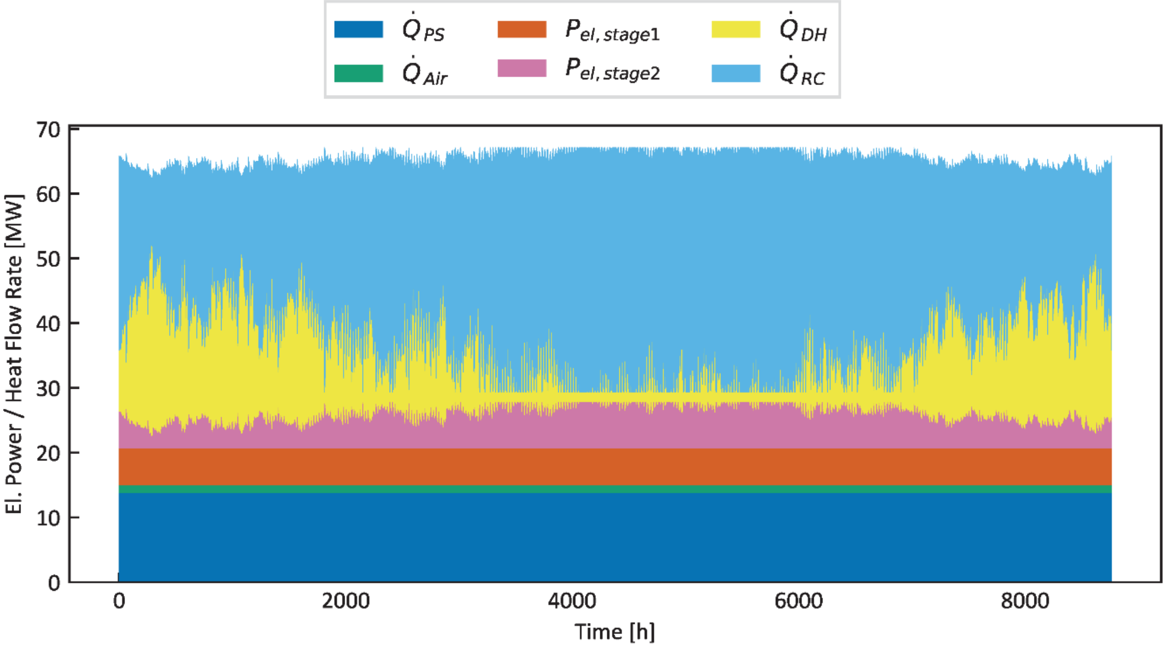

Figure 10: Stack plot of extracted heat flow rates and electric powers of the system.

2.3.2. Analysis and Optimization

Step 1: Perform System Performance Analysis

- Evaluate KPIs: analyse the system's energy efficiency, CO_2 capture rate, heat recovery potential, and other KPIs identified in the objectives.
- Identify bottlenecks: use the model to identify inefficiencies or areas of improvements.

Step 2: Optimization[9]

- Explore scenarios: simulate various operational scenarios, such as changes in steam flow rates, integration of heat pumps, or alternative configurations by defining these variabilities as mentioned in Step 2 of Section 2.3.1.
- Optimize system parameters: use optimization techniques (e.g., parameter sweeps, sensitivity analysis) to identify the best settings for maximum performance.

Step 3: Economic Analysis

- Estimate costs and savings: incorporate cost models into the simulation to estimate capital costs, operating costs, and potential savings from improved efficiency or emissions reduction.
- Perform cost-benefit analysis: evaluate the economic viability of different integration and optimization scenarios.[10]

3 Results

The results sections are the learnings from the results that are extracted from PICC.

3.1 Key Performance Indicators (KPIs)

When evaluating CO_2 capture integration, focus on these KPIs. Use them as a reference to model and compare different integration scenarios at your site.

Energy Efficiency

What to Check: Quantify the reduction in thermal and electrical energy consumption relative to a standalone CO_2 capture system and different strategies.

Generic Insight: Process optimizations (AIC, RSS) typically yield 10–12% energy savings. Heat pump integration can further enhance efficiency if low-temperature heat demand exists.

CO_2 Capture Efficiency

What to Measure: Determine the achievable CO_2 capture rate under thermal and operational constraints.

Generic Insight: Thermal integration limits may cap capture rates at 70–80%, but heat pump integration can boost this to 90%, assuming electricity costs remain manageable.

Economic Metrics

What to Model: Calculate CAPEX, OPEX, and specific CO_2 capture costs (CHF/ton CO_2). Include opportunity costs from lost electricity sales.

Generic Insight: Economies of scale significantly influence unit costs. Smaller plants face higher CHF/ton CO_2 costs, while larger plants benefit from scale but have higher absolute investments.

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[9] Example of this can be found in Agner et al. (2023), Piecewise-Steady-State Modelica Simulations for the Conceptual Design Phase of Industrial Processes, 15th International Conference 2023, Aachen, Germany.

[10] Formula can be found in Appendix.

Environmental Impact

What to Evaluate: Net CO_2 emissions reduction, including potential for negative emissions when biogenic fuels are involved.

Generic Insight: Integration of CO_2 capture can lead to significant emissions reductions, but resource constraints (e.g., waste heat availability) directly affect environmental benefits.

3.2 Challenges and Solutions Integration

When planning the integration of CO_2 capture systems into industrial processes, practitioners will encounter several recurring challenges. These challenges are not exhaustive but represent key barriers identified across the PICC project case studies. Below, each challenge is outlined with proposed solution to assess its relevance at your site and to address it. Some of the solutions have been carried out in PICC, other projects, or ongoing projects or research needed.

Challenge 1: Capital Cost Sensitivity

One of the primary challenges is the high capital investment required for integrating CO_2 capture systems, especially for small and medium-sized emitters. The specific cost per ton of CO_2 captured tends to increase disproportionately for smaller plants due to scale inefficiencies.

How to detect it at your site:

- Estimate the capital expenditure (CAPEX) per ton of CO_2 capture capacity.
- Assess physical constraints that could increase installation costs (e.g., limited space, infrastructure modifications).

Potential Solution Pathways:

- Consider a phased implementation, starting with a partial capture system (e.g., 70–80%) that can be scaled up as CO_2 infrastructure becomes available.
- Engage in industrial CO_2 hub initiatives to explore shared infrastructure and cost-sharing opportunities.
- Prioritize process optimizations and energy efficiency measures.

Challenge 2: Energy Cost Sensitivity

The operational cost of CO_2 capture is highly sensitive to the price of energy inputs, including electricity, fuel, and steam. Energy-intensive configurations, such as those involving HPs, may become economically unfeasible in regions with high or volatile energy prices.

How to detect it at your site:

- Analyze your site's exposure to energy price fluctuations (e.g., grid electricity tariffs).
- Simulate economic scenarios/sensitivity analysis with varying energy prices to understand their impact on operating costs.

Potential Solution Pathways:

- Explore the integration of on-site renewable energy sources (e.g., photovoltaic, wind) to reduce exposure to market price volatility[11].
- Implement flexible operation strategies, such as adjusting CO_2 capture rates during peak electricity price periods[12].
- Ensure that heat pump integration is only pursued where sink temperatures are sufficiently low to ensure high coefficient of performance.

Challenge 3: Thermal Integration Constraints

The extent to which a CO_2 capture plant can be efficiently integrated is often limited by the site's thermal energy profile. This includes the availability of waste heat, the temperature levels of heat sources and sinks, and the match between supply and demand patterns[13].

How to detect it at your site:

- Conduct a Pinch Analysis to identify the potential for internal heat recovery.
- Map out seasonal variations in heat supply and demand, especially for district heating networks.
- Evaluate the supply and return temperature levels of your district heating system to assess suitability for heat pump integration.

Potential Solution Pathways:

- Optimize the site's existing HEN to maximize internal heat recovery.
- Consider integrating heat pumps, particularly where district heating demand is at low temperatures (<75°C).
- Assess the potential for hybrid system designs, such as coupling CO_2 capture technologies or incorporating thermal storage to balance supply-demand mismatches.

Challenge 4: Knowledge Gaps on Operational Variations and System Dynamics

A key challenge in integrating CO_2 capture systems is the lack of detailed knowledge about how the combined process behaves under varying operational conditions, such as seasonal demand shifts, fluctuating flue gas compositions, and varying process loads.

How to detect it at your site:

- Review available operational data to assess how well variations in flue gas flows, heat demands, and external factors are understood.
- Identify gaps in dynamic performance knowledge (e.g., How does the plant respond to load changes? What are the seasonal variations in heat recovery potential?).
- Assess whether existing design models account for these conditions.

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[11] Method and example can be found at SFOE co-funded project, Eco-Targeting – Decarbonization of Swiss Industry through extended Eco-Targeting based on Pinch Analysis method, https://www.aramis.admin.ch/Grunddaten/?ProjectID=51154

[12] Currently being conducted by the CO_2 Hub in HSLU, which will be completed in December 2025.

[13] Detailed methods and case studies can be found on SFOE co-funded project, DeCarb-PUI – Decarbonization of industrial processes through redesign of the process-utility interface, https://www.aramis.admin.ch/Grunddaten/?ProjectID=49367

Solution Pathways:

- Perform piece-wise steady state simulations (e.g., using Modelica or similar tools) to model the integrated system's behavior over an annual operation profile.
- Use piecewise steady-state simulations to evaluate system stability and energy performance across variable load conditions.
- Ensure that the design phase includes flexibility buffers, allowing the integrated system to cope with operational uncertainties (e.g., conservative design margins in heat exchanger sizing).
- Collaborate with plant operators to collect empirical data on operational variabilities, which can be used to refine simulation models.

Challenge 5: CO_2 Transport and Storage Infrastructure Limitations

The absence of CO_2 transport and storage infrastructure can be a significant barrier, particularly for plants not located near existing or planned CO_2 pipelines or storage hubs.

How to detect it at your site:

- Assess the proximity of your site to existing or upcoming CO_2 transport networks and storage facilities[14].
- Engage with regional infrastructure planning bodies to understand future availability timelines.

Solution Pathways:

- Develop a phased deployment strategy, starting with partial capture until transport and storage infrastructure becomes accessible.
- Explore the use of intermediate on-site CO_2 storage solutions to allow flexibility in operation.
- Participate in regional CO_2 hub initiatives that align multiple emitters and infrastructure stakeholders.
- Assess possibilities for CO_2 utilization pathways (e.g., Power-to-X, building materials) as long-term or interim solutions before large-scale storage becomes viable.

3.3 Recommendations

These recommendations provide a structured approach for practitioners to design and evaluate CO_2 capture integration concepts tailored to their specific industrial site conditions. Each recommendation outlines what to do in practice, followed by general insights derived from the PICC project.

Customization

What to Do:

- Conduct a detailed site assessment of energy flows, including waste heat availability, district heating network characteristics, and existing utility systems.
- Perform a PA to identify heat recovery opportunities.
- Consider operational profiles (seasonal load variations, flue gas composition variability) in system design.

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[14] Information on transport and storage can be found in DemoUPCARMA Demonstration und Upscaling von Kohlenstoffdioxid-Management-Lösungen für Netto-Null-Schweiz, https://www.aramis.admin.ch/Grunddaten/?ProjectID=49400

Generic Insight:

Integration strategies are never one-size-fits-all. The feasibility of CO_2 capture depends heavily on site-specific factors such as available waste heat at appropriate temperature levels and infrastructure constraints. Tailored designs significantly improve energy efficiency and economic viability.

Energy Cost Management

What to Do:

- Analyze energy cost exposure (electricity, fuel, steam) and simulate its impact on OPEX under various price scenarios.
- Investigate the integration of on-site renewable energy sources (solar, wind) to reduce dependence on volatile grid prices.
- Explore flexible operation modes that allow for adjusting capture rates in response to market conditions.

Generic Insight:

Energy costs are a dominant factor in operational feasibility. Sites with access to stable or subsidized energy supplies are inherently more favorable for CO_2 capture integration. Flexibility in operation and diversified energy sourcing can significantly mitigate price risks.

Integration Concept Selection Based on Thermal Profile

What to Do:

- Analyze DH supply and return temperatures to assess the viability of heat pump integration.
- Prioritize direct waste heat recovery through process optimization (AIC, RSS) where possible.
- Consider hybrid solutions if thermal recovery limits are reached.

Generic Insight:

Heat pumps has the best COP in systems with low DH temperatures and sufficient low-grade heat availability. Where thermal integration potential is limited, hybrid or multi-purpose solutions may offer a better return on investment.

Addressing Knowledge Gaps on Operational Dynamics

What to Know:

- Utilize dynamic simulation tools (e.g., Modelica) to predict system behavior under variable operating conditions.
- Simulate full-year operational scenarios to evaluate seasonal impacts on CO_2 capture performance.
- Design for operational flexibility even if control systems are not yet advanced (e.g., by incorporating conservative design margins).

Generic Insight:

A robust design must consider not only steady-state operation but also dynamic responses to load variations, seasonal demand shifts, and transient conditions. Dynamic modeling in the design phase is critical to avoid unexpected performance bottlenecks post-implementation.

Stakeholder Engagement

What to Esnure:

- Engage early with plant operators, policymakers, and technology providers to align integration strategies with regulatory frameworks and market mechanisms (e.g., CO_2 pricing, subsidies).
- Participate in regional CO_2 hub initiatives and infrastructure development programs.

Generic Insight:

Early alignment with stakeholders ensures that technical solutions are not developed in isolation from economic and policy realities. Collaboration can unlock co-financing opportunities, regulatory support, and shared infrastructure access, which are critical for project success.

4 Conclusions

The guideline aimed at outlining the work and learning from the PICC project which aimed to develop and validate a methodology for integrating CO_2 capture processes into various industrial point sources, focusing on assessing the technical and economic feasibility of such integration. This methodology combines process simulation, PA, and piecewise steady-state modeling to evaluate the demand and supply dynamics of industrial processes when coupled with CO_2 capture systems.

Through detailed application of the guidelines to the three case studies, KVA Linth, KSV Werdhölzli, and HHKW Galgenen, the methodology enables the identification of thermal commitments and the effects of the process interactions resulting from the integration of CO_2 capture systems. The results of these simulations provide specific plant operating data, including thermal and electrical energy demands per ton of CO_2 captured. By analyzing different process configurations and seasonal operating scenarios via Pinch Analysis, it becomes possible to assess the changes induced by CO_2 capture integration and to evaluate the effectiveness of process optimizations such as Absorber Intercooling (AIC) and Rich Stream Splitting (RSS). These analyses form the foundation for detailed economic evaluations.

Potential benefits demonstrated through case studies: The simulation generated for the three case studies can be used to evaluate different scenarios. For example, for KVA Linth, to evaluate how the integration of a planned absorption heat pump of 20 MW affects the integrated system. For HHKW Galgenen, a full load system scenario of wood fired boiler is studied as a scenario for the partners.

Potential impact: In Switzerland, the three industries emit approximately the following amount:

Waste incineration plant : 4’465’700 t CO_2/a

Wood-fired power plant : 990’500 t CO_2/a

Sludge incineration plant : 129’000 t CO_2/a

From the energy perspective of the results, integrating CO_2 capture to these three industries, with heat pump has minimal impact on the system in terms of heat, however, competes slightly with electricity. When CO_2 capture processes, are integrated in these three industries, it will capture approximately **5.6 million tonnes of CO_2**.

5 Appendix

Specific Costs of CO_2 Capture

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

$$TAC = ANF \times C_{cap} + C_{op,a} + B \qquad (1)$$

where C_{cap} is the capital cost, $C_{op,a}$ is the annual operating cost and B is annual benefits from the integration

To then get the specific CO_2 cost LCO_2, the TAC is divided by the total annual CO_2 captured (M_{CO2}):

$$LCO_2 = \frac{TAC}{M_{CO2}} \qquad (2)$$

The annuity factor, ANF is calculated with

$$ANF = \frac{i_r(1+i_r)^n}{(1+i_r)^n - 1} \qquad (3)$$

whereby the i_r is the interest rate in % and n is the depreciation period in years.

$$B=\sum_{j=0}^{J} \mathrm{J} \times P_j + (CA \times P_{CO2}) - (ELS \times P_e) - (HLS \times P_H\ ) \qquad (4)$$

where, P_{CO2} is CO_2 levy (CHF/t_{CO2}) levy and its CO_2 abatement potential of technology integration, CA (t/a). P_e and P_H is price of electricity and heat (CHF/MWh). ELS and HLS are electricity losses and heat losses due to the integration and J is any other benefits due to the integration with its CHF per unit, P_j.