UNIVERSITA' DEGLI STUDI DI PADOVA

Dipartimento di Ingegneria Industriale DII

Corso di Laurea Magistrale in Energy Engineering

Process integration and intensification:

saving energy and water

Relatrice: Prof. ANNA STOPPATO
Correlatrice: Dott. Benedetta Scalzotto

Studente:
Joseph Teyrouz, 2106066

Anno Accademico 2025/2026

ACKNOWLEDGMENT

First and foremost, I would like to express my sincere gratitude to Professor Anna Stoppato for her invaluable guidance, support, and trust throughout the development of this thesis. Her expertise, feedback, and encouragement were essential at every stage of this work.

I am also deeply thankful to PhD candidate Benedetta Scalzotto, whose continuous assistance, insights, and dedication helped me navigate the technical and research challenges of this project. Her availability and patience made a significant difference in the quality of this work.

My heartfelt appreciation goes to all the professors who taught me and enriched my knowledge throughout this Master's program. Their passion, dedication, and deep expertise provided me with a strong academic foundation and inspired me to pursue excellence in the field of energy engineering.

A special thanks goes to the staff and coordinators of the Master program in Energy Engineering at the University of Padua, whose academic structure and support allowed me to carry out this project with confidence and curiosity.

ABSTRACT

The present thesis is the result of a project conducted under the supervision of Professor Anna Stoppato and PhD student Benedetta Scalzotto, focused on Process Integration and Intensification: saving energy and water at the Waste-to-Energy plant "San Lazzaro" of Padova. The aim of the activity was to analyze and optimize internal resource usage by implementing pinch analysis methodologies for both heat and water treatment, in order to enable the integration of several technologies that enhance efficiency, sustainability, and cost-effectiveness within the plant.

The first part of the project is based on Heat Treatment (Temperature-Based Process Integration). It begins with a comprehensive introduction to the plant structure and waste streams mapping the types of waste entering the plant, their origin, previous usage, treatment pathway, and energy potential. A detailed description of the plant's internal processes is provided, followed by an extensive pinch analysis to identify waste heat streams that can be recovered and reused internally to supply other processes requiring thermal energy followed by an extensive pinch analysis to identify waste heat streams that can be recovered and reused internally to supply other processes requiring thermal energy, which facilitates the integration of heat engines such as steam turbines and gas turbines, accompanied by heat pumps and distillation columns. A comprehensive MATLAB code was developed to simulate and analyze these technologies, and all components and results were explained in detail within the report. As mentioned this analysis was supported by a custom MATLAB code, with results illustrated through graphs, comparison tables, and schematic representations. This led to the proposal of several innovative integration techniques to enhance internal energy reuse, reduce dependency on external utilities, and improve the plant's overall performance.

The second part of the thesis is centered on the Water Pinch Methodology and Recovery Goals in the Water Treatment System. It includes a full description of the water cycle within the plant, identification of wastewater streams, their sources and previous uses, and an evaluation of the original freshwater supply. A step-by-step water pinch analysis was performed to highlight how wastewater streams, often still containing valuable thermal energy, could be internally reused instead of being discharged. This phase involved developing a generalized MATLAB code for Source and Sink Allocation, capable of automatically detecting all potential sources and sinks in the plant and matching them based on contaminant concentrations and flow compatibility, using mass balance constraints and complex condition-based logic. The developed code is adaptable to any similar system, not limited to a single case study. A comprehensive cost and environmental impact analysis was also performed, and the final results were examined in detail.

Table of Contents

Part 1: Process Integration and Intensification for Heat Recovery

List of Figures

List of Tables

Part 1: Heat Treatment (Temperature Based) using Process Integration and Intensification for Heat Recovery

Introduction

The San Lazzaro Waste-to-Energy (WtE) Plant is situated in Padova's eastern industrial area, near the Piovego canal. Operational since 1962, the plant holds historical significance as Italy first incineration facility to not only dispose of waste via combustion but also to recover energy from the process a major technological advancement for that era. Originally constructed in the 1950s with a single incineration line, the facility has undergone continuous upgrades to meet evolving environmental and emissions regulations, which have become increasingly stringent over time.

Since 2015, the plant has been managed by HestAmbiente, under the coordination of HerAmbiente S.p.A., reflecting a strong commitment to structured and environmentally responsible waste management. Currently, the plant consists of three incineration lines, treating up to 160531 tons of waste yearly, with more than half processed by Line 3 alone.

Each incineration line consists of a furnace for waste combustion, a boiler, a steam turbine energy recovery system, and a sophisticated flue gas treatment section to ensure compliance with emission standards. The plant also includes a wastewater treatment system and a demineralized water production unit both essential for maintaining the integrity and efficiency of the thermal cycle. The demineralization process significantly reduces the conductivity of water from 400 µS/cm to below 0.2 µS/cm (European Standards – EN 12953-10) to prevent salt deposits and ensure optimal boiler performance.

Despite its history of innovation and modernization, Lines 1 and 2 constructed in the mid-20th century were designed with now outdated principles and require frequent maintenance, although they continue to comply with current regulations. To improve the plant's operational reliability, environmental performance, and energy efficiency, a comprehensive renovation project has been proposed. This involves replacing Lines 1 and 2 with a new line that mirrors the advanced configuration and capacity of Line 3.

Figure 1: Padova Plant

In this context, the present thesis applies the concepts of Process Integration and Intensification, highlighting their importance in optimizing industrial systems, reducing energy consumption, and improving resource efficiency. The work focuses specifically on Pinch-Based Process Integration and Cost Analysis applied to the heat treatment and water management processes at the Padova Waste to Energy Plant.

This comprehensive approach includes the evaluation of all waste streams entering the plant, the mapping and description of internal operations, the identification of hot and cold utility streams, and the implementation of advanced integration methods. These include Pinch Analysis**,** Heat Cascade**,** Problem Table Algorithm, and Source and Sink Composite Curves, all of which aim to optimize heat recovery, reduce water and energy usage, and enhance the plant's overall sustainability.

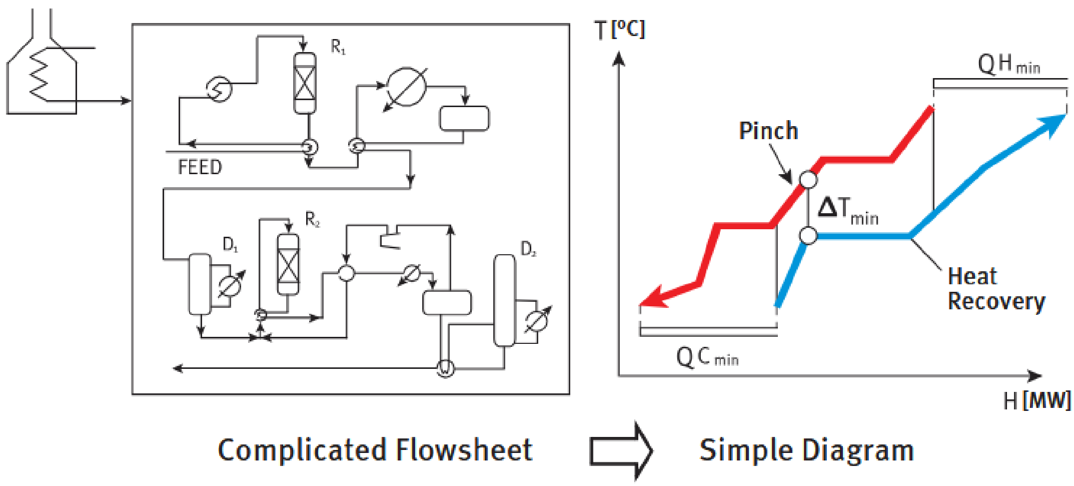
The detailed steps performed in the first part of the thesis are listed below:

- Introduced general concepts of Process Integration and Intensification, highlighting their importance in optimizing industrial systems and improving sustainability.
- Provided a historical background on the evolution of Process Integration, from its early development in the 1970s during the energy crisis to its modern applications in energy, water, and material efficiency.
- Identified and examined all waste streams entering the San Lazzaro Waste-to-Energy facility .
- Described the main operations and processes within the plant.
- All hot and cold streams involved in energy and water integration were identified and analyzed.
- Performed a Pinch Analysis to determine energy targets and opportunities for internal heat recovery.
- Developed Source and Sink Composite Curves to optimize internal water reuse and minimize freshwater demand.
- Applied the Heat Cascade and Problem Table Algorithm to design optimal heat exchanger networks and visualize energy flow across temperature intervals.
- Proposed potential integration of auxiliary systems such as heat engines, heat pumps, or distillation units based on pinch point data and thermal profiles.
- Performed a financial assessment encompassing cost projections and potential savings in utility consumption.
- Evaluated the environmental impact, with a focus on CO_2 emissions reduction and sustainability gains from the integration strategies.
- Developed and executed a custom MATLAB code to support all calculations, produce visualizations, and simulate integration scenarios.
- Explained each MATLAB step, detailing data processing, model implementation, and interpretation of results.
- Compared multiple integration scenarios using graphical representations and performance indicators to demonstrate the benefits of optimized designs.
- Performed a comparative evaluation between the plant current state and the proposed integrated model, highlighting quantitative improvements in energy efficiency, heat treatment and overall system performance.

2.General Knowledge: Process Integration and Intensification

- Process integration and intensification are pivotal methodologies in engineering aimed at enhancing the efficiency of industrial processes. Process integration focuses on the systematic design and operation of processes to optimize resource utilization, such as energy and water, by emphasizing the interconnections between different process units. The method aims to reduce waste generation while enhancing the efficiency of the overall system. On the other hand, process intensification involves developing innovative equipment and techniques that lead to significant improvements in manufacturing and processing, including higher throughput, reduced energy consumption, and smaller equipment sizes.

- The significance of these methodologies is underscored by estimates indicating that many industrial plants consume up to 50% more energy than necessary. By implementing process integration and intensification strategies, industries can achieve substantial reductions in resource consumption and pollutant emissions. These strategies often involve internal recycling and the reuse of energy and material streams, leading to both economic benefits and enhanced public perception.



2.1.Process intensification

Originally developed by the Imperial Chemical Industries , Process Intensification aimed to drastically reduce process plant sizes by two to three orders of magnitude to cut capital costs related to equipment and infrastructure. Over time, the scope of PI has broadened beyond CAPEX reduction, encompassing enhanced efficiency, selectivity, and product quality through innovative technologies. PI is now recognized as a transformative approach, not merely an incremental improvement.

According to the Process Intensification Network (PIN), key benefits of PI include:

- Improved product quality and safety through reduced inventories.
- Feasibility of just-in-time and decentralized manufacturing.
- Lower waste and energy consumption.

- Easier control over reaction environments, leading to better conversions and selectivities.

PIN and HEXAG support both industry and academia by promoting PI awareness and research. Comprehensive resources such as Reay et al. (2008, 2013) offer in-depth coverage of PI applications in reactors, micro-heat exchangers, separation processes, and more. As highlighted by Reay, PI often relies on enhancement methods commonly used in heat and mass transfer, both active and passive.

2.2.Process Integration (PI)

- Process Integration (PI) is a comprehensive and systematic approach aimed at optimizing resource use primarily energy and water across industrial processes. Instead of treating individual units in isolation, PI evaluates processes holistically to uncover synergies that reduce resource consumption and minimize environmental impact. This methodology is widely adopted in the processing and power generation industries, with its origins in Heat Integration (HI), developed during the 1970s energy crisis.

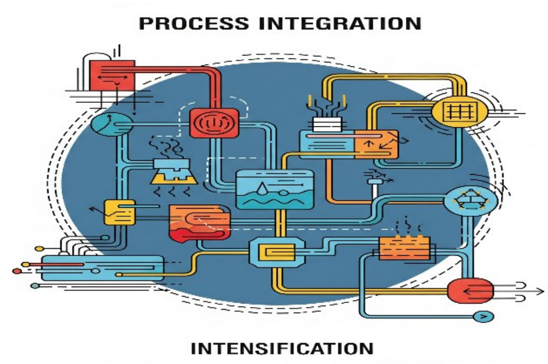
- Initially focused on heat recovery, PI has since evolved into a broader discipline that encompasses energy, water, and material integration. While Process Intensification (PIs) aims to enhance efficiency at the unit level, Process Integration scales these improvements to the system level, offering more substantial gains in sustainability and performance.

Objectives of Process Integration

1. Reduce energy consumption through optimized heat recovery and energy flow.
2. Minimize waste and emissions via internal recycling of heat and water.
3. Enhance financial efficiency by reducing utility requirements and decreasing operating expenses.
4. Enhance environmental sustainability through efficient resource use and reduced pollutant emissions.

Key Techniques in Process Integration

- Pinch Analysis:
  A cornerstone of Heat Integration, Pinch Analysis determines the minimum energy requirements of a process and the maximum potential for heat recovery. By analyzing temperature enthalpy (T–H) profiles of hot and cold process streams, we can design heat exchanger networks (HENs) that meet strict energy targets, thus reducing utility needs.
- Water Integration:
  Similar in concept to energy integration, water integration focuses on the reuse, recycling, and regeneration of water within the process. Techniques such as Water Pinch Analysis and Water Allocation Networks help in minimizing freshwater intake and wastewater discharge, improving both environmental and economic outcomes.



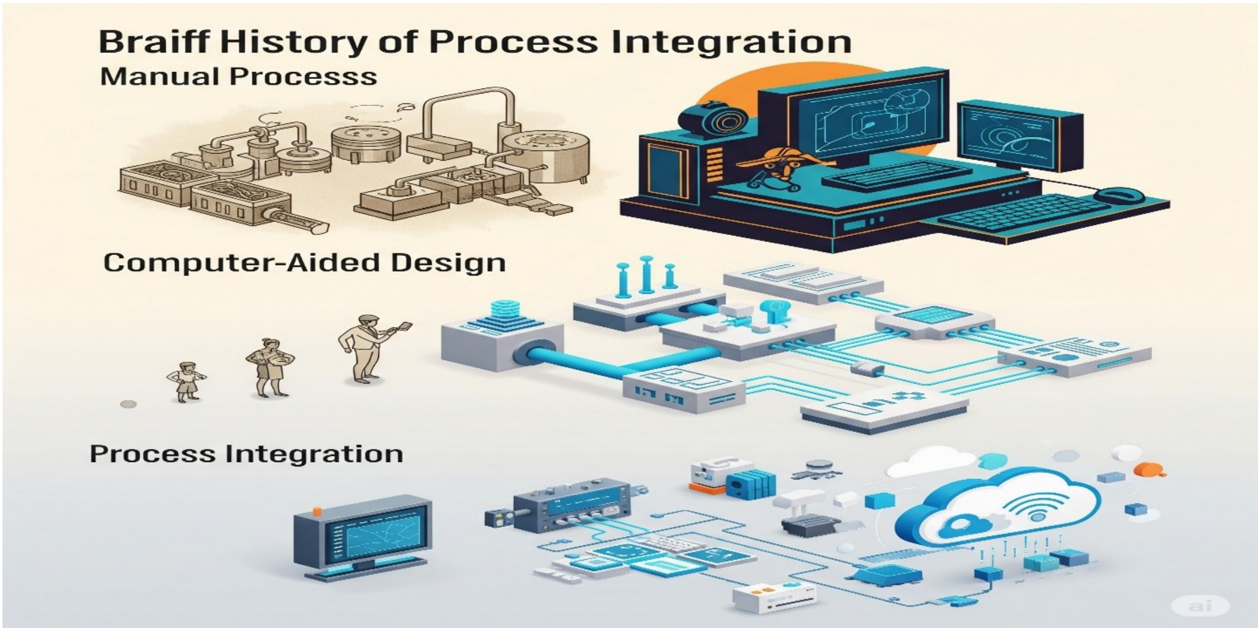
2.3.Brief History of Process Integration

- Process Integration (PI) emerged in the late 1970s in response to energy and environmental challenges, gaining traction through the work of pioneers like Hohmann, Linnhoff, and Flower. Hohmann's 1971 PhD introduced thermodynamic-based approaches to Heat Exchanger Network (HEN) synthesis, which later evolved into Pinch Analysis a central PI technique.

- Linnhoff's collaboration with Flower, and subsequent efforts at UMIST in the UK, led to the foundational "red book" (1982) that systematized Pinch Analysis. Parallel contributions from Japanese researchers (Umeda et al.) enriched the field, and the 1980s–2000s saw significant progress in computerization, mathematical modeling, and industrial applications.

- PI extended beyond heat to include water and mass integration. Mass Pinch (El-Halwagi, 1989) and Water Pinch (Wang and Smith, 1994) adapted the principles to minimize resource use and emissions. Further developments include Total Site Integration, carbon constrained planning, and holistic frameworks for sustainable resource conservation.

Today, PI remains a vital, evolving field, with applications spanning energy efficiency, emissions reduction, wastewater minimization, and sustainable process design.



Dates: History and Evolution of Process Integration (PI)

1970s – Foundations Laid

- Hohmann (1971): Pioneered systematic heat exchanger network (HEN) analysis using thermodynamics and introduced the Feasibility Table in his PhD work.

- Nishida et al. (1977): Laid groundwork for process synthesis methodologies.

- Ponton and Donaldson (1974) and Umeda et al. (Japan): Early contributors to HEN synthesis methods.

1978–1982 – Birth of Pinch Analysis

- Linnhoff and Flower (1978): Introduced Pinch Analysis, revolutionizing heat integration with a thermodynamics-based, graphical method.

- Linnhoff’s PhD thesis (1979) and the first "red book" (1982): Formalized Pinch methodology, including Composite Curves, Utility Targets, and Heat Recovery Strategies.

- In 1980, Umeda and Takama in Japan conducted research on water distribution and heat exchanger network (HEN) synthesis, independently and concurrently with Linnhoff’s work.

- Linnhoff and Hindmarsh (1983): Further advanced Pinch methods; publication became highly cited.

- Dhole and Linnhoff (1993): Developed Total Site Heat Integration, optimizing heat recovery across entire industrial sites.

- Smith (1995): Authored a major book on PI strategies, updated in 2005.

- Ptáčník and Klemeš (Czech Republic): Focused on computerized heat integration approaches.

1990s–2000s – Broadening PI to Mass and Water

- Wang and Smith (1994) introduced the Water Pinch methodology, which focuses on optimizing water reuse strategies.

- El-Halwagi (1997): Introduced Mass Integration, linking PI with pollution prevention; extended in his 2006 and 2012 books.

2000s–2010s – Resource Conservation & Sustainability

- Foo and Manan (2006–2012): Developed tools like SHARPS and STEP for energy and mass integration.

- Tan and Foo (2007): Applied PI to carbon-constrained energy planning.

- Foo et al. (2009): Introduced Cascade Analysis.

- Rozali et al. (2012): Integrated power systems into Total Site Analysis.

Advanced Concepts and Warnings

- In 2002, Furman and Sahinidis provided a comprehensive overview of progress in the field of heat exchanger network (HEN) synthesis.

- Kapil, Pan, Zhu (2000–2012): Worked on heat transfer intensification and retrofit strategies.

- Manenti et al. (2011) and Klemeš & Varbanov (2010): Emphasized data reconciliation and the risks of poor data.

•	Gundersen (2013): Reasserted core Pinch principles – targeting before design, composite curves, and Pinch decomposition – in Klemeš' PI Handbook.

3.Waste Heat Treatment Pinch Analysis

3.1. Mapping and analyzing all waste inputs entering the San Lazzaro Waste to Energy plant.

This section focuses on heat transfer based on the temperature profiles of the process streams.

Specifically, there are four input streams directed into the combustion chamber:

1- The undifferentiated segment of municipal solid waste typically includes household refuse, negligible fraction of food, various packaging materials, mixed plastic items, and used diapers.

- Sent directly to Line 3, the largest incineration line.
- Burned without separation and generates high heat, especially from plastics and organic matter.

2- Special non-hazardous waste: commercial or industrial waste that is non-toxic, like paper sludge, textiles, or rejected goods.

3-Sanitary ones: used medical gloves, bandages, diapers, personal hygiene products.

- Typically sent to Line 2 or Line 3**,** where high-temperature combustion ensures full destruction.
- Helps avoid infections or biological contamination.

4-Medicinal products: expired pills, syrups, vaccines, hospital pharmaceutical waste.

- Burned at high temperatures
- Ensures total molecular breakdown

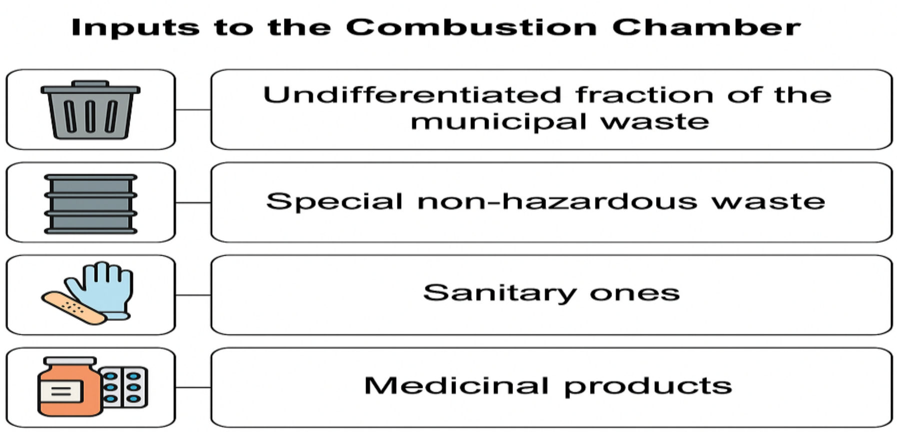


Figure 2: Waste Types

In 2020, the municipal waste and the special one that can be considered as such represent more than the 98% of the total amount of waste treated by the plant. The contribution given by sanitary waste and medicinal products can be considered negligible.

So we neglect waste 3 and 4 will have just two source of the waste entering the combustion chamber.

3.2. Operations inside the plant

- In the traditional operation of the Padova Waste to Energy plant, municipal solid waste combustion produces hot flue gases that transfer heat to the boiler, generating steam which fully powers the turbine to produce electricity. Following expansion in the turbine, the steam undergoes condensation, and the resulting condensate is returned to the boiler for reuse.

Typically, any remaining low-grade heat from the system is lost through condensers or cooling towers, with no internal recovery to meet other process heat demands, resulting in inefficiencies.

- My work focused on enhancing energy recovery within the plant by integrating a detailed pinch analysis of the hot and cold streams involved. Specifically, I analyzed the residual flue gases exiting the boiler at lower temperatures (around 250°C and 200°C) and identified opportunities to recover their heat to preheat boiler feedwater and combustion air, thereby improving overall thermal efficiency. I clarified that within the boiler, water is heated and converted to superheated steam (500°C) while the flue gases remain in the gas phase and lose heat as they pass around the tubes.

- To maintain accuracy in the pinch analysis and avoid overlapping energy paths, I separated the preheating of combustion air using heat recovered from turbine condensate—performed outside the pinch analysis from the main flue gas heat recovery. This involved installing a dedicated heat exchanger to raise combustion air temperature from ambient (20°C) to 140°C before entering the pinch system for further heating (230°C). Additionally, I accounted for the cold streams, where demineralized feedwater sourced from AcegasApsAmga is preheated by the residual flue gases prior to steam generation, and combustion air is preheated through heat recovery mechanisms to reduce fuel consumption.

- This integrated approach allows effective utilization of low-grade heat that was previously wasted, resulting in improved plant efficiency and reduced auxiliary energy demands, which will be shown and explained in detail in the following report.

3.3. Identification and characterization of all hot and cold streams relevant to energy and water integration.

In a typical waste to energy plant like the one in Padova, municipal solid waste and special non-hazardous waste are combusted in the combustion chamber at very high temperatures, typically between 850°C and 1000°C. This combustion process generates hot flue gases, which are the primary carrier of the heat energy released from burning the waste and can be utilized in our heat treatment process through the application of pinch analysis.

- **Related to Hot streams**

These hot flue gases then flow into the boiler section of the plant. The boiler functions as a major heat exchanger, where water inside the internal tubes is heated and transformed into steam, while flue gases flow externally around the tubes to transfer thermal energy through the tube walls. The key point is that the water inside the tubes absorbs heat and changes phase into steam, whereas the flue gases themselves do not convert into steam. Instead, they remain in the gas phase and lose temperature as they transfer heat to the water.

- Steam generated in the boiler is often superheated to approximately 500°C. The high-temperature steam is directed to the steam turbine, where it expands and powers the generation of electricity. After expanding through the turbine, the steam becomes low-pressure steam or condensate at a much lower temperature, often between 80°C and 120°C. This low-pressure steam or condensate can still contain useful thermal energy, which can be recovered, by using heat exchangers to preheat the combustion air and demineralized water, thus improving the overall energy efficiency of the process.

- In order to avoid overlapping energy paths in the pinch analysis, the preheating of combustion air is deliberately separated from the main flue gas recovery. Instead of wasting this heat, I considered the installation of a heat exchanger that transfers this remaining heat to the incoming air used for combustion. This allows effective recovery of low-grade heat without compromising the integrity of the pinch methodology. The combustion air, initially drawn at ambient temperature (20 °C), is thus heated to the required 140 °C via a dedicated heat exchanger, ensuring an energy-efficient and thermodynamically consistent system design.
- Post-combustion, the hot flue gases travel over the boiler tubing system, transferring thermal energy to the water or steam flowing inside.
- The boiler outputs:
    1. Steam superheated to about 500°C flows into the turbine, where its energy is converted into electrical power.
    2. Residual flue gases, the combustion gases themselves which have lost some heat but remain hot (250°C) and exit the boiler as flue gas.

Returning to the flue gases, after giving up a significant portion of their heat to generate steam, they exit the boiler at a much lower temperature usually around 250°C.
These residual flue gases will enter my pinch analysis to continue through other heat recovery sections, where they may be used to preheat feedwater and combustion air further.

The flue gases used in my pinch analysis come after the boiler, where the primary steam generation has already occurred. The residual flue gases still carry significant heat energy but at lower temperatures (250°C and 200°C). This heat can be effectively recovered to further preheat feedwater and combustion air, improving the overall plant efficiency and reducing the need for additional fuel or auxiliary heating sources. They are the waste heat streams available for heat recovery. The flue gases continue through cleaning and cooling before release.

➢ Related to Cold streams

- In the Padova Waste-to-Energy plant, boiler feedwater originates from aqueduct water, which is supplied by AcegasApsAmga (part of the Hera Group). This water is typically cleaner and more stable in quality compared to open canal water, as it comes from municipal or treated groundwater sources. However, before being used in the plant, this raw water must undergo demineralization to meet the purity requirements of boiler systems. Boilers require ultra-pure water to prevent issues like scaling and corrosion, which can severely damage equipment.

- The demineralization process which is external to the pinch analysis includes technologies such as reverse osmosis occupied by ion exchange and mixed-bed polishing, reducing the water conductivity from approximately 400 µS/cm to below 0.2 µS/cm. Once treated, this demineralized water enters the pinch-integrated part of the system as Cold Stream. It is still in liquid form and is preheated using hot flue gases generated from the combustion of municipal solid waste and special non-hazardous waste (Hot Streams 1 and 2). This preheating improves overall plant efficiency by lowering the fuel demand in the main boiler. Finally, the preheated water enters the combustion side boiler, where it is converted into high-pressure steam used to generate electricity.

- Water from the Piovego canal is not utilized as boiler feedwater. Instead, it is:

- Used for **c**ooling purposes, like condensers
- Discharged directly to the piovego channel since it is not exposed to any contamination

- Cold streams are the feedwater and combustion air:

- The feedwater, initially cold (around 20°C), enter the pinch analysis and exit at a higher temperature, after that the Water is preheated and can now enters the boiler, where it becomes steam
- The combustion air is similarly preheated from ambient temperature (20°C) to 140°C using recovered heat from condensate (after the turbine and condenser) outside the pinch analysis, then will enter the pinch analysis to be heated by the hot streams to reach 250°C.

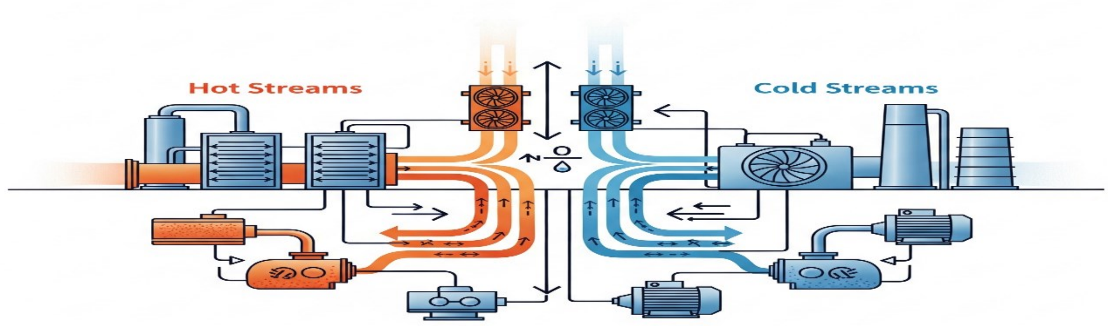


Table 1: Hot and Cold Streams

Stream	**Type**	**Description**	**Tin (°C)**	**Tout (°C)**	**Cp** (kW/°C)
H1	Hot	MSW Flue Gas	250	40	15
H2	Hot	Special non-hazardous waste (papers, rejected goods)	200	80	25
C1	Cold	Boiled feed water	20	180	20
C2	Cold	Combustion air	140	230	30

Explaining MATLAB Code

First, we look at the temperatures and heat of the streams in the process. Streams are either hot or cold. For each stream, we note:

- The starting temperature
- The target temperature
- How much heat it can carry

Hot streams:

- MSW flue gases cool from 250°C to 40°C, with heat capacity 15.
- Flue gas from special waste cools from 200°C to 80°C, with heat capacity 25.

Cold streams:

- Boiler feed water is heated from 20°C to 180°C, with heat capacity 20.
- The combustion air temperature rises from 140°C to 230°C, with a heat capacity of 30.

Minimum temperature difference (ΔTmin):
This is set to 10°C. It means hot and cold streams should always be at least 10°C apart when they exchange heat, to make sure heat flows properly.

3.4. Heat Cascade and Problem Table Algorithm

In the following sections, the methodology for Pinch Analysis will be explained, covering key steps such as shifting process stream temperatures, setting up temperature intervals, calculating heat capacities and enthalpy balances needed to build the Problem Table Algorithm (PTA).

➢ Temperature Shifting for Pinch Analysis

In this step, the temperature values of hot and cold streams are adjusted to account for the minimum temperature difference (ΔTmin) between them. This adjustment is a crucial part of Pinch Technology and is necessary for conducting Pinch Temperature Analysis since PTA uses temperature intervals to evaluate heat flows between streams. To ensure thermodynamic feasibility, it is essential to maintain a minimum temperature difference (ΔTmin) between any hot and cold stream during heat exchange. This avoids unrealistic overlap in heat recovery and ensures that the actual physical constraint of non-zero driving force for heat transfer is respected.

If real stream temperatures were used directly, parts of the heat content could be wrongly considered recoverable, violating this constraint and leading to overestimated recovery.

To solve this issue:

- Hot streams are shifted down by ΔTmin/2
- Cold streams are shifted up by ΔTmin/2

➢ Defining Temperature Intervals and Heat Capacities

All the unique temperatures from the shifted hot and cold streams are collected, duplicates removed, and then sorted from highest to lowest to create temperature intervals. Next, for each interval, the heat capacities (Cp) of the active hot streams and cold streams are summed up. This provides the necessary data for performing energy balance calculations in subsequent steps.

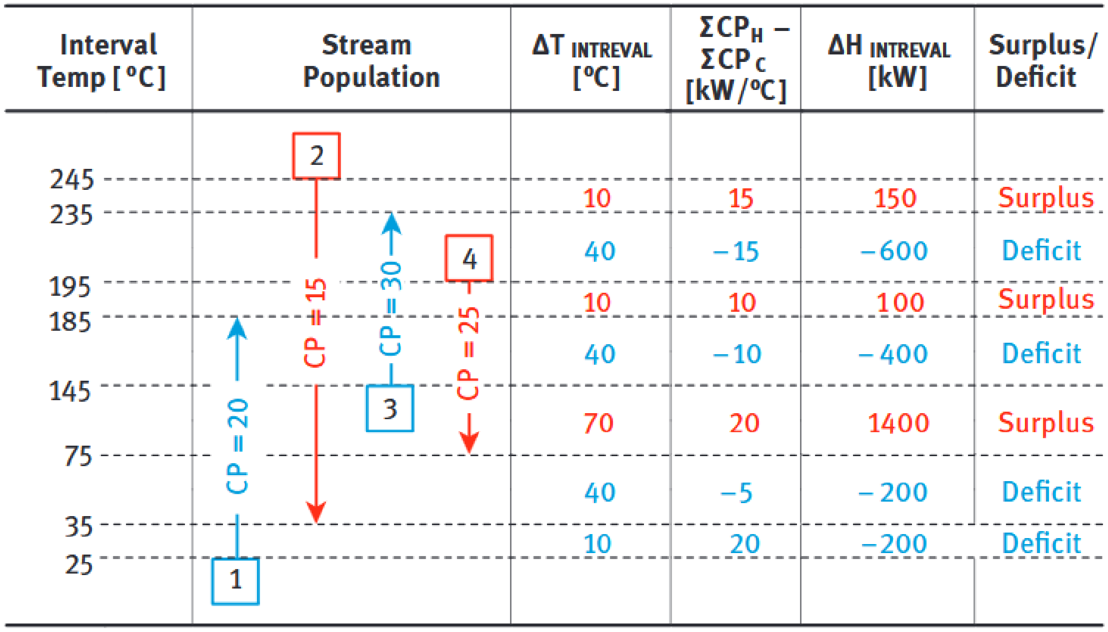
➢ Calculating Heat Capacities and Net Heat Flow for Each Interval

For each temperature interval, checking which streams are active there. A hot stream is active if its inlet temperature is above the interval's top and outlet is below the bottom. A cold stream is active if its inlet is below the top and outlet is above the bottom. When a stream is active, its heat capacity (Cp) contributes to the total for that temperature interval. Then, calculating the net heat capacity by subtracting the total cold stream Cp from the hot stream Cp. A positive result means the interval releases heat, while a negative result means it needs heat.

- ### Calculating Temperature and Enthalpy Intervals

The temperature difference (ΔT) between each pair of adjacent temperatures is found to define intervals. Then, calculating the enthalpy change (ΔH) for each interval by multiplying the net heat capacity by ΔT. A positive ΔH means there is extra heat that can be recovered, while a negative ΔH means more heat is needed from utilities or other streams.

Results from MATLAB Code:



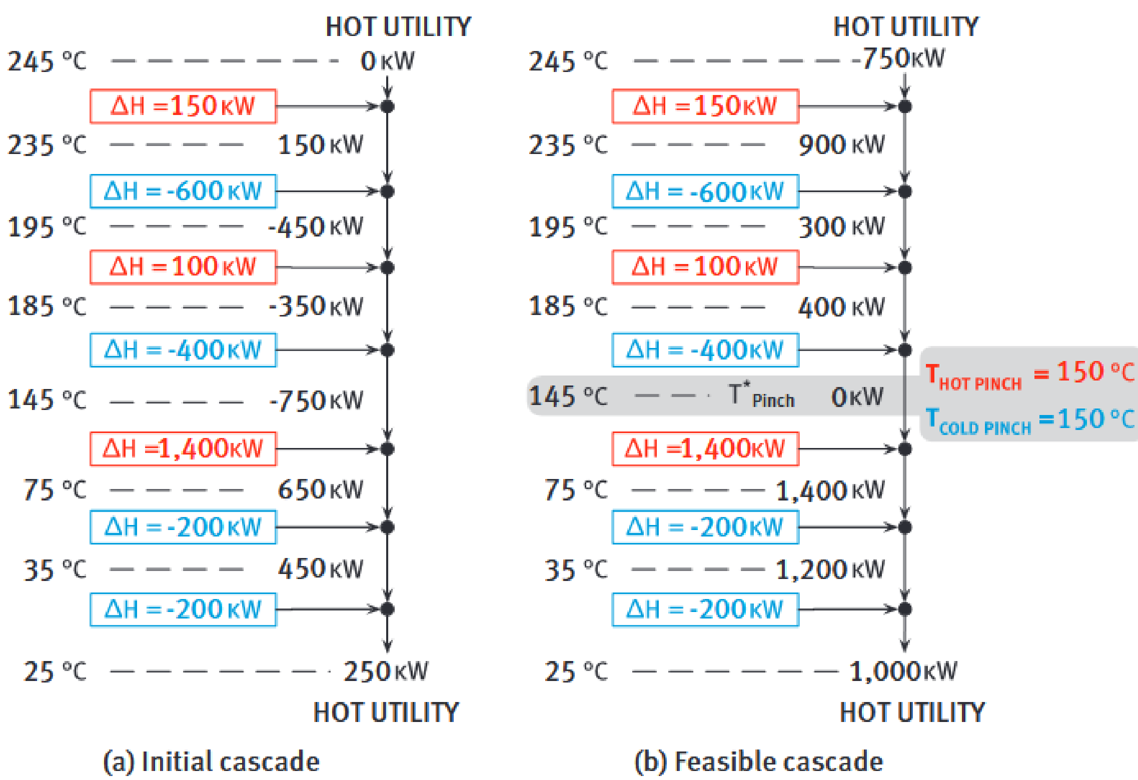
Temp_Upper	Temp_Lower	Delta_T	CpH_CpC	Delta_H	Initial_Cascade	Feasible_Cascade
" "	" "	" "	" "	" "	0	750
"245"	"235"	"10"	"15"	"150"	150	900
"235"	"195"	"40"	"-15"	"-600"	-450	300
"195"	"185"	"10"	"10"	"100"	-350	400
"185"	"145"	"40"	"-10"	"-400"	-750	0
"145"	"75"	"70"	"20"	"1400"	650	1400
"75"	"35"	"40"	"-5"	"-200"	450	1200
"35"	"25"	"10"	"-20"	"-200"	250	1000

Figure 3: Heat Cascade

- **Heat Cascade:**

Following the calculation of the heat cascade across temperature intervals, the requirements for hot and cold utilities are identified. Starting from zero hot utility, we sum the enthalpy balances interval by interval to build the cascade down to the cold utility. To ensure the system is thermodynamically feasible, we check the minimum value of this cascade. If it's negative, we shift the entire cascade upward by adding the absolute value of that minimum this becomes the required hot utility. The adjusted, feasible heat cascade is normalized to start at zero, which ensures accurate allocation of utilities: the highest point indicates the minimum hot utility, the lowest point the cold utility, with the pinch located in between point is where the heat flow reaches zero

Code Results:



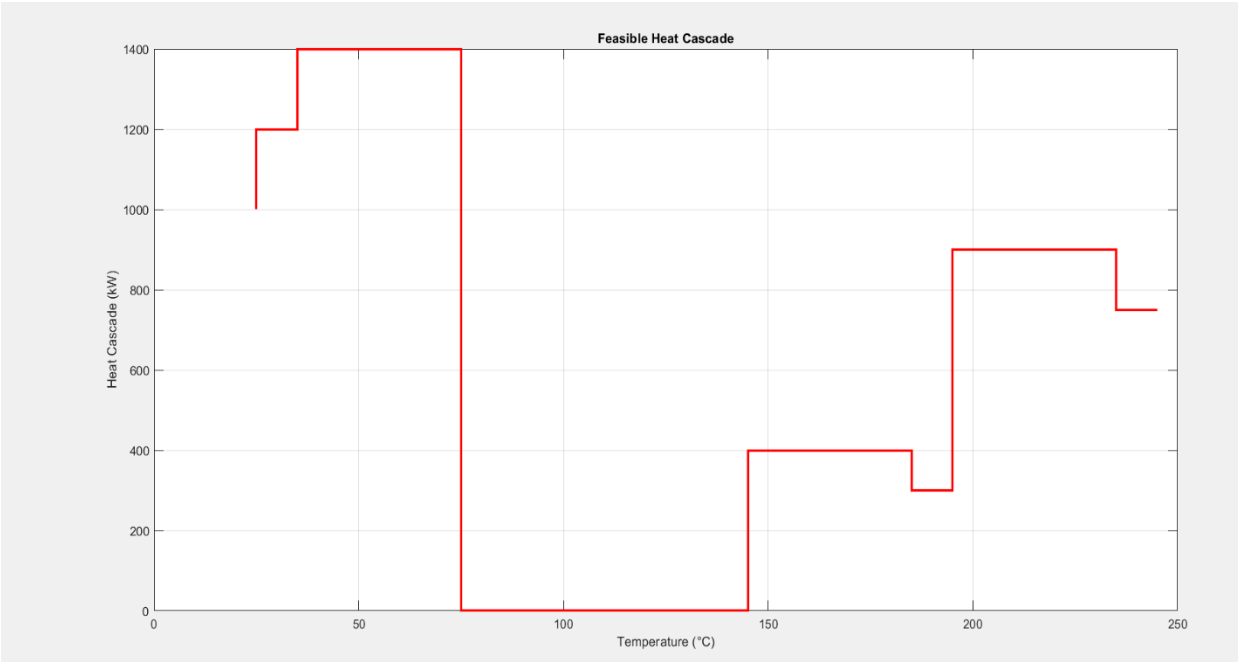


Figure 4: Feasible Cascade

3.5. Identifying Pinch Location

Pinch Technology enables efficient Heat Recovery by combining hot and cold process streams into Hot and Cold Composite Curves. These curves, created using a specified minimum temperature difference (ΔTmin), demonstrate the maximum potential for internal heat recovery. Their overlap indicates the recoverable heat, while non overlapping areas define the need for external utilities. Typical utilities include steam, hot oils, and fired heaters for heating; and water, air, or refrigeration systems for cooling, depending on process needs and temperature ranges.

From the heat cascade analysis, we determine:

- QH_min (Minimum Hot Utility) refers to the amount of heat that must be supplied to the system to adjust the cascade so that all heat flow values are non-negative.
- QC_min (Minimum Cold Utility): The net heat that must be removed, given by the final value of the feasible cascade.

The pinch point is located where the feasible heat cascade first reaches zero, marking the location of zero net heat transfer; the associated pinch temperature is then divided into hot and cold pinch temperatures based on ΔTmin. If no zero point exists in the cascade, no pinch is defined, and related values are set to NaN.

Code Results:

```
Pinch Temperature: 145.00°C (Adjusted: 150.00°C / 140.00°C)
Minimum Heating Utility (QHmin): 750.00 kW
 Minimum Cooling Utility (QCmin): 1000.00 kW
```

In the feasible cascade, the temperature boundary with zero heat flow is at 145 °C, which indicates the Pinch location as 140/150 °C. The minimum utility heating is 750 kW identified by the heat flow at the top of the cascade and the minimum utility cooling 1000 kW identified by the heat flow at the bottom of the cascade.

3.6. Composite Curves

- This step focuses on generating composite curves, both original and shifted for pinch analysis. Composite curves help visualize how heat is supplied and demanded across temperature levels in a process.

- The analysis starts by merging all hot streams and cold streams into two Composite Curves (CCs). There are two separate curves for each process: the Hot Composite Curve (HCC) for the hot streams and the Cold Composite Curve (CCC) for the cold streams. Each of these curves consists of a temperature-enthalpy (T-H) profile, which represents the overall heat availability (HCC) and the overall heat demands (CCC) of the process.

- In heat exchanger design, the minimum allowed temperature difference (ΔTmin) is the lower bound on any temperature differences to be encountered in any heat exchanger in the network.

- The analysis begins by extracting all unique temperatures from both hot and cold streams, including their inlet and outlet values. These temperatures are then sorted in descending order to define the boundaries of the temperature intervals, which form the basis for composite curve calculations.

- To generate the Hot Composite Curve, each temperature interval is examined to determine which hot streams are active, streams that span the interval. The corresponding heat capacity flowrates (Cp) are summed, multiplied by the temperature difference (ΔT), and used to compute interval enthalpies (ΔH). The cumulative sum of these enthalpies yields the hot enthalpy profile, which is then reversed in direction to align with standard plotting conventions.

- The Cold Composite Curve is generated using the same logic, but with cold streams: only those that cover the entire interval are included. The calculation of Cp, ΔH, and cumulative enthalpy is performed identically, followed by reversing the cold enthalpy profile. Both original composite curves are then plotted using their real temperatures.

- Finally, to account for the minimum temperature approach (ΔTmin) required for effective heat exchange, the process is repeated using shifted temperatures. These adjusted values, stored in the array, reduce hot stream temperatures and increase cold stream temperatures by ΔTmin/2. New Cp values, ΔH, and cumulative enthalpy profiles are computed for both shifted hot and cold streams, followed by a second plot that displays the shifted composite curves, which are critical for accurately locating the pinch point and determining minimum utility targets.

Code Results

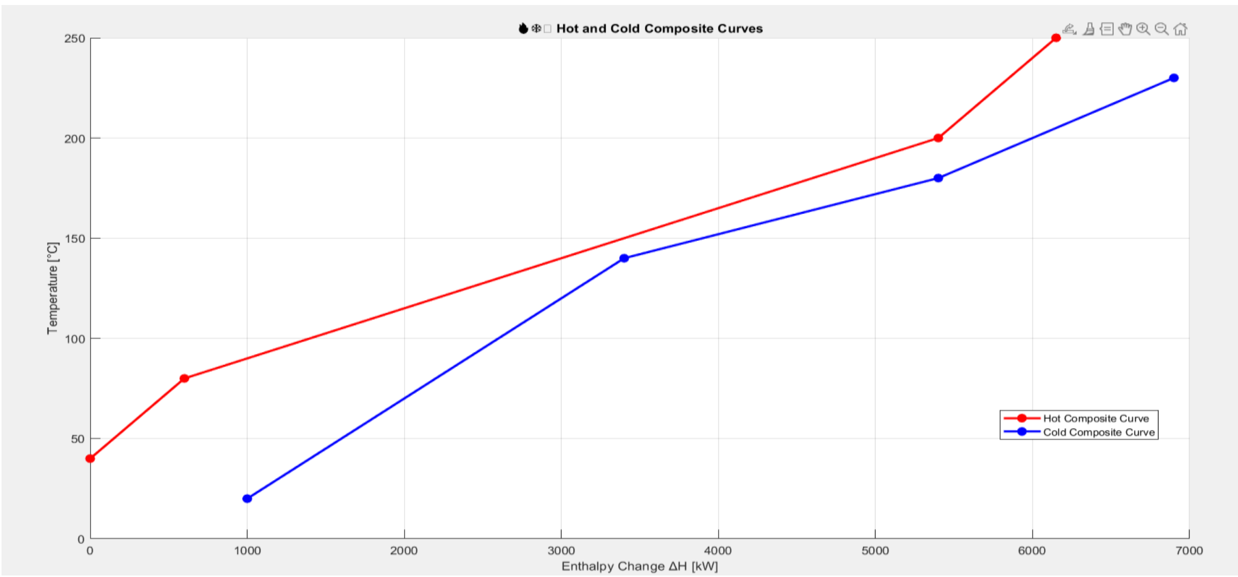


Figure 5: Composite Curves before shifted T

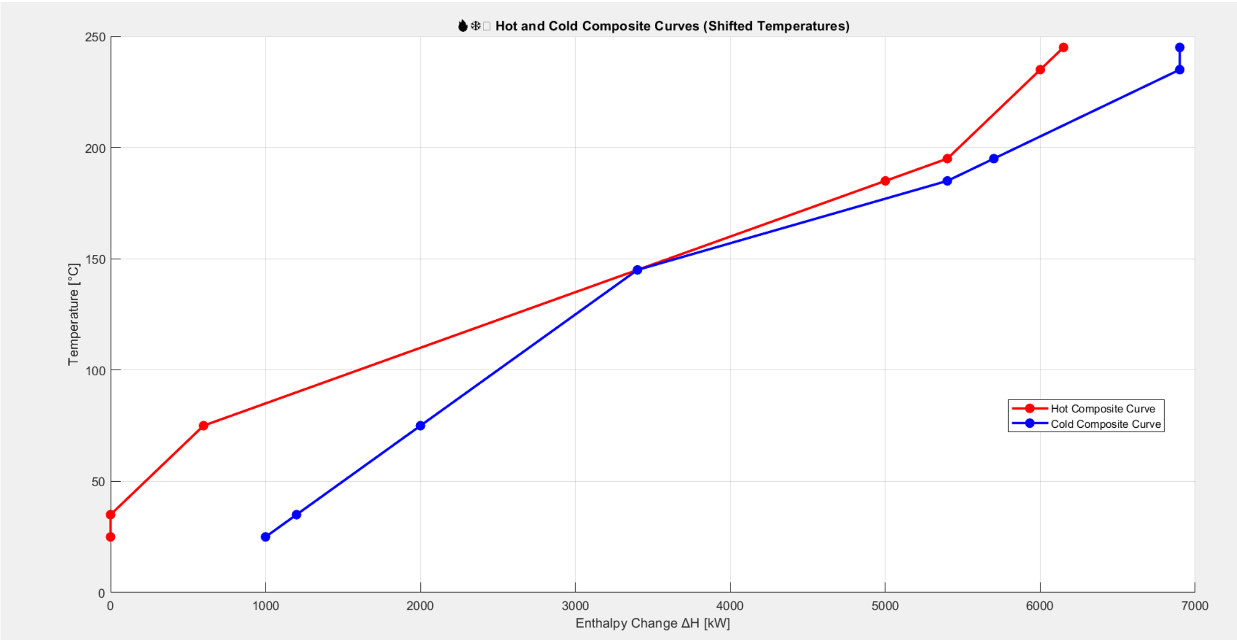


Figure 6: Composite Curves after shifted T

3.7. Grand Composite Curves

The Grand Composite Curve (GCC) is a powerful graphical tool used in pinch analysis to determine optimal utility placement and heat recovery targets in industrial processes. While traditional Composite Curves (CCs) help identify general heat recovery potential, the GCC goes further by enabling decision making when multiple utility levels (steam, hot oil, cooling water, refrigeration) with different costs are available.

For effective cost minimization, the goal is to:

- Maximize use of cheaper utilities (LP steam, cooling water)
- Minimize use of expensive utilities (HP steam, refrigeration)

The Grand Composite Curve (GCC) is generated from the Problem Table Algorithm (PTA) and the heat cascade data, and is plotted on a Temperature versus Enthalpy (T–ΔH) graph. The curve highlights:

- Positive slope segments → Dominated by cold streams → Potential for hot utility addition

- Negative slope segments → Dominated by hot streams → Potential for cold utility addition
- Shaded pockets → Represent heat recovery zones between process streams

By analyzing the shape and segments of the GCC, we can determine the best temperature levels for placing utilities and the respective energy loads to assign.

The script generates the GCC by plotting the heat surplus/deficit across temperature levels. Each point is labeled as Point i (enthalpy, temperature) to ease interpretation. It then calculates the cold utility as the negative minimum of the cascade and marks it with a blue line from the coldest point. Similarly, the hot utility is derived from the same cascade and shown with a red line at the hottest point. The plot is finalized with labels, a title, legend, and grid for clarity.

MATLAB Code Results:

By Working on a single steam level

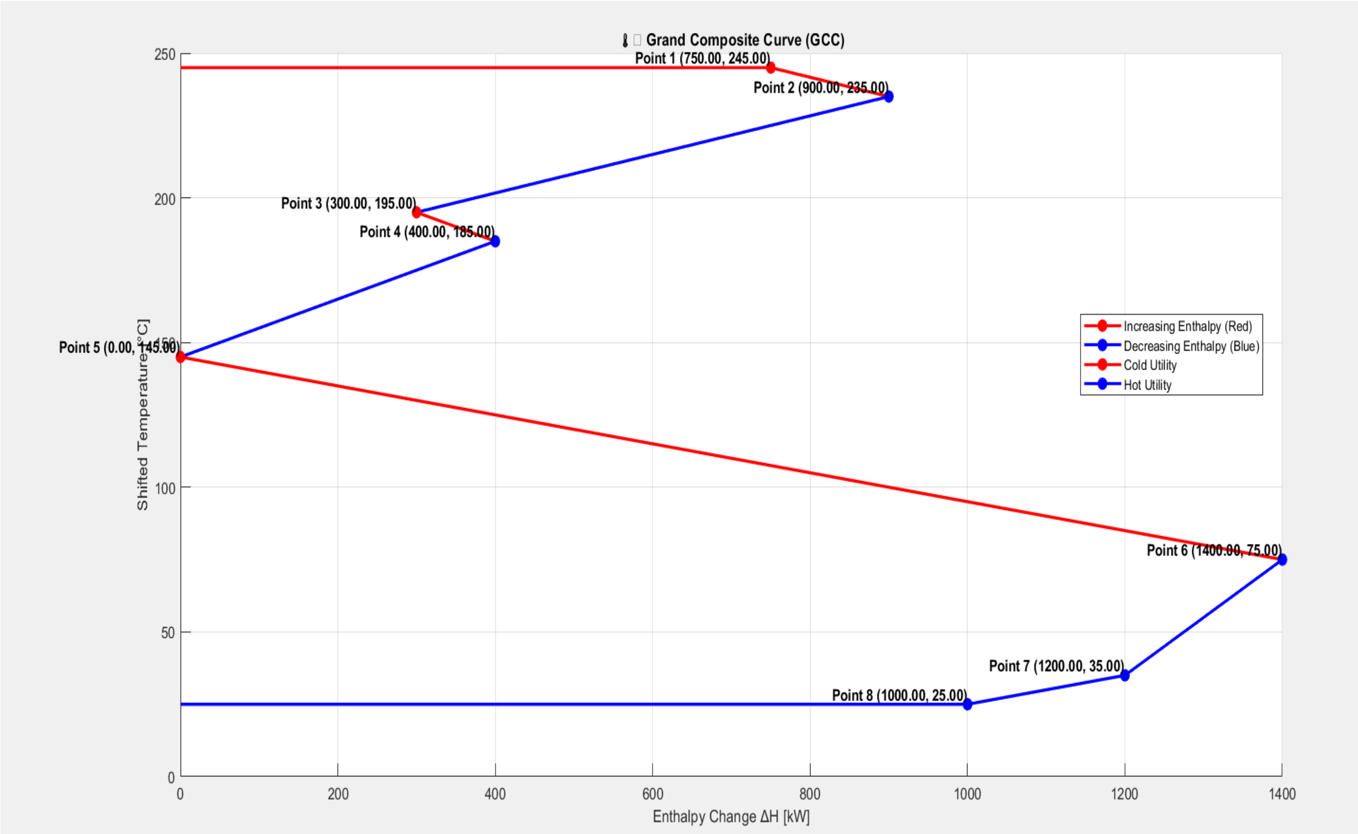
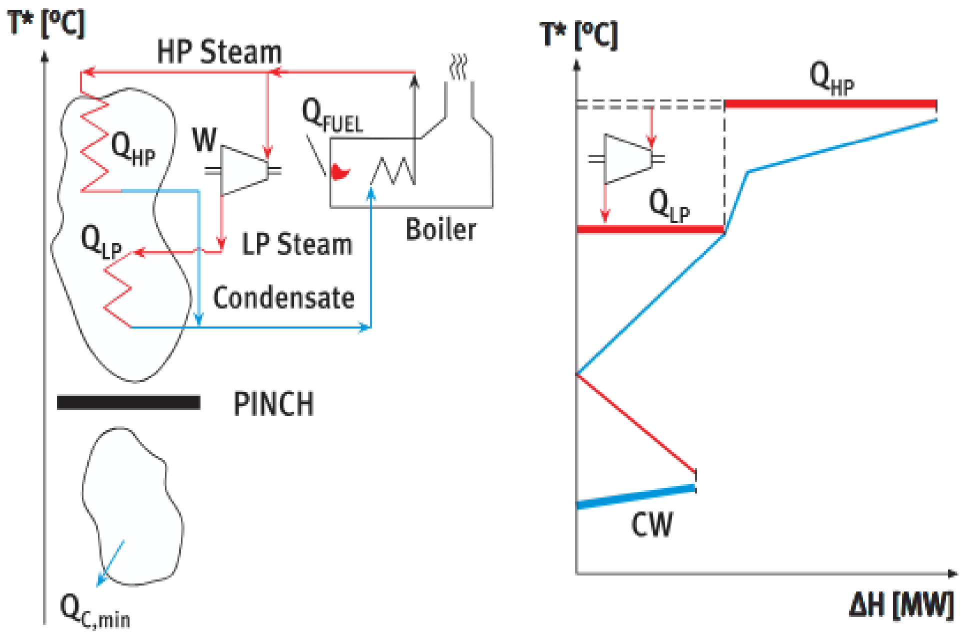


Figure 7: Grand Composite Curves

The internal pocket, visible on the Grand Composite Curve, represents a critical opportunity for internal heat recovery. This region indicates that the process has zones where heat is required followed by zones where heat is available to be rejected. By recovering heat from higher-temperature process streams and reusing it in lower-temperature areas, the system can significantly reduce its reliance on external hot and cold utilities. Internal pockets like this enable more sustainable and cost-effective energy use within the plant.

4.Heat Engines Integration of Energy Intensive Processes



Heat Engine Integration (Rankine Cycle - Steam Turbine)
Instead of just using QHmin to heat the process and then wasting the heat**,** we pass the heat through a heat engine first like a steam turbine (Rankine cycle).

- The engine uses part of this heat to generate work such as electricity and mechanical.
- The remaining unused heat called exhaust heat is still hot, but at a lower temperature.

Now by explaining the operations that occur in Heat engines, such as steam turbine, it operate by extracting heat from a high-temperature source, converting part of it into mechanical work, and rejecting the rest at a lower temperature. When integrating heat engines into a process, care must be taken with respect to the Pinch point. Integrating it above the Pinch, offer several benefits which will be shown in the following steps.

Above the pinch, my process needs a lot of heat, usually from external sources, but having extra high-temperature heat available i can:

- Use a steam turbine to extract work
- The leftover heat (lower temp steam) can still be used for heating in the process.

This means:

- Generating power for free.
- No waste of any valuable heat.
- Reduced fuel usage because the process heat demand is still satisfied.
- Reduce operation costs by having a lower utility usage (fuel, steam) + internal power generation.
- Lower CO_2 Emissions by using less fuel and emitting fewer greenhouse gas, improving the plant's environmental footprint.
- Improved Overall Energy Efficiency by extracting electricity without sacrificing useful heat recovery
- Supported Heat Cascade Concept by a top-down use of energy, where high grade heat is used first for power, and lower grade heat is cascaded to meet process needs efficiently.

MATLAB Code:

```
%% Step 17: Integration of Heat Engine (Rankine Cycle - Steam Turbine)
% Pinch temperature is already identified from previous calculations
if ~isnan(pinch_temperature)
    % Assume a Rankine cycle efficiency (eta) for heat engine, typically 30-40%
    eta = 0.35;  % Example: 35% efficiency

    % Use the minimum hot utility (QC_min) as the heat available for the engine
    heat_available_for_engine = QH_min;  % Minimum hot utility is the heat available for the engine (kW)

    % Convert heat available to work using the Rankine cycle efficiency
    work_generated = eta * heat_available_for_engine;  % Work produced by heat engine (kW)

    % Display the work generated by the heat engine
    fprintf('\n Work Generated by Heat Engine: %.2f kW\n', work_generated);

    % The cooling duty will be reduced by the work generated by the heat engine
    % This affects the minimum cooling utility (QC_min)
    QC_min_after_engine = max(0, QH_min - work_generated);  % Reduce QC_min by the work generated, ensuring no negative value

    % Display the updated minimum cooling utility
    fprintf(' Minimum Cooling Utility after Heat Engine: %.2f kW\n', QC_min_after_engine);
else
    % If no pinch is detected, indicate no heat recovery
    fprintf('\n No Pinch Detected: No Heat Engine Integration Possible\n');
end
```

Figure 8: step 17 MATLAB Code

In this step we considered using the available high temperature heat (hot utility) to drive a Rankine Cycle heat engine common in energy integration to generate mechanical work and reduce cooling utility.

Line-by-Line Breakdown:

Using QHmin as input and the efficiency (η) as 35% of the Rankine Cycle, we calculate the work output, which represents the mechanical energy (in kW) that the engine can generate from the recoverable process heat. This gives a clear indication of the potential energy savings or recovery through heat engine integration.

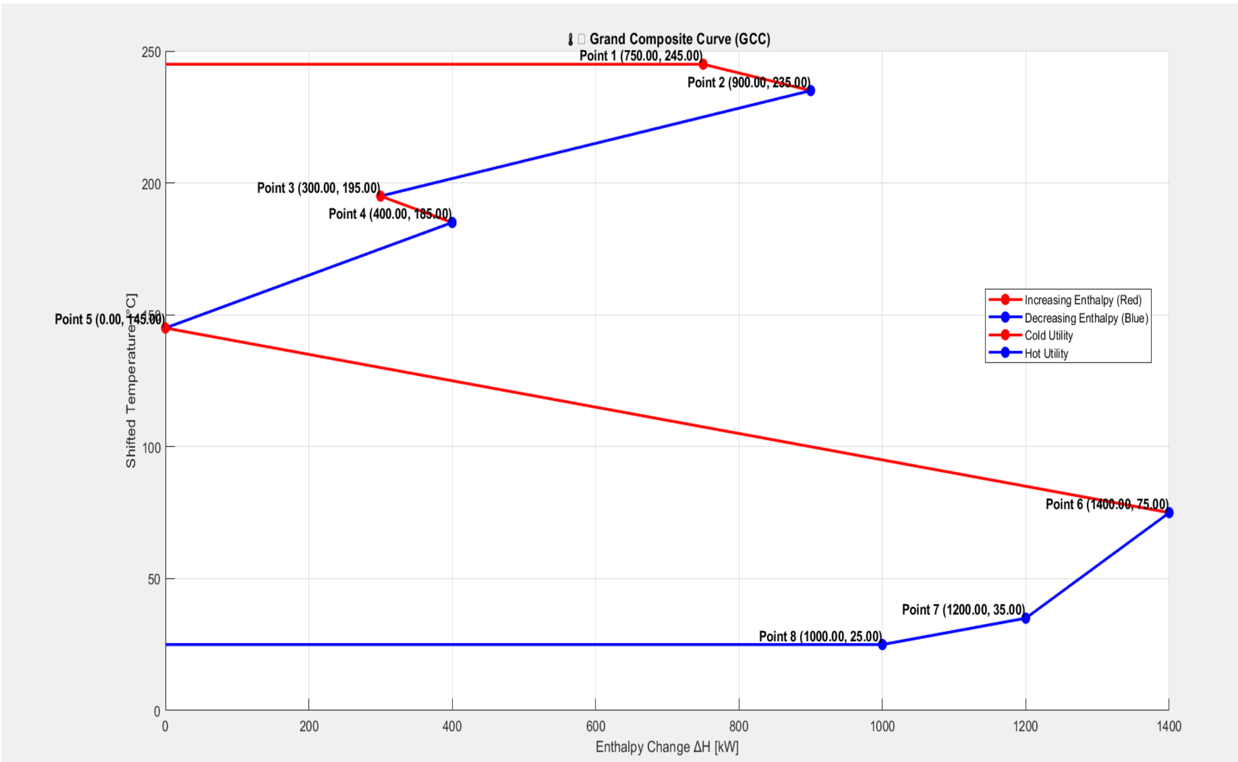
Updated Cooling Utility**:**

- Since part of the heat is now converted to work, less heat needs to be rejected.
- The cooling utility is reduced accordingly.

Code Results:

The integration of a heat engine (Rankine Cycle - Steam Turbine) significantly impacts utility demand by recovering excess heat above the pinch point. Using MATLAB-based Grand Composite Curve analysis, we assess the changes in energy flow after turbine integration. This enables optimization on multiple levels, enhancing efficiency and reducing external utility requirements.

Before:



After:

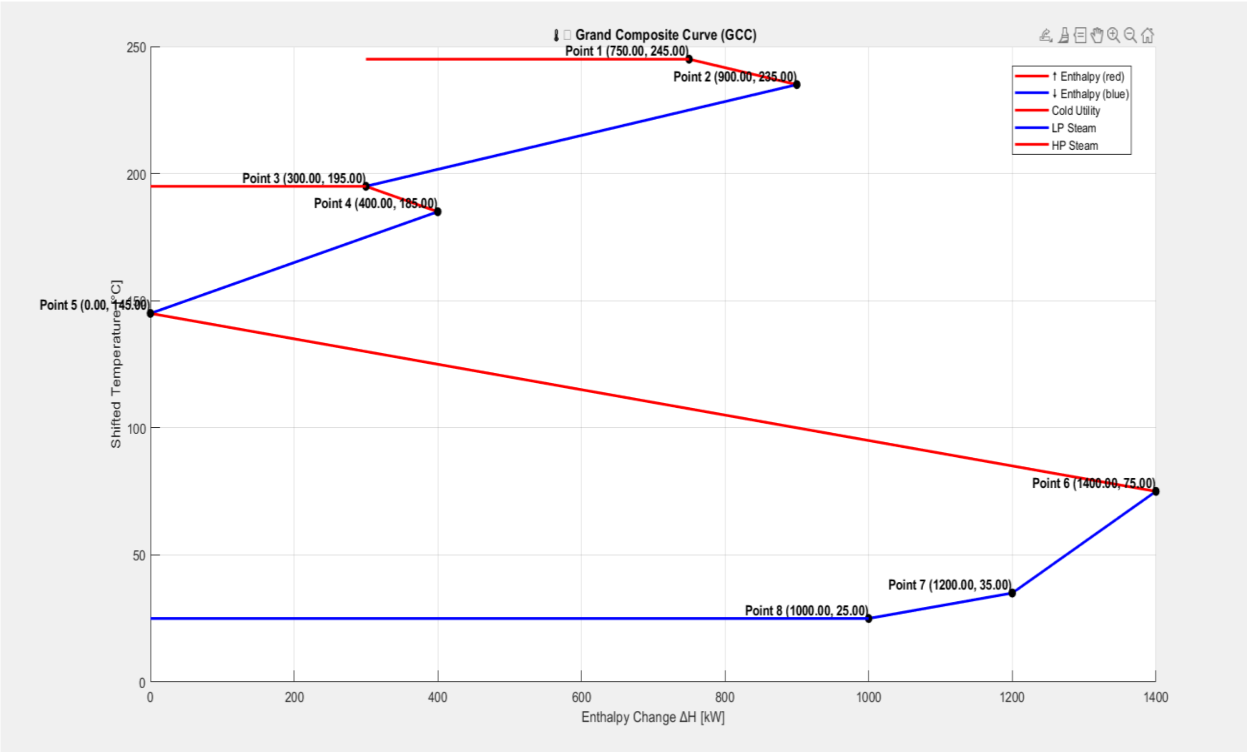


Figure 9: Grand Composite Curves After Optimization

4.1. Interpreting the outcomes alongside the Grand Composite Curves.

Diving into a detailed comparison of the Grand Composite Curves (GCCs) and the significance of switching from high-pressure (HP) steam to medium-pressure (MP) steam for hot utility supply.

1. Initial Utilities Before Integration:

   The heat engine operates with a heat input of QH_min = 750 KW
   Minimum Cooling Utility (Qc min) = 1000 KW

2. Integration of a Steam Turbine (Above the Pinch)

Assumptions:

   Heat engine efficiency (η) = 35%

   Heat input for the engine is QHmin

3. Work Generated by Heat Engine

   $\text{Work} = \eta \times QH_{min} = 0.35 \times 750 = 262.5$ kW

So we recovered 262.5 kW of mechanical/electrical energy from the process waste heat.

4. Effect on Cooling Utility (QCmin)

   Since a portion of the heat is utilized for useful work, it is no longer necessary to discard the entire 1000 kW.

   $QC_{min,\,after} = QH_{min} - \text{Work} = 750 - 262.5 = 487.5$ kW

That's a 51.25% reduction in our cooling utility demand

4.2. Cost analysis and environmental impact

Following the integration of a steam turbine (Rankine cycle) above the pinch point, will analyze both economic and environmental benefits arising from:

1. Work generation from recovered heat
2. Reduced cooling utility demand

Economic Analysis

- The turbine generated 262.5 kWh of work, which was transformed into electrical energy..
- This reduces the need to purchase electricity from the grid.

Electricity Savings:

- Electricity Generated: 262.5 kWh
- Monetary Value: €31.50

Cooling Savings:

- Heat rejection was reduced from 1000 kWh to 487.5 kWh**,** saving 512.5 kWh of cooling utility.
- Cooling Utility Saved: 512.5 kWh
- Monetary Savings: €25.63

Total Economic Benefit:

- €31.50 (electricity) + €25.63 (cooling) = €57.13 / hour total savings

Environmental Impact Analysis

Integrating the heat engine also contributed to CO_2 emissions reduction, as both cooling systems and electricity from the grid contribute to emissions:

CO_2 Emission Reduction from Cooling Utility:

- 512.5 kWh saved
- Emission factor: 0.1 kg CO_2/kWh
- Cooling related CO_2 Saved: 51.25 kg CO_2

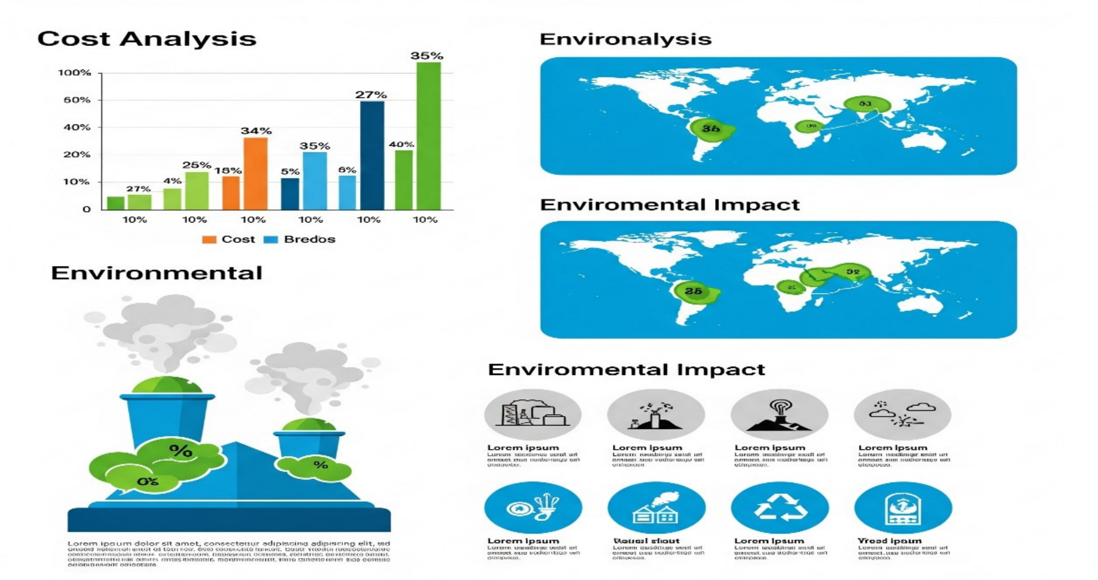
CO_2 Emission Reduction from Avoided Grid Electricity:

- 262.5 kWh generated onsite

- Emission factor: 0.4 kg CO_2/kWh
- Electricity related CO_2 Saved: 105.00 kg CO_2

Total CO_2 Emissions Saved:

- 51.25 + 105.00 = 156.25 kg CO_2 / hour



- The integration of the steam turbine above the pinch point led to a significant shift in the system's energy utilization, enabling the recovery of excess thermal energy that was previously wasted. This recovered energy was converted into mechanical work, reducing the system's reliance on external electricity sources and simultaneously decreasing the heat load that needed removal through cooling utilities. As a result, both the cooling demand and its associated operational costs were substantially lowered, reflecting improved internal energy recovery and enhanced system self-sufficiency.

- Economically, this integration yielded hourly savings of €57.13 by combining €31.50 in electricity cost reductions from onsite power generation and €25.63 from decreased cooling utility needs. Environmentally, the approach markedly cut CO_2 emissions by 156.25 kg per hour by avoiding grid electricity consumption and lowering cooling requirements. Thus, harnessing thermal energy above the pinch point not only improves overall system efficiency but also advances sustainability goals by minimizing the facility carbon footprint and operational expenses.

MATLAB code

```
%% Cost and enviromental impact analysis

cost_per_kWh_electricity = 0.12;   % €/kWh (value of generated electricity)
cost_per_kWh_cooling = 0.05;       % €/kWh (cost to reject heat)
CO2_emission_per_kWh_electricity = 0.4;  % kg CO2 / kWh (grid electricity)
CO2_emission_per_kWh_cooling = 0.1;      % kg CO2 / kWh (cooling-related emissions)

% Cooling utility saved
cooling_saving_kWh = QC_min - QC_min_after_engine;

% Work generated (already in kW)
electricity_generated_kWh = work_generated;

% Cost analysis
cooling_cost_saved = cooling_saving_kWh * cost_per_kWh_cooling;
electricity_value_generated = electricity_generated_kWh * cost_per_kWh_electricity;

% Display results
fprintf('\Cost Analysis:\n');
fprintf('Cooling Utility Saved: %.2f kWh → Savings: €%.2f\n', cooling_saving_kWh, cooling_cost_saved);
fprintf('Electricity Generated: %.2f kWh → Value: €%.2f\n', electricity_generated_kWh, electricity_value_generated);
fprintf('Total Economic Benefit: €%.2f\n', cooling_cost_saved + electricity_value_generated);

% Cooling-related emissions saved
cooling_emission_saved = cooling_saving_kWh * CO2_emission_per_kWh_cooling;

% Grid electricity emissions avoided
electricity_emission_saved = electricity_generated_kWh * CO2_emission_per_kWh_electricity;

% Total emission savings
total_emission_saved = cooling_emission_saved + electricity_emission_saved;

% Display results
fprintf('\n Environmental Impact:\n');
fprintf('Cooling Emission Reduction: %.2f kg CO2\n', cooling_emission_saved);
fprintf('Electricity Emission Reduction: %.2f kg CO2\n', electricity_emission_saved);
fprintf('Total CO2 Emission Reduction: %.2f kg CO2\n', total_emission_saved);
```

4.3. Exhaust Temperature

After the heat engine (steam turbine in a Rankine cycle) extracts useful work from the hot process stream, the remaining heat in the stream is not fully utilized. This remaining heat leaves the system as exhaust heat at an estimated temperature of 217.5 °C.

This exhaust temperature value is significant because it indicates that although the heat engine has converted part of the thermal energy into mechanical or electrical energy, a considerable amount of heat still remains in the stream. At 217.5 °C, this waste heat is still relatively high and therefore presents an opportunity for further recovery.

The assumption in this case were: T inlet = 250°C and Cp = 15 kW/°C

1. Based on Actual Process Data:
   - The highest temperature available from my hot streams is 250°C.
   - This represents the maximum thermal energy source in my system suitable for heat engine integration.
2. Corresponding Heat Capacity Flow Rate:
   - The stream at 250°C has a heat capacity flow rate Cp=15 kW/∘C
   - This means this stream transfers 15 kW of heat for every 1°C change in temperature.

4.4. Key Difference in the Two GCC obtained using matlab

Table 2: Compariosn of the GCC before and after optimization

Feature	**Before Optimization**	**After Optimization**
Hot Utility Source	HP Steam (High Temperature, 245°C)	Part of the heat is supplied at MP Steam (Lower Temperature, 195°C) and part at HP Steam (High Temperature, 245°C)
Utility Integration Point	High up in the temperature range	Closer to process pinch point
Utility Temperature Level	245°C (saturated)	195°C (saturated)
Energy Supply Strategy	Single level (1 steam level)	Multiple levels (optimized for process)

This table compares the Heat Exchanger Network designs through their Grand Composite Curves (GCC) one before optimization and one after optimization, focusing on how utility heat is supplied.

- Before Optimization:
  The hot utility comes entirely from High-Pressure (HP) steam at 245°C.
- After Optimization:
  The heat supply is split: some heat comes from Medium-Pressure (MP) steam at a lower temperature (195°C), and the rest still comes from HP steam (245°C).
- The utility integration point moves closer to the process pinch point, meaning heat is supplied more efficiently where it's really needed in the process.
- Instead of supplying all heat at the highest temperature (HP steam), heat is supplied at multiple pressure/temperature levels (HP and MP steam), which is more energy-efficient.
- By integrating a steam turbine in the system, we usually extract work by expanding steam from a high pressure to a lower pressure (MP or LP) level.
- The steam turbine recovers energy by using the pressure drop of steam (HP to MP), generating work.
- We reached a Multi-Level Utility Optimization by introducing a more strategic choice of utility sources by matching the heat supply levels to the actual process needs.
- The way the enthalpy increases along the curve indicates a more energy-efficient configuration, with sharper and more efficient matching of process streams.

4.5. Environmental and cost benefit of Using Multi Pressure Steam Instead of HP Steam

- Before**:** All process heat comes from HP steam which is expensive and CO_2-intensive
- After**:** Used part of the HP steam to generate electricity in a steam turbine.
  - The remaining steam exits the turbine at lower pressure (MP) and is reused to supply process heat.
  - This reduces:
    - High-grade utility use
    - Cooling needs
    - CO_2 emissions
    - And it generates valuable electricity

Energy Efficiency

- MP steam is closer in temperature to the process needs, meaning less exergy (useful energy) is lost.
- This reduces the temperature driving force, minimizing irreversibilities and enhancing thermal efficiency.

Operational Cost Savings

- Producing HP steam costs more since it need more fuel and higher pressure equipment
- MP steam requires less fuel input, hence lowers utility costs.

Flexibility

- Operating using multiple pressure steam levels, give a better control over energy management.

MATLAB code:

```
%% Cost and Environmental Analysis for Two-Level Steam Supply

Q_HP_initial = QH_min;      % Initial heat input at HP steam (kW)
QC_min = 1000;           % Cooling utility before integration (kW)

efficiency = 0.35;       % Steam turbine efficiency (35%)
work_generated = efficiency * Q_HP_initial; % Work generated by turbine (kW)

% After expansion: part heat supplied as MP steam
Q_MP = Q_HP_initial - work_generated;  % Heat now supplied at MP steam (kW)

% Costs (€ per kWh)
cost_per_kWh_HP_steam = 0.07;   % Cost per kWh HP steam
cost_per_kWh_MP_steam = 0.05;   % Cost per kWh MP steam
cost_per_kWh_cooling = 0.05;    % Cooling utility cost
cost_per_kWh_electricity = 0.12; % Electricity value

% CO2 emissions (kg CO2 per kWh)
CO2_HP_steam = 0.3;         % CO2 per kWh HP steam
CO2_MP_steam = 0.2;         % CO2 per kWh MP steam
CO2_cooling = 0.1;          % Cooling-related CO2
CO2_electricity = 0.4;      % Grid electricity CO2

% Cooling utility after turbine integration
QC_min_after = QC_min - work_generated; % Cooling utility reduced
```

```
% Calculate costs before integration (all heat at HP steam)
cost_before = Q_HP_initial * cost_per_kWh_HP_steam + QC_min * cost_per_kWh_cooling;

% Calculate costs after integration
cost_after = ...
    (work_generated * cost_per_kWh_MP_steam) + ...   % Heat replaced at MP steam cost
    (Q_MP * cost_per_kWh_MP_steam) + ...             % MP steam heat supplied
    (QC_min_after * cost_per_kWh_cooling) - ...      % Cooling utility cost after reduction
    (work_generated * cost_per_kWh_electricity);     % Value of electricity generated (negative cost)

% Calculate CO2 emissions before and after
emission_before = Q_HP_initial * CO2_HP_steam + QC_min * CO2_cooling;
emission_after = Q_MP * CO2_MP_steam + QC_min_after * CO2_cooling - work_generated * CO2_electricity;

% Savings and benefits
cost_savings = cost_before - cost_after;
emission_savings = emission_before - emission_after;
```

Figure 10: MATLAB Code for Optimization

4.6. Goal achieved from Integrating steam turbines

1.Multi-Level Steam Optimization

Introducing a multi-level steam integration approach that replaces single-level HP steam supply with both MP and HP levels, optimizing energy distribution closer to the pinch point, while many traditional systems don't split the steam network into optimized pressure levels to maximize efficiency and cost reduction which is considered an innovative point for my project

2. Cost and Environmental Evaluation Tool (MATLAB)

I developed a MATLAB model that not only performs the energy balance, but also evaluates the cost savings and CO_2 emission reductions, making it easier for decision makers to choose optimal operating conditions, so the innovation here was that many analyses focus only on thermodynamics. Bringing cost and environmental data into the loop gives my project practical value for real world applications.

3. Reallocation of HP Steam via Steam Turbine to MP Steam

I simulated the use of a steam turbine to reallocate HP steam into MP steam, which reduces cost and makes better use of waste energy. This cascading use of energy across pressure levels minimizes utility demand, so I am not just using the turbine for power but also benefiting from the waste steam after expansion to serve my process.

4. Exhaust Heat Valorization Planning

I didn’t stop at turbine integration but i proposed how to use the remaining 250 °C exhaust to generate additional steam or heat through direct integration or a heat pump so capturing remaining medium grade heat is often overlooked in conventional systems.

5. Pinch-Based Utility Adjustment

Restructuring the utility integration to supply heat closer to the process pinch point, lowering temperature gaps and reducing both external utility and cooling requirements optimizing the site energy profile**.**

5.Heat Engine Integration (Brayton Cycle – Gas Turbine) on Utility Demand

This approach represents an alternative integration method for enhancing energy recovery and system efficiency above the pinch point.

5.1. Calculating Exhaust Temperature

T_exhaust = (QC_min / (m_exhaust * Cp_exhaust)) + T_ambient;

- The exhaust temperature of the gas turbine is determined using the minimum cooling utility, the exhaust gas mass flow rate, and its specific heat capacity.5.2. Integrating the Gas Turbine

- Assuming that the gas turbine provides the entire minimum heating utility in an ideal scenario, where no energy losses are considered, having an efficiency of the gas turbine is assumed to be 85% will represents the proportion of useful work obtained relative to the energy supplied.

- The net thermal energy supplied by the gas turbine is calculated by applying its efficiency factor to the ideal heat input. This represents the amount of heat that is actually converted to work by the turbine.

5.3. Brayton Cycle Efficiency Calculation

- The heat capacity ratio for air is 1.4
- The inlet temperature to the gas turbine is taken as the ambient temperature **(**pinch temperature) converted to Kelvin (by adding 273.15).
- T_Turbine_inlet = 1200 K

5.4. Work Generated by the Gas Turbine

- The work generated by the gas turbine is calculated by multiplying the heat delivered by the turbine by the Brayton cycle efficiency. This is the useful work produced by the turbine.

5.5. Final Hot and Cold Utility Adjustments

- The new hot utility is calculated by subtracting the heat delivered by the gas turbine from the original minimum heating utility. This is because the gas turbine supplies part of the heating demand.
- Since the turbine generates useful work, it also decreases the required cooling load, thereby lowering the overall cold utility demand

MATLAB Code:

```
%% Step 18: Gas Turbine Integration and Temperature Calculation

% Given data
T_pinch = pinch_temperature; % °C
QC_min = cold_intersection_value; % kW
QH_min = hot_intersection_value; % kW

% Assumptions for exhaust gas properties (for the gas turbine)
m_exhaust = 1; % Mass flow rate of exhaust gases (kg/s)
Cp_exhaust = 1.2; % Specific heat capacity of exhaust gases (kJ/kg°C)

% Ambient temperature (Pinch temperature is often used as a base)
T_ambient = T_pinch;

% Step 1: Calculate the exhaust temperature (T_exhaust) based on QC_min
T_exhaust = (QC_min / (m_exhaust * Cp_exhaust)) + T_ambient;

% Output exhaust temperature
fprintf('-----------------------------------------------\n');
fprintf('Estimated Exhaust Temperature: %.2f °C\n', T_exhaust);
fprintf('-----------------------------------------------\n');

% Step 2: Integrate the gas turbine into the system
% Total heat provided by the gas turbine (Q_G)
Q_G_ideal = QH_min; % Assume gas turbine provides minimum heating utility in an ideal scenario

% Assumed efficiency of the gas turbine (Brayton cycle efficiency)
eta_turbine = 0.85; % Efficiency of the gas turbine (85% efficiency)

% Actual heat delivered by the gas turbine (considering efficiency)
Q_G = Q_G_ideal * eta_turbine;

% Brayton cycle efficiency calculation
gamma = 1.4; % Heat capacity ratio for air
T_inlet = T_ambient + 273.15; % Convert to Kelvin
T_max = 1200; % Assume max turbine inlet temperature in Kelvin

eta_Brayton = 1 - (T_inlet / T_max) ^ ((gamma - 1) / gamma);

% Work generated by the gas turbine
W_turbine = Q_G * eta_Brayton;

% Step 4: Calculate new hot utility and cold utility after gas turbine integration
QH_new = QH_min - Q_G;
QC_new = QC_min - Q_G;
```

Figure 11: step 18 MATLAB CODE

MATLAB Results

1. New Hot Utility (QH_new): 112.50 kW

- Initial Hot Utility (QH_min): 750.00 kW

- After integrating the gas turbine, the new hot utility requirement is reduced to 112.50 kW.
- This reduction reflects the fact that part of the thermal energy from the hot stream is being used by the gas turbine to generate work. By harnessing energy from the high-temperature input, the gas turbine helps lower the overall energy demand of the system

2. New Cold Utility (QC_new): 362.50 kW

- Initial Cold Utility (QC_min): 1000.00 kW
- After integrating the gas turbine, the cold utility requirement has been reduced to 362.50 kW.
- Similar to the hot utility reduction, the cold utility requirement is also decreased because the gas turbine effectively reuses the energy. This lower cold utility suggests that less cooling is required to handle the remaining heat from the process.

3. Work Generated by the Gas Turbine: 165.80 kW

- This energy, generated by the gas turbine, is extracted from the hot utility using the thermal energy available in the system, reducing the heat needed for the main process.
- The work generated by the gas turbine can be used to offset part of the energy needed by other parts of the system or for other operational uses, adding efficiency to the overall process.

5.6. Comparison between steam turbine and gas turbine integration

1. Technical Summary of Both Integrations

Table 3: Technical Summary of both integrations

Feature	Steam Turbine (Rankine)	Gas Turbine (Brayton)
Heat Source	QHmin = 750 kW	QHmin = 750 kW
Work Generated	262.5 kW	165.8 kW
Efficiency (η)	35%	22.1%
Cooling Utility After Integration	487.5 kW	362.5 kW
Hot Utility AfterIntegration	QHmin	112.5 kW
Exhaust Temp	217.5 °C	High

2. Economic Comparison

- Electricity price: €0.12 / kWh
- Cooling utility cost: €0.05 / kWh

Table 4: Economic Comparison of both integrations

Economic Factor	Steam Turbine	Gas Turbine
Electricity Savings per hour	262.5 kW × €0.12 = €31.50	165.8 kW × €0.12 = €19.90
Cooling Utility Savings per hour	512.5 kW × €0.05 = €25.63	637.5 kW × €0.05 = €31.88
Hot Utility Savings per hour	no reduction	637.5 kW × €0.05 = €31.88
Total Economic Benefit per hour	€57.13 / hr	€83.66 / hr

3. Environmental (CO_2) Comparison

Emission factors:

- Grid electricity: 0.4 kg CO_2 / kWh
- Cooling utility: 0.1 kg CO_2 / kWh

Table 5: CO2 comparison of both integrations

CO_2 Savings	**Steam Turbine**	**Gas Turbine**
From Electricity Offset	262.5 kWh × 0.4 = 105.00 kg CO_2	165.8 kWh × 0.4 = 66.32 kg CO_2
From Cooling Utility	512.5 kWh × 0.1 = 51.25 kg CO_2	637.5 kWh × 0.1 = 63.75 kg CO_2
From Hot Utility (Brayton only)	—	637.5 kWh × 0.1 = 63.75 kg CO_2
Total CO_2 Savings	156.25 kg CO_2 / hr	193.82 kg CO_2 / hr

Final Comparative Analysis

Table 6: Final Comparative Analysis

Category	Better	Reason
Electricity Output	Steam Turbine	Generates more useful work (262.5 kW vs. 165.8 kW)
Cooling Utility Saved	Gas Turbine	Larger cooling reduction due to deeper energy reuse
Hot Utility Saved	Gas Turbine	Additional savings by reducing heat demand
Economic Savings	Gas Turbine	€83.66 vs. €57.13 more cost-efficient overall
CO_2 Savings	Gas Turbine	Higher total environmental benefit
Efficiency Simplicity	Steam Turbine	Easier integration and control

Evaluating Turbine Options for Pinch Integration

- The comparative analysis of integrating a steam turbine versus a gas turbine above the pinch point reveals distinct trade-offs in energy recovery, efficiency, and economic benefits. Both turbines utilize the same minimum heat load (QHmin = 750 kW), but the steam turbine generates significantly higher mechanical work (262.5 kW) compared to the gas turbine (165.8 kW), resulting in a higher efficiency of 35% versus 22.1%. This translates into greater electricity savings per hour (€31.50 for the steam turbine versus €19.90 for the gas turbine).

- However, the gas turbine achieves more substantial reductions in cooling and hot utility demands after integration (a combined €63.76 per hour) than the steam turbine, which only reduces cooling utility by 512.5 kW and does not affect hot utility consumption. Consequently, the gas turbine attains a higher total economic benefit of €83.66 per hour, compared to €57.13 per hour for the steam turbine, driven primarily by greater utility cost savings. The gas turbine's higher exhaust temperature and its ability to reduce both cooling and hot utilities make it economically attractive, despite its lower efficiency and work output. Therefore, the choice between steam and gas turbine integration should weigh the priorities of maximizing electricity generation versus achieving broader utility cost reductions.

- The comparison of CO_2 emissions savings further highlights the environmental trade-offs between steam and gas turbine integration above the pinch point. The steam turbine achieves a total reduction of 156.25 kg CO_2 per hour, primarily through offsetting electricity consumption (105 kg CO_2) and reducing cooling utility demand (51.25 kg CO_2). In contrast, the gas turbine provides greater overall CO_2 savings of 193.82 kg per hour, despite generating less mechanical work. This advantage arises from the gas turbine ability to reduce not only electricity and cooling utilities but also hot utility consumption, contributing an additional 63.75 kg CO_2 savings. The larger utility reductions in the gas turbine scenario result in a more significant decrease in carbon footprint, emphasizing its potential for higher environmental benefits. Therefore, while the steam turbine offers better efficiency and higher electricity generation, the gas turbine integration is more effective in lowering overall greenhouse gas emissions due to its broader impact on multiple utility demands.

- I performed a comparative techno economic integration of both Rankine and Brayton cycles within the pinch framework, showing that the gas turbine is more cost and CO_2 effective

6.Heat Pump Integration

- After the steam turbine or gas turbine recovers some of the high-grade heat turning it into work or electricity, there is still waste heat left at a moderate temperature which refers to the exhaust gases released at 200–250°C or the steam leaving the turbine at approximately 217°C.
- No more work could be generated since this heat that remained have low grade.
- A heat pump can elevate this low to medium temperature waste heat to a more usable, higher temperature range
- The steam turbine recovers high-temperature thermal energy (above the pinch point) to generate electricity or mechanical work, improving overall system efficiency by utilizing excess heat.
- The heat pump typically operates at lower temperatures (often below or around the pinch point) to upgrade low-grade waste heat to useful heating levels or reduce heating utility consumption.

- This allows to:
    - Reuse the heat in processes that require higher temperatures than the exhaust offers.
    - Reduce additional heating utility needs.
    - Improve overall energy efficiency and reduce fuel consumption and emissions.
    - A heat pump uses mechanical energy usually electricity to drive a refrigeration cycle.
    - It absorbs heat from the waste heat stream and outputs this heat at a higher temperature suitable for reuse.

- The coefficient of performance (COP) is defined as the ratio between the heat transferred to the sink and the work supplied to the system
- A higher COP means better efficiency, but it's not linear it drops when the temperature difference (temperature lift) between source and sink increases.

Best Placement of a Heat Pump:

The most effective place to install a heat pump is across the pinch point in a thermal system. That means:

- Extracting heat from below the pinch (cold side)
- Releasing it above the pinch (hot side)
- This reduces the need for both external heating and cooling utilities**,** improving overall process efficiency.

COP selection as four represent the release of four units of heat for every unit of work.

Using the following code to determine how much heat can be transferred by the heat pump and calculating how much work in kW is needed to run the heat pump using the formula, so will have that the total heat delivered above the pinch, equal to the sum of:

- Heat extracted from below the pinch
- Work input (mechanical energy)

MATLAB Results:

6.1. Analyzing the energy situation before and after integrating the heat pump

1. Before Heat Pump Integration

- Minimum Heating Utility (QHmin)**:** 750.00 kW
- Minimum Cooling Utility (QCmin)**:** 1000.00 kW

2. After Heat Pump Integration

- Heat Extracted**:** 750.00 kW
- Work Input**:** 187.50 kW
- Heat Released (above pinch)**:** 937.50 kW
- New QHmin**:** 0.00 kW
- New QCmin**:** 250.00 kW

What this means:

- We used the heat pump to recover the full 750 kW from the cold side.
- We supplied only 187.5 kW of mechanical energy to run the pump.
- We released 937.5 kW of useful heat to the hot side.

Results:

- QH min = 0.
- Reducing cooling utility from 1000 to 250 kW (a 75% reduction).
- Total work input was just 187.5 kW for this massive gain.

Efficiency Comparison (Before vs. After)

Table 7: Efficiency Comparison

Metric	Before	After
Heating Utility (QHmin)	750.00 kW	0.00 kW
Cooling Utility (QCmin)	1000.00 kW	250.00 kW
Work Input	0.00 kW	187.50 kW
Energy Recycled	0.00 kW	937.50 kW

Thermodynamic Matching (Additional kJ Data)

- Energy extracted at T_source (135°C)**:** 200 kJ
- Updated Cold Utility**:** 800 kJ
- Energy required at T_sink (195°C)**:** 300 kJ

6.2. GCC after heat pump integration

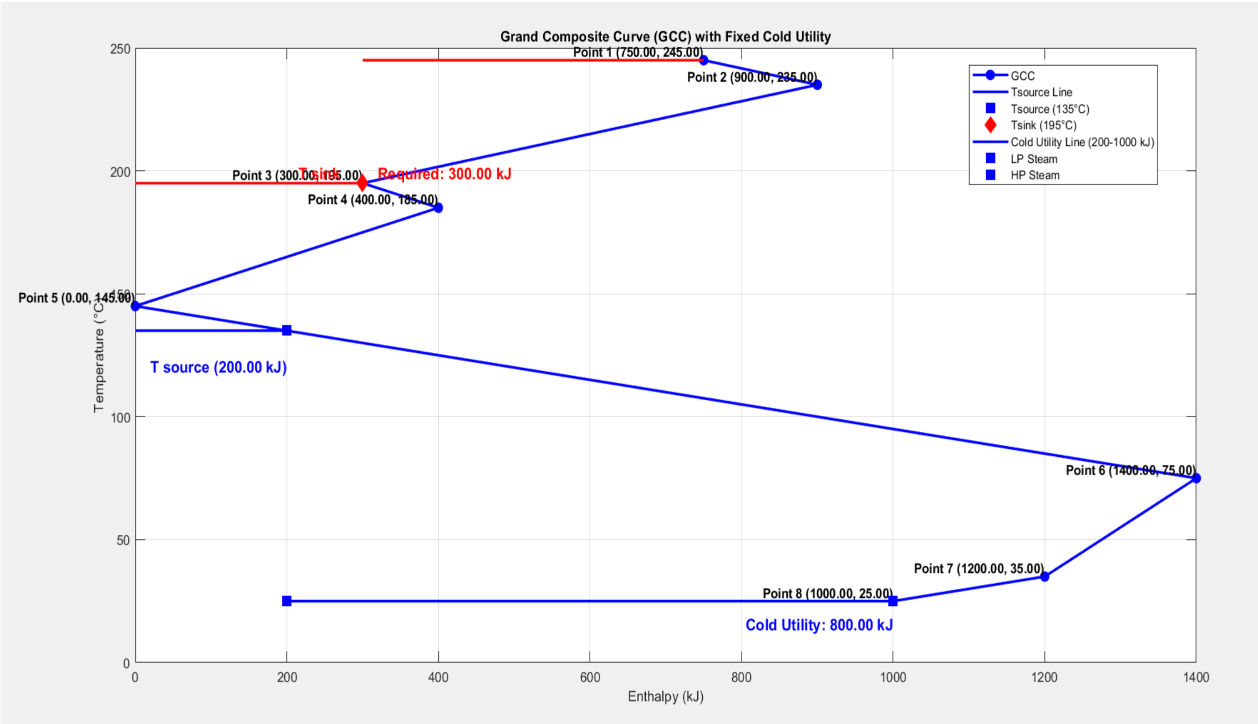


Figure 12: GCC after heat pump integration

Using the Heat Pump we:

- Extracted 200 kJ at 135°C (instead of the usual 25°C cold utility level).
- Delivered 300 kJ at 195°C (instead of the usual 245°C hot utility level).

This temperature shift (extracting heat at a higher temperature below pinch, and delivering it at a lower temperature above pinch**)** has several core benefits**:**

1. Extracting Heat at 135°C (Not 25°C): More Valuable Recovery
2. Before cold utility was handling heat at 25°C, this is low-quality heat
3. Now we're recovering heat from a process stream at 135°C**.**

Benefits**:**

- Recovering more thermodynamically valuable heat, closer to useful process temperatures.
- Less temperature lift required by the heat pump (from 135°C to 195°C instead of from 25°C → 245°C).

- Improves the Coefficient of Performance (COP) of the heat pump (lower work input for same output).

Delivering Heat at 195°C (Not 245°C): Matching Lower Demand

- Before steam utility had to supply heat at 245°C → high temperature, high-grade energy.
- Now delivering heat at 195°C, lower than steam temperature, but above pinch.

Benefits:

- Replacing expensive high-pressure steam with recycled process heat.
- Matching actual process demand more efficiently and not overheating or overpressuring.
- Reducing exergy destruction by delivering heat at closer to need temperatures.

6.3. Achievements Using the Heat Pump

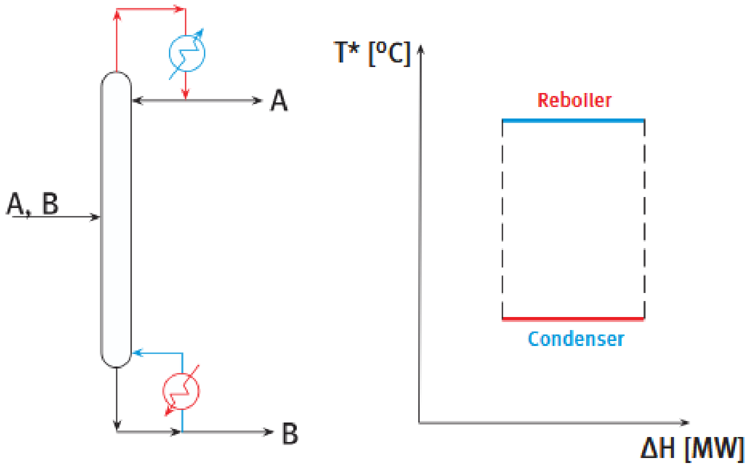
Table 8: Comparison with and without heat pump

Without HP	With HP
Extract at 25°C (too low to reuse)	Extract at 135°C (process temp)
Deliver at 245°C (needs steam)	Deliver at 195°C (within useful range)
No temperature lift	Heat pump lifts from 135°C → 195°C

The heat pump bridges the gap between available heat (T_source) and needed heat (T_sink) using mechanical work, it's basically recycling energy from one part of the process to another, thermodynamically efficiently.

7.Distillation processes (Additional Option)

Integrating a distillation column into a process using pinch analysis is a smart way to minimize utility consumption



7.1. Basic Structure of a Distillation Column

A basic distillation column typically consists of a single reboiler and condenser, which are responsible for the majority of its energy consumption.

- Reboiler: Supplies heat at the bottom of the column to vaporize the liquid mixture usually uses high-temperature utility like steam.
- Condenser: Removes heat at the top of the column to condense the overhead vapors uses cooling utility like cooling water.
- These two components alone can use up a big portion of the plant heating and cooling utilities.

7.2. Pinch Representation of the Distillation Column

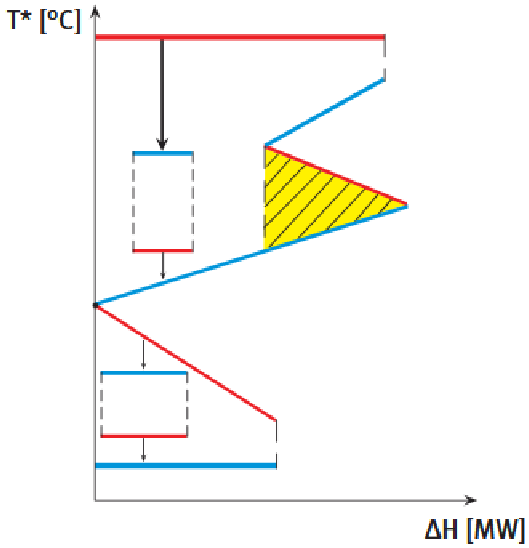
In the representation, the reboiler appears as a cold stream at the top, while the condenser is shown as a hot stream at the bottom

This means:

- The reboiler is treated like a cold stream → it needs heat.
- The condenser is a hot stream → it rejects heat.

7.3. Column Split Integration: Double Effect Distillation and Better Heat Use

In this method, one effect is positioned below the Pinch point, while the other is located above it



How it Works:

- We have two columns
- The thermal energy released by one column condenser can be utilized to supply the reboiler of a subsequent distillation column
- Placing them on opposite sides of the pinch (one above, one below) prevents internal integration.

This allows using a heat pump or intermediate utility to transfer heat from low temp to high temp and reduce fresh utility demands.

Condenser Integration (Above the Pinch)
The condenser is integrated at a temperature slightly above the pinch point, specifically at the pinch temperature plus a 5°C margin to ensure practical feasibility (T_condenser = pinch_temperature + 5°C). The heat duty of the condenser (Q_condenser) is assumed to be equal to the minimum heating utility requirement (QH_min). By doing this, the condenser handles a portion of the heat rejection, effectively reducing the overall hot utility demand in the system, calculated as Q_Hot_new = QH_min - Q_condenser. This integration allows for efficient heat recovery and better energy management.

Reboiler Integration (Below the Pinch)
The reboiler is positioned just below the pinch point, with a 5°C margin below the pinch

temperature (T_reboiler = pinch_temperature - 5°C), allowing it to utilize available waste heat rather than relying solely on fresh steam. The reboiler heat requirement is equivalent to the condenser rejected heat, allowing for potential heat recovery between the two units. This reduces the cooling utility demand by the amount of heat supplied to the reboiler, expressed as Q_Cold_new = QC_min - Q_reboiler. This strategy enhances energy efficiency by recovering and reusing heat within the process.

8. Energy Integration of Distillation Column, Steam Turbine, and Heat Pump in San Lazzaro Waste-to-Energy Plant

In the San Lazzaro Waste-to-Energy treatment plant, efficient energy management is crucial to optimize operational costs, reduce environmental impact, and ensure sustainable resource use. Among the key process units, the distillation column plays a vital role in treating wastewater streams that often contain complex mixtures of organic solvents and volatile contaminants and it can be used and have a big role in the second part of this thesis. These mixtures need to be separated and purified to enable water reuse and recover valuable compounds, both of which are essential for the plant economic and environmental performance.

Role of the Distillation Column

The distillation column achieves separation by vaporizing the liquid mixture in its reboiler, typically using steam as the heat source. When the mixture is heated, the more volatile components evaporate first and move upward through the column, where they condense at different stages, enabling separation into purified products. This purification is essential for recovering solvents and treating wastewater to meet discharge or reuse standards.

However, this process requires a significant amount of thermal energy in the form of steam, which adds to the plant heat demand (hot utility).Not to mention the cooling water need at the condenser. These heating and cooling requirements are significant components in the plant's overall energy balance and must be carefully managed to maximize efficiency.

Integration with the Steam Turbine

To meet the distillation column steam demand efficiently, the plant can integrate a steam turbine system. High-pressure steam generated by waste incineration or boilers can first pass through the steam turbine, producing mechanical or electrical work and then exhaust at a lower pressure and temperature. The low-pressure exhaust steam can be reused to heat the distillation column reboiler, supplying the required vaporization energy without consuming extra fuel.

This integration offers a dual benefit:

- The steam turbine recovers energy by generating electricity, offsetting external power purchases.
- The exhaust steam effectively recycles heat within the plant, reducing the need for fresh steam and lowering fuel consumption.

Thus, the steam turbine acts as a bridge, converting thermal energy into mechanical work and then cascading low-grade heat for the distillation process, which significantly enhances the plant overall energy efficiency.

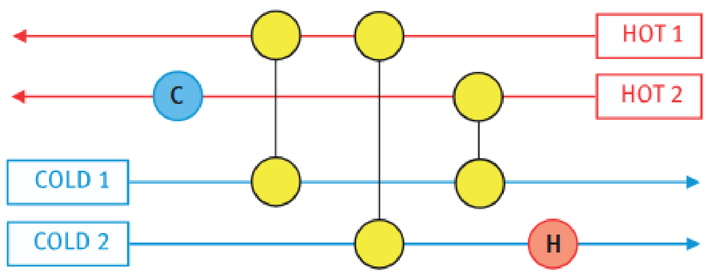
Role of the Heat Pump

Complementing this system, a heat pump can be installed to upgrade low-temperature waste heat streams to the temperature level required by the distillation column reboiler or other heating demands. For example, if some waste heat in the plant is at a temperature too low for direct use, the heat pump can raise its temperature efficiently, reducing the reliance on steam and fuel.

In pinch analysis, heat pumps are powerful tools to close heat loops and recover energy that would otherwise be lost, especially below the pinch point where temperature differences limit direct heat recovery. The heat pump reduces external hot utility demand and helps minimize cooling needs by efficiently recycling thermal energy.

9. Heat Exchanger Network (HEN) Analysis Under Minimum Energy Requirement (MER) Conditions

Heat Exchanger Network (HEN) synthesis is one of the most important components of process integration and energy optimization in industrial systems. The goal is to design a network that facilitates optimal heat recovery between process streams, thereby minimizing the requirement for external utilities. This detailed analysis provides a complete study of the HEN above and below the pinch point using the data provided, emphasizing MER conditions and the four core rules of Pinch Technology. The synthesis has been done while carefully ensuring heat transfer feasibility through stream matching and stream splitting, where needed.



2. Problem Data and Background

- **Hot Streams:**
  - H1: Tin = 250°C, Tout = 40°C, CP = 15 kW/°C
  - H2: Tin = 200°C, Tout = 80°C, CP = 25 kW/°C
- **Cold Streams:**
  - C1: Tin = 20°C, Tout = 180°C, CP = 20 kW/°C
  - C2: Tin = 140°C, Tout = 230°C, CP = 30 kW/°C
- **Pinch Temperatures:**
  - Hot Pinch: 150°C
  - Cold Pinch: 140°C
- **Minimum Utility Requirements:**
  - Minimum Heating Utility (QHmin): 750 kW
  - Minimum Cooling Utility (QCmin): 1000 kW

3. Role of Heat Exchanger Network (HEN) Under MER Conditions

Operating a HEN under Minimum Energy Requirement (MER) conditions means designing the network to ensure that the system consumes the least possible external heating and cooling utilities. This approach reduces operational costs and environmental impact. The core of this design is to maximize internal heat recovery between streams within the process, guided by the pinch point and associated rules.

Under MER conditions:

- No heat crosses the pinch.
- Heat is only transferred within the zones above and below the pinch.
- Heat exchanger matches are optimized for energy efficiency.

This approach not only meets the utility targets (QHmin and QCmin) but also guides the structure of the network and the sequence of operations to be followed for design.

4. The Four Fundamental Rules of Pinch Technology

Rule 1: One Stream at a Time Matching
The first rule of pinch technology is that the HEN must fulfill the heating/cooling requirement of one stream at a time. This ensures localized heat recovery optimization. In practice, this means we evaluate each cold (or hot) stream independently and attempt to satisfy its thermal requirement from available hot (or cold) streams within the same pinch zone.

Application in Our Case:

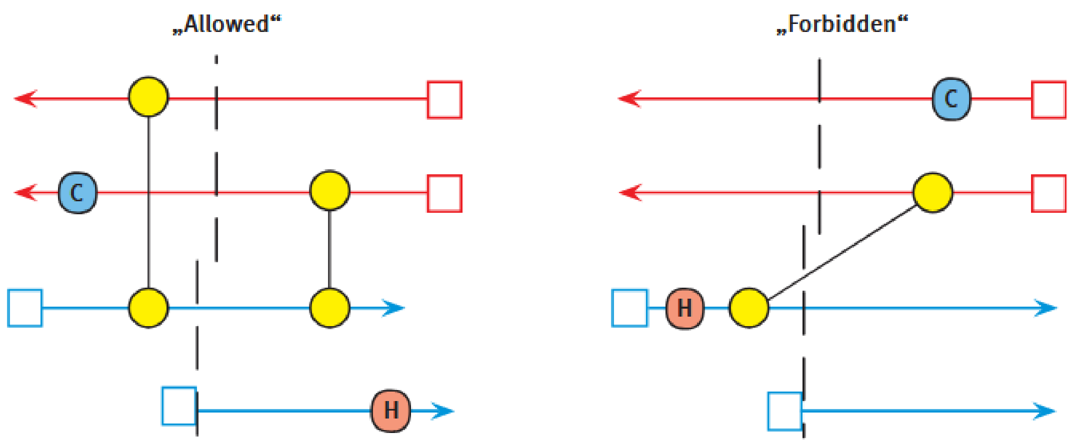
- Above the pinch: H1 and H2 are matched to C2 independently.
- Below the pinch: C1 was split to allow independent and feasible matching with H1 and H2.

This approach prevents over-complication and aids in sequential, logical design.

Rule 2: Start from the Pinch Point
The second rule emphasizes beginning the network design at the pinch point and extending both upward and downward. The pinch represents the thermodynamic bottleneck of the system. Ensuring the design adheres to MER at the pinch is crucial before addressing other regions.

Application in Our Case:

- The design began with matches just above and below the pinch temperature.
- Careful attention was paid to not transfer heat across the pinch.
- The first matches were between H2 (200°C) and C2 (230°C), and between H1 (140°C) and split portions of C1 (ending at 180°C).



Rule 3: Stream Splitting
Stream splitting is a strategic technique used when a single stream cannot be matched feasibly due to CP (heat capacity flow rate) constraints. Splitting allows partial matches with multiple streams to fulfill thermodynamic requirements.

Application in Our Case:

- Below the pinch, the cold stream C1 had a CP of 20 kW/°C, which exceeded H1 CP of 15. This violated the feasibility condition (CPcold ≤ CPhot).
- To resolve this, C1 was split into C1a (CP = 15) and C1b (CP = 5).
- C1a was matched with H1, and C1b was matched with H2. This made both matches feasible.

Rule 4: Avoid Cyclic Heat Transfers
This rule prevents designs where a stream is indirectly heating itself through a cyclic path of heat exchangers. Cyclic heat transfers violate thermodynamic principles and lead to redundancy or errors in heat integration.

Application in Our Case:

- All matches were strictly unidirectional and thermodynamically valid.
- No stream was part of a feedback loop.
- The pinch separation ensures heat transfer does not cross zones, further preventing any cycles.

5. Final Matches Summary

Above the Pinch (CPcold ≥ CPhot)

- Match 1: H2 (200°C → 80°C, CP = 25) → C2 (140°C → 230°C, CP = 30)
- Match 2: H1 (250°C → 150°C, CP = 15) → C2 (CP = 30)

Below the Pinch (CPcold ≤ CPhot)

- Split C1:
    - C1a (CP = 15): matched with H1 (140°C → 40°C)
    - C1b (CP = 5): matched with H2 (CP = 25)

All matches meet CP constraints, and no heat crosses the pinch.

6. Utility Check

- Total heat recovered matches target recovery.
- Minimum Heating Utility (QHmin): 750 kW
- Minimum Cooling Utility (QCmin): 1000 kW

This confirms that our HEN respects the MER condition.

7. Benefits of Adhering to the Rules

- Thermodynamic feasibility: All CP-based matching constraints are respected.
- Simplicity and clarity: Stream-by-stream matching reduces complexity.
- Energy efficiency: Full internal heat recovery was maximized.
- Scalability: The HEN can now be expanded with intermediate utilities or optimized further with cost analysis.

Designing a HEN under MER conditions using pinch analysis is a methodical, rule-based approach that significantly improves energy integration. The four guiding rules act as cornerstones to ensure feasibility, efficiency, and clarity. In this project, these rules were applied rigorously. Through proper stream matching and strategic stream splitting, the resulting network minimizes utility consumption, complies with heat transfer feasibility conditions, and is free from thermodynamic violations. This structured approach sets the foundation for further optimization, such as cost targeting, exchanger network design, and operational flexibility.

The analysis provided here forms the core of an energy-optimized process, and these methods can be generalized to more complex multi-stream, multi-unit processes in real-world industrial settings.

Full HEN Study

Hot Streams

Stream	Tin (°C)	Tout (°C)	CP (kW/°C)	ΔT
H1	250	40	15	210
H2	200	80	25	120

Cold Streams

Stream	Tin (°C)	Tout (°C)	CP (kW/°C)	ΔT
C1	20	180	20	160
C2	140	230	30	90

Pinch Temperatures

- Hot Pinch: 150°C
- Cold Pinch: 140°C
- $\Delta T_{min} = 10°C$

ABOVE THE PINCH STUDY

Design Rule Above Pinch:

No use of cold utility, and no heat from utilities. All heating must come from hot process streams.

We include:

- Hot streams: above 150°C
- Cold streams: above 140°C

Applicable Streams:

- **Hot streams:**
  - H1 (250 → 40) → above pinch section: 250 → 150
  - H2 (200 → 80) → above pinch section: 200 → 150
- **Cold streams:**
  - C2 (140 → 230) → above pinch section: 140 → 230

Step 1: Dividing streams above the pinch

- H1 above pinch: 250 → 150°C, ΔT = 100°C, Q = 15 × 100 = 1500 kW
- H2 above pinch: 200 → 150°C, ΔT = 50°C, Q = 25 × 50 = 1250 kW
- Total heat available above pinch **=** 2750 kW
- C2 above pinch: 140 → 230°C, ΔT = 90°C, Q = 30 × 90 = 2700 kW
- Total heat required above pinch = 2700 kW

Perfect heat balance: 2750 kW available and 2700 kW needed → excess 50 kW → likely sent to below pinch or minimized by design.

Heat Matching Above the Pinch

Proposing two main matches:

Match 1: H2 (200 → 150°C) → C2 (140 → 190°C)

- H2 releases: 25 × 50 = 1250 kW
- C2 absorbs: 30 × (190–140) = 1500 kW
- Match limit is on H2 side → match Q = 1250 kW
- C2 now requires: 2700 – 1250 = 1450 kW

Match 2: H1 (250 → 150°C) → C2 (190 → 230°C)

- H1 available: 1500 kW
- C2 needs: 1450 kW
- Perfect match! Q = 1450 kW

Result:

- No heating utility needed above pinch
- No cooling utility above pinch
- Heat recovery = 2700 kW
- H1 has 50 kW left unused

BELOW THE PINCH STUDY

Design Rule Below Pinch:

No use of hot utility, and no heat rejection to cold utility. All cooling must go to cold process streams.

Applicable Streams:

- **Hot streams**:
  - H1 (150 → 40°C): ΔT = 110°C → Q = 15 × 110 = 1650 kW
  - H2 (150 → 80°C): ΔT = 70°C → Q = 25 × 70 = 1750 kW
  - Total heat to remove = 3400 kW
- **Cold stream**:
  - C1 (20 → 180°C): ΔT = 160°C → Q = 20 × 160 = 3200 kW

Heat available below pinch = 3400 kW
Cold demand = 3200 kW

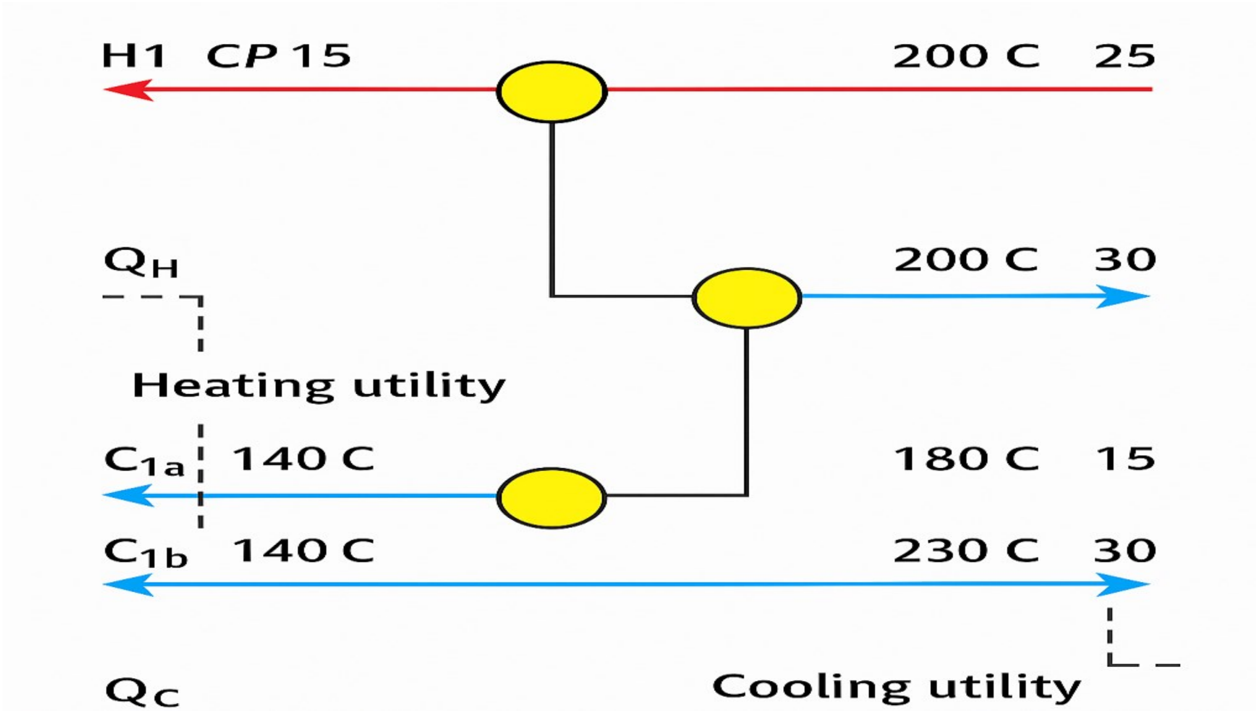
Heat Matching Below the Pinch

Match 1: H1 (150 → 40°C) → C1 (20 → 93.3°C)

- H1 has 1650 kW
- C1 CP = 20 → T rise = 1650/20 = 82.5°C
- Final C1 temp = 20 + 82.5 = 102.5°C
- C1 still needs: 180 – 102.5 = 77.5°C → Q = 20 × 77.5 = 1550 kW

Match 2: H2 (150 → 80°C) → C1 (102.5 → 180°C)

- H2 available = 1750 kW
- C1 needs = 1550 kW



Result:

- No cold utility needed below pinch
- No hot utility below pinch
- Heat recovery = 3200 kW
- H2 still has 200 kW extra

This final HEN synthesis confirms the feasibility and effectiveness of the pinch-based integration strategy:

- Full compliance with pinch design rules
- Achieved the QHmin and QCmin targets
- Minimum utility use
- Four well-defined exchanger matches
- Clear division of responsibilities between streams

Conclusion Part 1: Heat Treatment through Process Integration and Intensification

This first part of the study has successfully explored and demonstrated how thermal-based process integration and intensification strategies can significantly improve energy recovery and efficiency in complex industrial systems, with a focus on the San Lazzaro Waste-to-Energy (WtE) plant. By applying the principles of pinch analysis, all relevant waste heat sources, cold demands, and internal streams were systematically identified and analyzed. The construction of Composite Curves, Grand Composite Curves, and the application of the Problem Table Algorithm allowed the precise determination of pinch points and energy targets for the plant.

Through this analysis, energy-intensive components such as steam turbines (Rankine cycle), gas turbines (Brayton cycle), and heat pumps were evaluated and strategically integrated above or below the pinch point to maximize internal energy reuse. The steam turbine integration notably reduced external electricity demand and cooling utility loads, while the gas turbine showed superior total economic and CO_2 savings due to its high exhaust temperature and ability to reduce hot utility needs. The heat pump provided additional flexibility, enabling thermal upgrading of low-grade heat for reuse, particularly around the pinch region.

In parallel, the distillation column was introduced as an optional yet valuable thermal process, especially when integrated with reboilers and condensers across the pinch point. This facilitated not only effective component separation but also deeper energy recovery by smart placement of thermal loads within the existing system.

Overall, this part confirms that a thoughtful combination of thermal mapping, process integration, and the integration of advanced thermal systems can lead to a highly efficient, cost-effective, and environmentally responsible waste-to-energy operation.

Part 2: Water Pinch Methodology and Recovery Goals in Water Treatment Systems

1. Introduction

Water Pinch Analysis (WPA) helps industries cut down on water use and wastewater output by analyzing processes to find where water can be reused or recycled within the system. The methodology consists of several key steps, each crucial for designing an efficient water network.

In the San Lazzaro Waste-to-Energy (WTE) plant, water enters the facility through three primary sources: the Public Grid (Acquedotto), the Piovego Canal and rainwater. The Public Grid provides already treated municipal water, often used for processes requiring higher purity and potentially undergoing further conditioning such as softening or desalination. The Piovego Canal supplies raw surface water, typically used for lower-grade applications like condenser cooling. These two sources constitute the plant's freshwater inputs, and minimizing their consumption is a central goal of Water Pinch Analysis (WPA), adding to them the rainwater source**.** Once introduced into the system, this water is distributed across various industrial processes such as boiler operations, cooling systems, ash quenching, equipment washing, cleaning procedures, after which it becomes contaminated and exits as wastewater.

These wastewater streams, include wet ash removal effluents, boiler blowdowns, cleaning water, cooling loop blowdowns, cleaning parking lot and contaminated rain water called first flush rainwater, the first 5 mm of rainfall. Though these streams are no longer clean, many of them still hold potential for internal reuse in processes with less stringent water quality requirements. Therefore, the application of WPA in this context aims to match suitable wastewater sources with appropriate process sinks, reducing the need for fresh water, optimizing resource use, and minimizing environmental discharge and cost. While not all wastewater streams can be reused for high-purity applications, several can be safely and efficiently repurposed within the plant for some uses forming the basis for a single integrated water system guided by targeted reuse strategies.

2.Water management overview

The industrial sector is a major consumer of water, accounting for 22% of global usage, following agriculture (70%) and domestic use (8%) as reported by UNESCO (2003). Water is essential in industry for purposes such as heating, cooling, cleaning, product formulation, transport, and separation processes. Due to increasing water costs, stricter environmental regulations, and limited access to clean water, industries are adopting strategies to minimize water usage. These include improving water-use efficiency, reducing waste, implementing water-saving technologies, recycling and treating wastewater, and utilizing alternative water sources like rain or river water.

The concept of the water footprint, introduced by Hoekstra in 2003, measures the total volume of freshwater used throughout a product's life cycle. It includes three components:

- Blue water footprint: Use of surface and groundwater.
- Green water footprint: Refers to the portion of rainwater that is absorbed by soil and used by plants before any excess becomes surface runoff.

Water Pinch Analysis (WPA) is a systematic method used to minimize water usage by integrating industrial processes to maximize water efficiency. The term "pinch" identifies the limiting point for water recovery in a system. WPA helps determine the maximum possible water savings, acting as a benchmark for achieving significant improvements rather than small, incremental changes. It enables industries to answer key questions about potential water savings, investment needs, and financial returns by designing an optimal water recovery network

3. Representation of the PLANT

Water Pinch Analysis will be applied on these streams at their current quality level before they enter the comprehensive wastewater treatment system. This analysis aims to identify how to internally reuse and recycle water flows within the plant processes, minimizing the need to draw additional freshwater and reducing the load on the wastewater treatment system.

By targeting these partially treated wastewater streams, the Water Pinch method helps to optimize water consumption and promote sustainability. It looks for the best matches between wastewater sources that are streams that can be reused and sinks that are processes that require water, balancing contaminant concentrations and flowrates to maximize reuse without compromising process requirements.

This approach not only lowers freshwater demand but also decreases the volume and contamination load entering the treatment plant, resulting in operational cost savings and environmental benefits.

Water Pinch Analysis is usually applied before the full wastewater treatment process that is, it focuses on the wastewater streams as they are generated or after minimal preliminary treatment but before the main treatment plant.

Here is why:

- The main goal of Water Pinch is to optimize internal reuse and recycling of water within the plant. To do this effectively and according to the methodology, it is necessary to need to analyze the wastewater streams at their current contamination levels before they are cleaned by the treatment system.
- By finding opportunities to reuse wastewater internally, the plant can reduce freshwater intake and lower the load on the treatment plant, which saves costs and energy.
- Applying Water Pinch after wastewater treatment is less common because treated effluent is usually cleaner and less flexible for reuse in certain processes that require specific water qualities.

While Water Pinch Analysis reduces the need for treatment, it doesn't treat water itself, so for the wastewater will use the source/sink allocations method.

4. Steps for the water pinch analysis

4.1. Step 1: Water Network Analysis

Assessing the Water System:

- Identifying all water using operations or units
- Understanding the Water Network
- Developing mass balance diagrams around each process to quantify water consumption and wastewater generation.
- Clearly defining the scope of the analysis whether it covers the entire plant or a specific section.

4.2. Step 2: Data Extraction

After mapping the water flows, the next step is to extract key data from the audit. This includes:

- Water sources: Streams that contain water which could potentially be reused
- Water sinks: Units that require water input, each with specific quality requirements
    - Flowrate (F)**:** Volume of water available or required.
    - The contaminant concentration (C**)**, usually expressed in parts per million (ppm), indicates the water quality.

4.2.1 Source/Sink Explanation

In the Padova Waste-to-Energy plant water balance for 2024, the total wastewater outlet from the on-site wastewater treatment (WWT) plant is reported to be 80,609 m^3/year. This wastewater flow is composed of multiple contributing sources and needs to be carefully accounted for in the water balance and water pinch analysis.

4.2.2 Breakdown of Wastewater Components:

1. **Wastewater from Demineralization Unit**
   The total water entering the demineralization unit is estimated as 75,000 m^3/year, from which 50,000 m^3/year of high-quality demineralized water is produced. The difference, 25,000 m^3/year, is reject water or wastewater from the demineralization process.
   This reject water is reused for slag quenching and yard washing operations (which include floor washing, parking lot cleaning, truck and equipment washing, dust suppression).
   Accounting for typical losses due to evaporation and retention during these operations (assumed here at 10% loss), the wastewater exiting from yard washing and slag quenching amounts to:

At 10% loss: $25{,}000 \times 0.9 = 22{,}500$ m3/year

This is identified as Source 1 in the water balance.

- **Water Supplied for Boiler Feedwater and Boiler Blowdown**
  From the 50,000 m^3/year of demineralized water produced, 35,000 m^3/year is supplied as boiler feedwater.
  Boiler Blowdown: Boiler blowdown, the deliberate release of some boiler water to manage impurity levels, is estimated to be about 7% of the boiler feedwater.

  $35{,}000 \times 0.07 = 2{,}500$ m3/year

Discharged blowdown water contributes to the wastewater flow and is identified as Source 2.

3. **Water Supplied for Cooling Purposes and Resulting Wastewater**
   The remaining 15,000 m^3/year of demineralized water (from the total 50,000 m^3/year) is used for sensitive or closed-loop cooling systems (such as turbine bearings, transformers, auxiliary equipment).
   Assuming typical cooling water losses of 10% due to evaporation and retention, the wastewater generated from cooling is: $15{,}000 \times 0.9 = 13{,}500$ m3/year.

   This represents Source 3.

4.First Flush Rainwater (Contaminated Rainwater)
The plant also receives rainwater which contributes to the wastewater volume after being contaminated through contact with surfaces (roof runoff, yard areas).
The most contaminated portion of rainwater is the so-called first flush, typically the first 5 mm of rainfall, which contains the highest pollutant loads due to initial wash-off of accumulated dust, oils, and solids.
This first flush rainwater is part of the wastewater balance but its volume is not directly given and must be calculated.
This represents Source 4.

5.Sludge from the WWT Plant
During treatment, sludge is generated as a byproduct of contaminant removal, here reported as 78 tons/year. While sludge volume is usually expressed in tons, its volume equivalent is subtracted in the water balance as it represents solids removed from the wastewater.

Water Balance Equation:

Total Wastewater Outlet = Wastewater from Demineralization + Boiler Blowdown + Cooling Wastewater + First Flush Rainwater − Sludge Volume

Given the total wastewater outlet volume as 80,609 m^3/year, the equation becomes:

80,609 = 22,500 + 2,500 + 13,500 + Rainwater − Sludge Volume

Estimating the Volume of Sludge in m^3:

Sludge weight is 78 tons/year. Assuming typical sludge density around 1,000 kg/m^3 (similar to water, depending on solids content this can vary but it's a reasonable estimate), sludge volume can be approximated as:

78,000 / 1,000 = 78 m^3

Calculating the First Flush Rainwater Volume:

Rearranging the equation to solve for rainwater:

Rainwater = 80,609 + 78 − (22,500 + 2,500 + 13,500) = 80,687−38,500=42,187 m3/year

4.2.3 Sources Table

Table 9: Listing the Sources

SOURCE ID	DESCRIPTION	FLOW (M^3/Y)	CONTAMINANT CONCENTRATION (PPM)	MASS FLOW (KG/Y)
SRC4	Wet ash removal effluent including wastewater from ash quenching and yard washing operations using demineralized water (truck/equipment washing/ parking lot)	22500	190	5175
SRC2	Boiler blowdown	2500	100	350
SRC1	cooling loop blowdown (wastewater that results after that the furnace/Turbo Pump/ Water sampling benches/ Vacuum group has been cooled by aqueduct water from public grid)	13500	70	1350
SRC3	Contaminated Rain water	42187	140	7593.6

4.2.4. Sinks Table

Table 10: Listing Sinks

SINK ID	DESCRIPTION	FLOW (M^3/Y)	CONCENTRATION REQUIREMENT	MASS FLOW (KG/Y)
SINK4	Ash/slug quenching and yard quenching (Truck/equipment washing + Floor washing/ internal and external areas + Cleaning of parking lot)	35000	< 140 PPM	4900
SINK2	Fire-fighting reserve	7000	< 70 PPM	350
SINK1	Boiler feed pre-treatment for steam treatment	5000	< 1 PPM	5
SINK3	Cooling purposes (Furnace/ Turbopump / water sampling benches/ vacuum group)	22000	< 80	1100

4.2.5 Detailed Explanation of the sources

Source 1: cooling loop blowdown

- In the waste-to-energy plant, different cooling needs are served by carefully selecting appropriate water sources to ensure both operational efficiency and environmental protection.

- Water from the Piovego channel is used specifically for cooling the steam turbine condenser. This system uses a once-through cooling method where water from the Piovego is pumped through the condenser. The system takes in latent heat from the exhaust steam, leading to its condensation into water. In this process, the Piovego water does not come into direct contact with the steam and therefore remains chemically uncontaminated. The only effect is a rise in temperature, which is controlled and kept within regulatory limits before discharging the water back to the Piovego channel. This approach ensures the water remains clean and safe for reintroduction into the environment.

On the other hand, cooling requirements for more sensitive or closed-loop systems, such as:

- Cooling for turbine generator bearings and their lubrication oil systems, which is crucial for preventing overheating and oil degradation.
- Transformers and electrical equipment where overheating may damage insulation.
- Auxiliary process equipment like heat exchangers and pumps which generate heat during operation.
- Furnace/Turbo Pump/ Water sampling benches/ Vacuum group

are all met using higher-quality water sources, such as demineralized water or water from the aqueduct. These systems require water with very low conductivity and minimal impurities to avoid corrosion, fouling, or operational risks.

- Cooling loop blowdown water, can be reused in several areas of the plant depending on its level of contamination. This blowdown typically contains dissolved salts, corrosion inhibitors, and small amounts of metals, and is generated to control the accumulation of these impurities in the loop. If the contamination is moderate, the blowdown can be reused in non-critical applications that tolerate lower water quality. Common reuse options include cleaning of parking lot, fire-fighting reserve, floor washing and dust suppression, where water is sprayed to control dust emissions, especially in bottom ash management areas. In plants with wet flue gas treatment systems, blowdown water may serve as make-up water for scrubbers, although this is not applicable in dry treatment setups which is used in this plant. Additionally, if deemed safe, it can be stored for utility purposes such as equipment cleaning or emergency firewater supply.

However, it cannot be reused in high-purity applications such as boiler feedwater without undergoing appropriate treatment.

- Estimating the outlet wastewater from cooling purposes based on the assumed cooling water usage**.**The cooling water intake is about 15,000 cubic meters per year, using demineralized water as its source. Cooling systems commonly lose water through evaporation, drift, blowdown, and retention. These losses usually range between 10% and 30%, similar to the losses observed in quenching and yard washing processes.

- Outlet wastewater after these losses:

- At 10% loss, 1,500 m^3 of water is lost to evaporation and other factors, resulting in an outlet wastewater volume of 13,500 m^3/year.

Source 2: Boiler Blowdown:

- Boiler blowdown is the process of removing some of the water inside a boiler to control the buildup of impurities such as dissolved solids, hardness, scale-forming minerals, and corrosion products. When the boiler heats water to produce steam, these impurities become more concentrated in the remaining water because the steam leaves but the minerals stay behind. If the concentration of these impurities becomes too high, they can form scale deposits on the boiler surfaces, cause corrosion, and reduce the boiler efficiency or even damage it.

- To prevent this, a portion of the concentrated dirty water is regularly removed or blown dow from the boiler and replaced with fresh, clean water. This blowdown can be done continuously or intermittently depending on the boiler operation.

- As mentioned previously, Boiler blowdowns refer to the intentional discharge of water from the boiler to control the concentration of dissolved solids and prevent scaling or corrosion. Typically, blowdown accounts for about 5–10% of the boiler feedwater. Given a boiler feedwater input of 35000 m^3/year, a reasonable estimate for boiler blowdown is approximately 2500 m^3/year assuming a 7 % rate.

- Boiler blowdown water contains high levels of dissolved solids, hardness, scale-forming minerals, and corrosion products, making it unsuitable for applications that require very clean or demineralized water. Boiler blowdown water could potentially be reused for uses with lower water quality requirements, such as truck and equipment washing, floor washing, or cleaning of the parking lot, provided that the contamination levels are within acceptable limits or after appropriate treatment. Fire-fighting reserve usually requires clean or potable water, so boiler blowdown water is generally not suitable for this purpose. The suitability of boiler blowdown water for these potential reuse options will be further verified and optimized through MATLAB code as part of the water pinch analysis to achieve effective internal water reuse to significantly reduce fresh water consumption**.**

Boiler feed pre-treatment for steam treatment (Related to source 2)

- Boiler feed pre-treatment for steam treatment refers to the process of preparing the water before it enters the boiler to generate steam.
Water pinch analysis is a powerful tool to optimize water reuse and minimize fresh water intake by matching contaminated wastewater streams to process needs. However, boiler feedwater requires exceptionally high quality to prevent scale, corrosion, and operational issues. The wastewater streams considered in pinch analysis such as ash quenching effluent, cooling blowdown, and rainwater runoff typically contain contaminants like suspended solids, dissolved minerals, or chemicals. Even low levels of these contaminants can harm the boiler system.

- Pre-treatment is crucial before any reclaimed water can be used as boiler feedwater. This step ensures the water meets the necessary quality standards to protect the boiler and maintain efficient operation. Processes such as filtration, softening, deaeration, reverse osmosis, and ion exchange are necessary to meet the strict water quality standards for boilers.

- While pinch analysis helps reduce fresh water consumption by maximizing reuse, it cannot replace the critical need for pre-treatment. Instead, a dedicated pre-treatment step should be planned after the water has been allocated by the pinch analysis and before it enters the boiler feed system. This guarantees that only appropriately treated water enters the boiler, which protects its operation and allows the plant to take advantage of the efficiency benefits of water reuse.

Instead of relying solely on fresh water for the boiler feed, I applied Water Pinch Analysis to identify and quantify the amount of reusable water available from internal wastewater streams. This identified volume is then directed to the boiler feedwater pre-treatment system. After proper treatment to meet quality standards, this water can be safely used as boiler feed, reducing the demand for fresh water and improving overall water efficiency, so the followings benefits were achieved:

1. Optimized Water Reuse: WPA identifies and maximizes the use of internal wastewater streams, reducing the need for fresh water intake for boiler feedwater makeup.
2. Reduced Water Consumption: By strategically matching available wastewater sources to the boiler feed pre-treatment stage, i minimized the volume of raw freshwater required, promoting sustainability and cost savings.
3. Efficient Allocation of Resources: WPA helps prioritize which wastewater streams are suitable for reuse in the boiler feed system based on their quality and contamination levels, improving the efficiency of pre-treatment processes.
4. Enhanced Environmental Performance: Reduced freshwater withdrawal and wastewater discharge help minimize environmental impact and support regulatory compliance.
5. Improved Process Integration**:** WPA provides a clear framework to integrate water reuse with boiler feedwater quality requirements, ensuring reliable steam generation while conserving water.

Source 3: Contaminated Rain water

Refers to the runoff collected from plant surfaces, equipment yards, and roofs, which becomes polluted as it comes into contact with contaminants such as dust, oil residues, and airborne particulates. In industrial facilities like power plants, this rainwater can accumulate significant levels of chemical and physical impurities, making it unsuitable for direct reuse without treatment. With a concentration of 180 ppm and an annual flowrate of 42,187 m^3, this source represents a substantial volume of recoverable water that, if properly matched to appropriate sinks or treated can lead to a substantial reduction in freshwater use and environmental discharge.

Source 4: Wet ash removal effluent including wastewater from ash quenching and yard washing operations

- Resulting Wet ash removal effluent Source, include wastewater from ash quenching and yard washing operations using demineralized water could be used in other plant processes with lower water quality requirements such as Ash/slug quenching and yard quenching (Truck/equipment washing + Floor washing/ internal and external areas + Cleaning of parking lot) floor washing, parking lot, truck/equipment cleaning and dust suppression

- Ash quenching is the process used to cool down the hot bottom ash produced during the combustion of municipal solid waste in the waste-to-energy (WTE) plant. In the San Lazzaro WTE facility, this operation typically uses demineralized water as the primary input.
In industrial facilities such as waste-to-energy plants, demineralization units treat raw water to remove dissolved salts, organic matter, and other impurities to produce high-purity water suitable for critical processes like boiler feedwater. However, these processes also generate a reject stream known as demineralization wastewater which contains concentrated salts, cleaning chemicals from and other residual contaminants.

- Instead of discharging this wastewater directly into drains, many plants practice internal reuse to improve water efficiency. One common approach involves using this lower-quality water in non-critical operations, where high purity is not required. Specifically, demineralized wastewater is often reused for:

- Yard washing, which includes cleaning internal roads, parking areas, and open yards where equipment is stored or transported.
- Slag quenching, a process where hot combustion by-products are rapidly cooled using water to stabilize them, reduce dust, and prepare them for disposal or further handling.

- This reuse strategy contributes to water conservation, lowers operational costs, and minimizes environmental impact by reducing freshwater demand and wastewater discharge.

- In the context of water pinch analysis, my role is to study the wastewater after it has been used in these operations that is, the effluent from yard washing and slag quenching. This is because water pinch methodology is focused on analyzing used water streams to identify opportunities for internal reuse before treatment or disposal. These streams, now considered as sources, can potentially serve other plant processes with lower water quality requirements called sinks, enabling a more circular and efficient use of water such washing floors, parking lots, and trucks/equipment, and suppressing dust.

- The quenching water, initially clean and low in dissolved minerals, comes into direct contact with the hot ash, resulting in significant thermal and physical changes. During this interaction, the water absorbs heat and becomes contaminated with ash particles**,** dissolved salts**,** trace heavy metals, and possibly a small amount of organic matter, depending on the ash's composition.

- Therefore, while the input to the quenching system is demineralized water, the output is a contaminated stream that originated from a high-purity source. This output stream can be considered a source stream in water pinch analysis, with known levels of contamination and it is represented as Wet ash removal effluent in my table and yard washing. It may be reused internally for less sensitive operations such as floor washing considering it as a sink, provided that the contamination levels are within acceptable limits. Or, it might need treatment before it can be reused or discharged.

- In contrast, the ash quenching system itself represents a water sink in the pinch analysis framework, as it requires water input. If other internal process streams can meet the required quality, they may partially replace fresh demineralized water in this application, improving overall water efficiency within the plant.

Demineralized Water Balance and Internal Reuse (Related to source 4)

- The total water input to the demineralization unit is 75,000 m^3/year, and the pure demineralized water output is 50,000 m^3/year. Therefore, the wastewater (reject) from demineralization is the difference between these two, which equals 25,000 m^3/year. This wastewater from the demineralization process is repurposed for yard washing and slag quenching. This implies that all of the 25,000 m^3/year reject water is reused for these purposes.

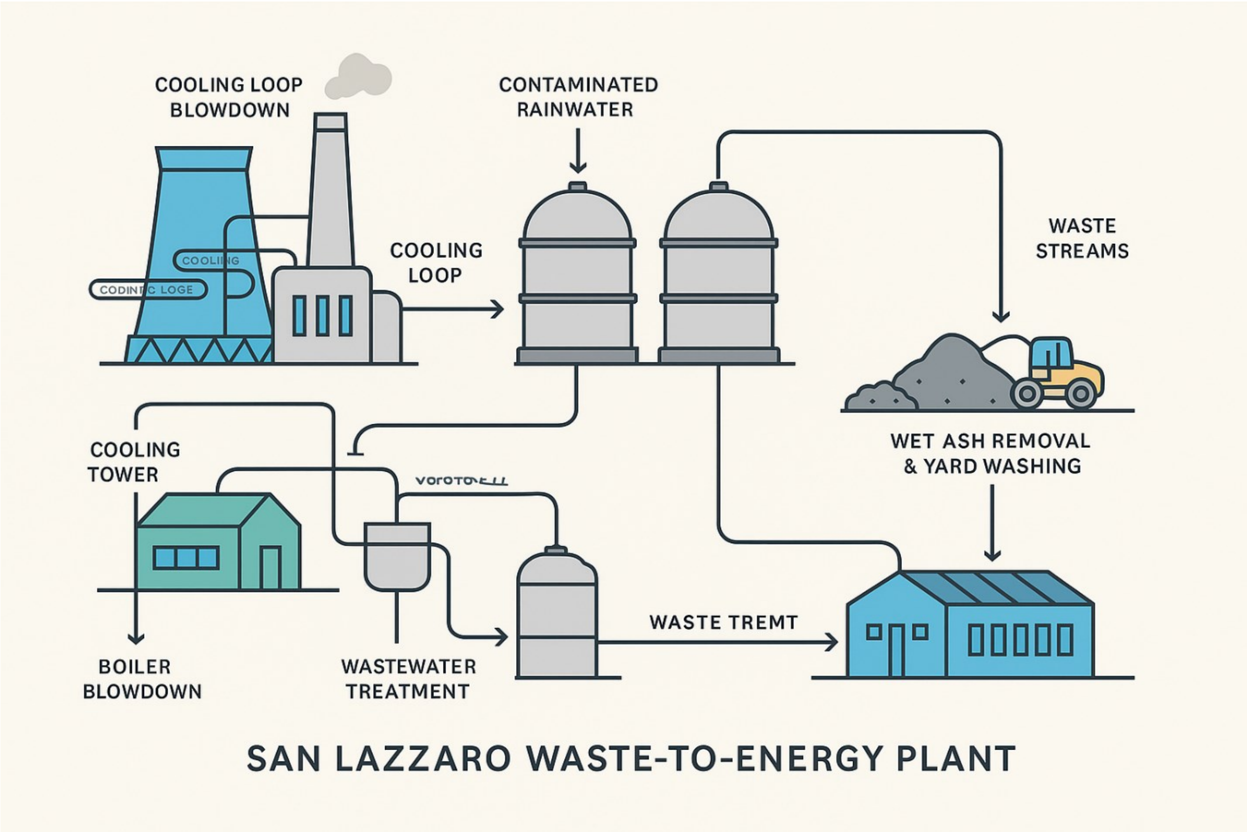
- After this reuse, the water picks up contaminants such as dirt, oil, ash, solids from yard washing, and heat, metals, particulates from slag quenching. This spent water then becomes wastewater contributing to the final wastewater volume sent to the treatment plant or discharge point.

- How much water actually exits after yard washing and slag quenching depends on losses through evaporation, absorption by slag or soil, and solids that do not return as water. A practical assumption is that typically 10–30% of water used in quenching and yard washing is lost due to evaporation and retention.

Based on this assumption, the volume exiting as wastewater after yard washing and slag quenching would be:

- At 10% loss: 25,000 × 0.90 = 22,500 m³/year

So 22,500 m³/year of wastewater would exit from yard washing and slag quenching operations for further use and here is the role of the water pinch analysis.



After completing the first two steps, we now proceed to Step 3.

4.3 Step 3: Setting Minimum Utility Targets

In this crucial step, the goal is to establish the minimum freshwater required and minimum wastewater generated, assuming optimal internal water reuse. This is achieved through:

- Matlab Code to have the Composite Curves and Water Cascade.

Based on the identified targets, a new and improved water network is designed to approach the theoretical minimum utility usage.

This step involves:

- Matching water sources to suitable sinks based on quality requirements.
- Prioritizing water reuse from the cleanest sources to the most tolerant sinks, following pinch principles.

4.3.1 Starting with the Water Cascade Analysis using Matlab

- In Water Pinch Analysis (WPA), two essential tools are used to optimize water usage in industrial processes: the Water Cascade Table (WCT) and the Source/Sink Allocation (SSA) method. Although they serve different purposes, both are integral to achieving sustainable water management. The Water Cascade Table is primarily a targeting tool. It helps determine the minimum freshwater requirement and minimum wastewater generation that a system can theoretically achieve, based on a global mass balance of contaminants and water flow rates across different concentration intervals. It gives a quantitative benchmark, known as the pinch point, below which no further water reuse is possible without violating quality constraints. However, the cascade does not provide a practical strategy or design on how to redistribute water among different process units.

- This is where the Source/Sink Allocation method becomes crucial. SSA is a design tool that takes the theoretical targets established by the cascade and identifies feasible matches between wastewater sources and water-consuming process units (sinks). It takes into account each stream flowrate and contaminant concentration, ensuring that water reused from a source meets the quality requirements of the sink. The result is a realistic water reuse network that minimizes freshwater intake and wastewater discharge without compromising process quality.

Matlab Code:

In my MATLAB code, a systematic analysis for evaluating and optimizing water usage in a material recycle/reuse process was presented. The approach aims to determine the minimum freshwater requirement through a water pinch analysis, and to identify the corresponding pinch point, where water reuse is maximized.

1. Definition of Inputs

The analysis begins by defining two sets of data:

- Sinks, which represent process units requiring water. Each sink is characterized by a flowrate (in m^3 per year) and a maximum allowable contaminant concentration (in parts per million, ppm).
- Sources, which are wastewater streams that can potentially be reused. Each source is defined by a flowrate and its actual contaminant concentration.

These data provide the basis for assessing how well sources can satisfy the demand of sinks without exceeding concentration limits.

2. Establishment of Concentration Levels

All unique concentration values from both sources and sinks are collected, combined with zero (to represent clean water), and sorted in ascending order. This creates a set of concentration intervals, which form the core of the water cascade calculations.

3. Calculation of Flow Contributions

For each concentration level, the total flowrate contributions from sinks and sources are evaluated. Sinks are treated as negative contributors (since they consume water), while sources contribute positively (since they provide reusable water). These are aggregated to calculate the net flow at each concentration level.

4. Freshwater Cascade Construction

A freshwater cascade diagram is then developed by cumulatively summing the net flow across the sorted concentration levels. This step reveals the variation of water availability (or deficit) across the system.

5. Mass Balance and Freshwater Flowrate Determination

The freshwater cascade method is used to calculate the mass of contaminant transferred within each concentration interval. The cumulative mass transfer is then determined, representing the total contaminant load moving through the system.

From this, the required freshwater flowrate at each concentration level is calculated, based on the principle that mass equals flowrate multiplied by concentration difference. This offers insight into how water demand is distributed throughout the system.

6. **Pinch Point Identification**

The pinch point is defined as the concentration level at which the minimum freshwater flowrate is observed. It indicates the limiting constraint for internal water reuse. Beyond this point, additional water reuse is not feasible without compromising sink requirements.

7. Updated Water Cascade with Minimum Freshwater

Once the minimum freshwater demand is known, the freshwater cascade is recalculated starting from this minimum value. This allows for a revised mass balance and shows how water is optimally distributed when the system operates at maximum reuse efficiency.

8. Final Water Cascade Table

The final results are summarized in a Water Cascade Table, which includes:

- Concentration levels and their intervals
- Flow contributions from sources and sinks
- Net flow and freshwater cascade (original and updated)
- Mass transfer values (original and updated)
- Cumulative mass changes
- Freshwater requirements at each level

Results from MATLAB

Ck, ppm	ΔCk, ppm	ΣFSKi, m^3/y	ΣFSRj, m^3/y	ΣF SKi + ΣFSRj, m^3/y	FC (Old), m^3/y	Δm, kg/y	Cum. Δm, kg/y	FFW, cum, m^3/y	FC (New), m^3/y
0	70	-5000	0	-5000	0	0	0	0	5464.3
70	10	-7000	13500	6500	6500	65000	0	0	11964
80	20	-22000	0	-22000	-15500	-3.1e+05	65000	812.5	-10036
100	40	0	2500	2500	-13000	-5.2e+05	-2.45e+05	-2450	-7535.7
140	20	0	42187	42187	29187	5.8374e+05	-7.65e+05	-5464.3	34651
160	30	-35000	0	-35000	-5813	-1.7439e+05	-1.8126e+05	-1132.9	-348.71

```
Pinch point (F FW min) = 5464.2857 m^3/y
```

```
Minimum Freshwater Required: 5464.29 m^3/y
Final Wastewater Produced: 22151.29 m^3/y
```

Those are figures, obtained as a result from my MATLAB code in the command Window.

From the WCT results, it can be clearly observed that the largest negative cumulative flowrate occurs at a contaminant concentration level of 140 ppm. This is the pinch point where at this concentration, the system reaches a balance where internal water reuse is maximized, and any additional water demand would require external freshwater input.

The magnitude of this negative cumulative flow at the Pinch point directly indicates the minimum freshwater target**.**

Furthermore, by continuing the cascade through the entire concentration range, the final cumulative value at the bottom of the cascade represents the minimum wastewater generation**.** The WCT ends with a value of 22151.29 m^3/y, meaning this is the minimum volume of water that must be discharged as wastewater from the system per year, after all internal reuse opportunities have been fully exploited.

4.4 Pinch Point

- Using the Water Cascade Table (WCT) approach implemented through a custom MATLAB code, the Pinch Point of the system was successfully identified at a cumulative flow value corresponding to a minimum freshwater requirement of 5464.29 m^3/y. This result marks a fundamental milestone in the water pinch analysis of the studied industrial process, as it provides the lower bound on the amount of external freshwater that must be introduced annually to maintain the process without compromising sink requirements or exceeding environmental limits.

- In Water Pinch Analysis, the Pinch point represents a critical concentration threshold that separates different operating regions within the system. This threshold governs the optimal allocation of water sources to water sinks, with the goal of maximizing internal water reuse while minimizing freshwater intake and wastewater discharge.

- The system is typically divided into three distinct regions relative to the Pinch point: below the Pinch, at or between the Pinch, and above the Pinch. Each region has its own rules to ensure water reuse is efficient and no unnecessary penalties are introduced.

1. Below the Pinch Region (Lower Concentration Region)

This region comprises water sinks with relatively low concentration limits. The rules in this region are as follows:

- Water sinks in this region must be satisfied only by internal water sources that have equal or lower contaminant concentrations or, when needed, by freshwater.
- No wastewater should be generated in this region. This means that all available water sources should be fully utilized to meet the sink demands.
- Violating this rule would lead to the premature discharge of usable water and a penalty in water efficiency, as this would increase freshwater usage unnecessarily.

2. Between the Pinch Region (At the Pinch Point)

The region between the two parts of the Pinch causing streams represents a balance point in the system. Here, the following rule must be strictly enforced:

- No freshwater should be added, and no wastewater should be discharged in this region.
- The flowrate and contaminant mass load of all water sinks must be satisfied entirely using internal water sources.
- This is the most constrained region: any deviation, such as adding freshwater or discharging wastewater, would directly violate the fundamental condition for maximum water recovery.

3. Above the Pinch Region (Higher Concentration Region)

This region includes water sinks with higher allowable concentrations, meaning they can accept more contaminated water.

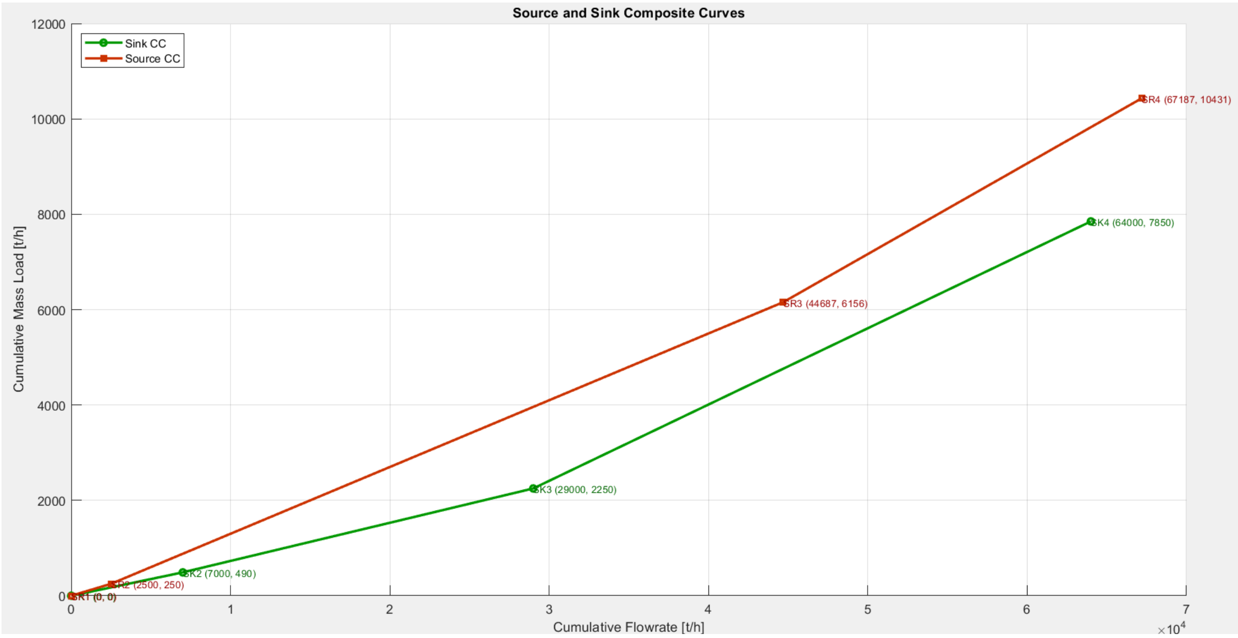
- Freshwater must not be used in this region. Doing so would waste clean water on sinks that could be served by lower-quality water, leading to inefficiencies.
- Water sources should only be used to supply water sinks that require equal or higher concentrations of contaminants, maintaining consistency with the contaminant balance.
- Excess water sources in this region that cannot be reused are discharged as wastewater.

4.5 Source and Sinks composite Curves

- The Source Sink Composite Curve (SSCC) illustrates the relationship between mass load (m) and flowrate (F). This approach aims to determine the minimum fresh resource consumption for systems involving material recycling and reuse. The Sink Composite Curve is constructed by cumulatively plotting each sink mass load and flow rate in increasing order of concentration. The Source Composite Curve is generated similarly. The Source Composite Curve is then horizontally translated until it is tangent to the Sink Composite Curve, ensuring the Source curve lies beneath the Sink curve in the overlapping section.

- The pinch point is identified where the two Composite Curves intersect. The Pinch concentration is determined by the concentration of the Pinch causing source stream. The minimum freshwater target is the flowrate distance difference between the beginning of the Source Composite Curve and the Sink Composite Curve. The minimum wastewater target is determined by the difference in flowrate between the conclusion of the Source Composite Curve and the Sink Composite Curve. This is illustrated in the Figures below. The targeted freshwater and wastewater quantities align with the results obtained from the Water Cascade Table (WCT).

- In the MATLAB code, source and sink streams are sorted by concentration to prepare for plotting. The cumulative flowrate and mass load (in t/h) are calculated for each, then adjusted to start from zero for consistency. Both curves are plotted on the same graph: sinks typically in green and sources in red, with labels added for clarity. This visualization helps identify water reuse opportunities by comparing the availability (sources) and demand (sinks) across the system.



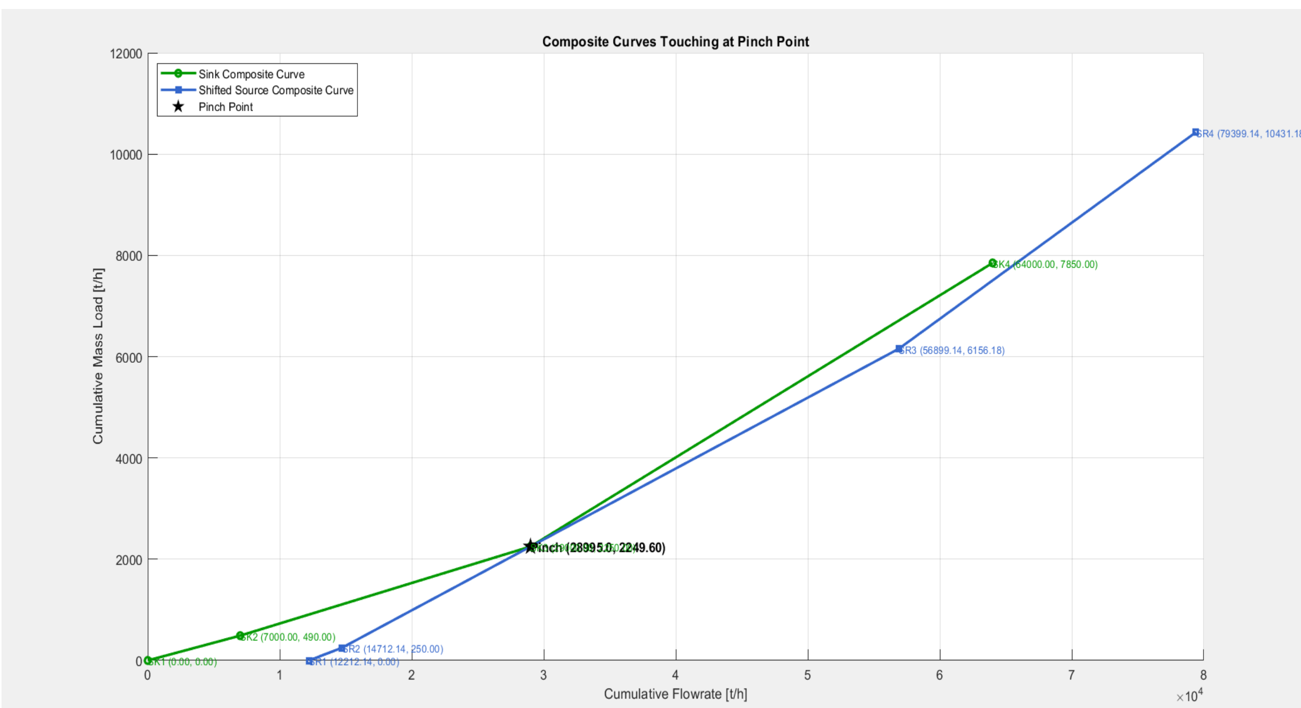


Figure 13: Composite Curves before and after for water pinch analysis

5. Source and Sink Allocation – Region Below the Pinch Point

- Source and Sink Allocation is used to both design and visually represent a water network by matching available sources with their respective demands (sinks). Originally introduced by El-Halwagi et al. (2003) for pure water sources and later extended by Kazantzi and El-Halwagi (2005) for impure sources, the method follows the "cleanest-to-cleanest" allocation rule. To address this, we will use both the cleanest and dirtiest sources within the Pinch region to fully meet the sink's requirements while respecting the Pinch point and utility targets. Additionally, we will introduce the Network Allocation Diagram (NAD) to translate SSAC into a more intuitive visual representation of the water network.

- In the first section of the MATLAB code, the objective is to identify all usable sources and sinks located below the defined pinch concentration (140 ppm) for further internal water reuse analysis.

1. Input Data Definition

The code begins by defining two main datasets:

- Sinks**:** Each sink is described by its flow rate (m^3/y), contaminant concentration (ppm), and mass flow rate (kg/y). These represent units that require water at specific purity levels.
- Sources**:** Each source is defined using the same parameters, representing water streams with varying levels of contamination that could be reused.

2. Identifying Sinks Below the Pinch

The script filters the sink streams to identify those whose contaminant concentration is less than or equal to the pinch point.

- A message is printed to emphasize that no wastewater should be generated in this region. Instead, water demand must be met either by internal water reuse or by freshwater.
- For each qualifying sink, the script computes and displays:
    - Flow rate
    - Required contaminant concentration
    - Corresponding mass flow rate

3. Identifying Usable Sources Below the Pinch

Similarly, the script filters the available source streams to identify those with contaminant concentration ≤ 140 ppm. These are the only ones permitted for reuse in this region.

For each usable source, the script computes and displays:

- Flow rate
- Contaminant concentration
- Mass load

5.1 Mass Flow Allocation Strategy Between SR1 and SK1 Based on Concentration and Demand Constraints

- In this section, the source to sink allocation algorithm focuses on determining how much of the available flow from Source 1 can be utilized to fulfill the demand of Sink 1. The matching is based on two main parameters: mass flow rate and contaminant concentration. The logic is structured using conditional statements that account for all possible scenarios based on the relationship between the required and available flow rates and their respective concentration levels.

- The following conditions were developed and implemented in my MATLAB code to cover all possible scenarios for source-to-sink allocation based on flow rate and contaminant concentration. These are general cases intended to ensure that, regardless of the input data, the program can correctly identify and classify the matching logic. While not all of these conditions apply to our specific plant, I am presenting and explaining each one here to demonstrate the structure and logic of the code. Afterward, I will identify which condition is relevant to our plant case and elaborate on it accordingly.

The analysis proceeds as follows:

1. Case A: SK1 Requires Ultra-Pure Water (0 ppm Contaminant)

When SK1 requires water at zero contaminant concentration, only treated streams like post-treatment from SR1 or freshwater can be considered:

- The algorithm first attempts to fulfill SK1 demand using the cleanest available stream, which is SR1 after proper treatment.
- If SR1 mass flow rate is less than or equal to what SK1 requires, all available flow from SR1 is used.
- Any remaining unmet demand is then supplied by freshwater, and the required freshwater mass flow is calculated and displayed.
- Remaining mass in SR1 (after allocation to SK1) is also computed and stored for potential use in supplying other sinks (e.g., SK2).

2. Case B: SR1 Is Clean Enough (SR1 concentration ≤ SK1 requirement)

Two sub-scenarios are considered:

B1. SR1 Flow < SK1 Demand

- SR1 supplies all of its available mass flow to SK1.
- The deficit is then met using freshwater, and its value is reported.
- The remaining mass flow in SR1 becomes zero in this case.

B2. SR1 Flow ≥ SK1 Demand

- Only the exact amount of mass needed is taken from Source 1 (SR1) to fully meet the demand of Sink 1 (SK1).
- There is no need for freshwater, as SR1 alone suffices.
- The remaining SR1 flow is computed and could be considered for reuse elsewhere.

3. Case C: SR1 Is More Polluted Than SK1 Can Accept (SR1 concentration > SK1 requirement)

Here, even if SR1 has enough mass flow, its contaminant concentration is too high for direct use by SK1. Still, two situations are assessed:

C1. SR1 Flow ≥ SK1 Demand

- Even if Source 1 (SR1) has a higher contaminant concentration, if it can be appropriately pretreated or its quality downgraded for the specific use, it can fully satisfy the demand of Sink 1 (SK1).
- There is no need for freshwater.
- The remaining SR1 mass flow is computed.

C2. SR1 Flow < SK1 Demand

- SR1 contributes its maximum available flow, even though it is not fully sufficient.
- The remaining portion is satisfied using freshwater.
- Any leftover in SR1 is zero, prompting the algorithm to proceed with evaluating Source 2 (SR2) in later sections.

5.1.1 Explanation of the specific condition that applies to our plant

The following conditions were designed and implemented in my MATLAB code to cover all potential matching scenarios between water sources and sinks, based on mass flow rates and contaminant concentration levels. These generalized conditions ensure the model can handle any set of input data by classifying and processing the streams accordingly.

After the algorithm identified the specific condition for my plant, I will present the detailed calculations and explanations.

- Condition – Sink 1 Requires 0 ppm

In the actual plant configuration, we fall under the condition where the sink (SK1) requires water with 0 ppm contaminant concentration. Among all available sources, SR1 has the lowest contaminant concentration (70 ppm), making it the most suitable candidate for treatment and reuse to satisfy SK1 demand before resorting to freshwater.

This means it can only accept:

- Freshwater or
- Treated water from the cleanest available source (SR1), provided the treatment process can bring the contaminant level down to 0 ppm.

Analysis Based on Mass Flow Rates:

1. **Sink Requirement (SK1):**
   - SK1 requires water with 0 ppm contaminant concentration (essentially pure water).
   - The required mass flow rate to SK1 is met by treating contaminated source water.
2. **Source (SR1) Availability:**
   - SR1 is identified as the cleanest source available.
   - Initially, SR1 has some mass flow available to supply SK1.
3. **Algorithm Decision:**
   - The algorithm treats a portion of SR1 flow corresponding to 5 kg/year of contaminant mass to meet SK1's pure water requirement.
   - Specifically, the mass flow allocated from SR1 to SK1 is calculated as: sr1 mass flow rate supplied to sk1 = min(sr1 mass flow rate, sk1 required mass flow rate). Here, SR1 mass flow rate refers to the total mass flow available from Source 1, while SK1 required mass flow rate is the mass flow demand of Sink 1.

This equation is a fundamental allocation rule often used in resource matching problems, such as water reuse or pinch analysis. It states:

- The amount of mass flow supplied from SR1 to SK1 cannot exceed either:
  - Total available mass flow from SR1, nor
  - The required mass flow in SK1 (sink demand limitation).

Therefore, the actual allocated flow is simply the smaller of these two values.

The remaining freshwater needed to fulfill SK1 demand after allocation from SR1 is:

  - Fresh Water needed mass = sk1 required mass flow rate – sr1 mass flow raet supplied to sk1
  - This treatment volume ensures that SK1 contaminant concentration reaches zero ppm.

4. **Contaminant Removal via Treatment:**
   Once the mass flow from SR1 is allocated, this water undergoes treatment to reduce the contaminant concentration from the source level down to the required 0 ppm for SK1. The total contaminant load removed during treatment corresponds to the allocated mass flow multiplied by the initial contaminant concentration in SR1:
   Contaminant Load Removed=Allocated Mass Flow×Initial Contaminant Concentration in SR1
   This ensures that the treated water meets SK1's strict purity requirements.

5. **Practical Considerations Regarding Treatment:**
   Since an existing wastewater treatment section in our plant is available, the calculated mass flow allocation from this analysis can be routed to that plant. The plant treats the allocated water flow to the required contaminant levels before supplying it to SK1. Hence, this calculated allocation provides critical input for treatment plant capacity planning and operational management.

6. **Outcome:**
   By combining pinch analysis allocation with treatment capacity, this approach maximizes the reuse of SR1 water, minimizes reliance on freshwater, and guarantees compliance with contaminant concentration limits set by the sink SK1.

7. **Remaining Demand and Supply:**
   - After this allocation, it is shown that SK1 total mass flow demand is fully satisfied by treated SR1 water.
   - Therefore, SK1 does not require any additional mass flow or freshwater supply.
8. **Remaining Mass Flow in SR1:**
   - SR1 still has 1345 kg/year of mass flow available after supplying SK1.
   - This remaining flow can be allocated to other sinks or uses.
9. **Freshwater Requirement:**
   - No freshwater is required since SK1's entire demand is met by treated SR1.

5.2 Source 1 to Sink 1 Water Allocation with Treatment and Freshwater Minimization for Ultra Pure Sink Requirements

As mentioned previously, in this scenario, Sink 1 (SK1) requires ultra-pure water contaminant concentration. Since no source inherently meets this stringent requirement, Source 1 (SR1) with the lowest available contaminant concentration was identified for treatment and reuse to minimize the need for freshwater (FW), in this part I will mention the most important parts related to my MATLAB code, to see the procedures, strategies, comparisons and calculations.

The algorithm begins by evaluating how much of SR1 flow can be allocated to SK1 while considering two main constraints:

1. The available mass flow in SR1.
2. The required mass flow to satisfy SK1 demand.

Allocation Rule:

sr1_mass_flow_rate_supplied_to_sk1 = min(sr1_mass_flow_rate, sk1_required_mass_flow_rate)

This ensures that SK1 receives the maximum possible contribution from SR1 without exceeding its own demand or the capacity of SR1.

1. Treatment Strategy and Freshwater Substitution

Since SR1 water still contains contaminants, it must be treated before being sent to SK1. The algorithm calculates the treatable flow based on SR1 concentration:

treatable_flow = sr1_mass_flow_rate_supplied_to_sk1 / (sr1_concentration / 1000)

Converting from mass flow to volumetric flow helps estimate the amount of contaminated water that needs processing to meet the required volume of treated water.

The algorithm evaluates all available sources and selects SR1 as the cleanest available stream. A volume of 71.43 m^3/year is extracted from SR1 to meet the target for SK1.

The mass of contaminant to be removed during treatment is calculated using:

removed_mass_rate = treatable_flow × (sr1_concentration / 10^6)

In this specific case, the treatment removes 5 kg/year of contaminants from SR1, enabling partial substitution of freshwater with treated water.

Removed contaminant load during treatment: 1.0204×10^{-6} kg/year
Despite SR1 relatively low concentration, only a very small mass of contaminant needs to be removed to achieve compliance with SK1 standard.

If the treatable flow is insufficient to fully satisfy SK1 demand, the remaining volume is supplied by freshwater, as described by:

remaining_fw_needed = sk1_required_flow_rate - treatable_flow

2. Post-Allocation Source Status

After satisfying SK1's demand (partially or fully), the algorithm checks the remaining flow capacity in SR1:

SR1_remaining_flow = sr1_flow - treatable_flow

Remaining flow in SR1: 13,428.57 m^3/year
After supplying SK1, SR1 still holds significant capacity, suggesting potential for reuse in other sinks.

In the present study, both monetary and environmental impacts associated with the water pumping system from Sources to Sinks are thoroughly analyzed to quantify potential savings and emissions in the context of an optimized water network. The monetary cost of pumping was calculated based on the annual treated water flow and the unit cost of pumping in euros per cubic meter. The formula applied is:

Pumping Cost (€) = Treated Flow (m^3/year) × Cost per Unit Volume (€/m^3)

In this case, the unit cost was set at 0.14 €/m^3, which is a typical average for water utilities in Italy based on recent regulatory data from ARERA (Autorità di Regolazione per Energia Reti e Ambiente).

To complement the economic analysis, the environmental implications in terms of carbon dioxide (CO_2) emissions from the electricity used in pumping operations were also estimated. Pumping water requires mechanical energy, which, when supplied from Italy's power grid, corresponds to a known CO_2 emission footprint. The energy required to pump 1 cubic meter of water was calculated using the classical mechanical work equation for pumping:

$E = (\rho \times g \times H) / (\eta \times 3.6 \times 10^6)$

Where:

- ρ is the density of water (1000 kg/m^3),
- g is gravitational acceleration (9.81 m/s^2),
- H is the pump head
- η is the pump efficiency (assumed at 65%),
- 3.6×10^6 is the factor to convert Joules to kilowatt-hours (kWh).

Substituting the values yields an energy consumption of approximately 0.1258 kWh/m^3. This energy use per cubic meter is then multiplied by the CO_2 emission factor of electricity generation in Italy, which, according to ISPRA's 2023 report (Italian Institute for Environmental Protection and Research), is 0.22 kg CO_2/kWh. Therefore, the emissions per cubic meter of pumped water are:

CO_2 per m^3 = $0.1258 \times 0.22 \approx 0.02768$ kg CO_2/m^3

To calculate the total emissions for the full annual flow, the formula used is:
Total CO_2 (kg/year) = Flowrate (m^3/year) × CO_2 per m^3

This estimation reveals that each cubic meter of water pumped contributes about 27.7 grams of CO_2.

The presented analysis not only highlights the operational savings achievable through strategic reduction in water pumping but also quantifies the environmental benefit in terms of greenhouse gas reduction. This dual-perspective approach reinforces the importance of integrating both energy and environmental dimensions in water network optimization, especially in sustainability-focused municipal and industrial systems.

- **SR1 to SK1 pumping cost: €10/year**

The energy cost to pump 71.43 m^3/y from SR1 is minimal due to the small treated volume.

- **Estimated CO_2 emissions from SR1 to SK1 pumping: 1.9764 kg/year**

The carbon footprint for this operation is negligible, contributing minimally to total system emissions.

3. Freshwater Supply Metrics

- **SK1 unmet demand: 4928.57 m³/year → supplied by FW**
  Since treated SR1 is insufficient, the bulk of SK1 requirement is met by freshwater.
- **Freshwater cost (blending): €3597.86/year**
  This is the cost of purchasing and blending freshwater to meet the remaining demand.
- **Freshwater pumping cost: €690/year**
  The energy cost to deliver freshwater to SK1 is significantly higher than for the small reused stream, reflecting the higher volume.
- **CO_2 emissions from FW pumping: 136.37 kg/year**
  This shows the environmental impact of relying on freshwater, even before accounting for the upstream emissions related to FW production.

```
%% Checking if sk1_remaining_flow is bigger than zero if ( F sk1 > F sr1)
if sk1_remaining_flow > 0
   disp(['SK1 has ', num2str(sk1_remaining_flow), ' m^3/y still available that need to be supplied']);
FW_supplied = sk1_remaining_flow;
disp(' The rest of SK1 is supplied using FW');
disp([' The amount of FW supplied is ',num2str(FW_supplied),'m^3/y' ]);


%% FW Cost for Blending - Annual Basis
cost_freshwater = 0.73;        % €/m³
cost_pumping = 0.14;           % €/m³

% FW_supplied is in m³/year
cost_FW_blending__per_y = FW_supplied * cost_freshwater;
disp(['Total freshwater cost (blending) per year: €', num2str(cost_FW_blending__per_y)]);

pumping_cost_FW_per_y = FW_supplied * cost_pumping;
disp(['Total pumping cost for FW (blending) per year: €', num2str(pumping_cost_FW_per_y)]);
```

4. Efficiency and Environmental Benefit of Reuse

- Water reuse efficiency for SK1: 1.43%
  A very small fraction of SK1's demand is met by reuse, primarily due to its strict water quality requirement.
- CO_2 emissions avoided: 107.14 kg/year
  By reusing SR1 water, even at low volume, over 100 kg of CO_2 emissions are avoided annually, illustrating the environmental merit of reuse even at small scale.

```
%% Environmental Study between FW and SK1: CO₂ Emissions from Pumping (Padova, Italy)

% Parameters
efficiency_pump = 0.65;       % Pump + motor efficiency (decimal)
pump_head = 30;               % Head in meters
g = 9.81;                     % Gravitational acceleration (m/s²)
density_water = 1000;         % kg/m³
co2_emission_factor = 0.22;   % kg CO₂/kWh (Italy, 2023 avg)

% Convert yearly volume to total energy (in Wh)
% Total energy = (ρ × g × H × volume) / η
% Units: kg/m³ × m/s² × m × m³ = J; then convert to kWh
energy_J = FW_supplied * density_water * g * pump_head / efficiency_pump;
energy_kWh_per_year = energy_J / 3.6e6;  % 1 kWh = 3.6e6 J

% CO₂ emissions (kg/year)
CO2_fw_to_SK1_yearly = energy_kWh_per_year * co2_emission_factor;

disp(['Estimated CO₂ emissions per year from FW to SK1 pumping: ', num2str(CO2_fw_to_SK1_yearly), ' kg']);

%% Water Reuse Efficiency

total_flow_to_sk1 = treatable_flow + FW_supplied;
reuse_efficiency_sk1 = (treatable_flow / total_flow_to_sk1) * 100;
disp([' Water reuse efficiency for SK1 is: ', num2str(reuse_efficiency_sk1), '%']);
```

5. Key Performance Metrics

Annual Cost Savings: €62.14/year

Although the absolute financial savings might seem modest at €62.14/year, this value must be viewed in context:

- The treated volume reused is only 71.43 m^3/year, a tiny fraction (1.43%) of SK1's total demand.
- Despite this, the system still achieves positive cost savings, which proves the economic viability of even minimal reuse when integrated smartly.
- This also demonstrates scalability: If similar reuse logic is applied to other sinks with less strict purity needs, or if more of SR1 is treated for less demanding sinks, the cumulative savings could grow substantially.

Annual CO_2 Reduction: 497,907.81 kg CO_2/year

This is the most significant and impactful result of the analysis.

- A reduction of nearly half a million kilograms (498 tonnes) of CO_2 emissions per year from just one sink is extraordinary.
- This figure shows the hidden carbon cost of freshwater reliance particularly due to:
  - Energy-intensive pumping and sourcing of freshwater

Environmental Insight:

This demonstrates that even small-scale internal reuse systems can dramatically reduce a plant's carbon footprint, especially in sectors dealing with ultra-pure water or energy-intensive fluid handling.

While the financial benefit is small, the environmental benefit is massive and this validates the approach not just economically, but more importantly, as a climate-conscious decision. If the reuse strategy is extended across multiple sinks and sources, both savings and emissions reductions would scale up significantly, enhancing sustainability and compliance with carbon neutrality goals.

```
%% Environmental Benefit from Blending and Avoiding Full FW
% Virtual CO₂ emission factor for freshwater (based on embodied emissions)
virtual_CO2_FW_factor = 1.5;  % kg CO₂ per m³ of freshwater

% Flow avoided by using SR1 instead of FW (already in m³/year)
avoided_FW_m3_per_y = treatable_flow;

% CO₂ emissions avoided (kg/year)
avoided_CO2_FW_in_SK1 = avoided_FW_m3_per_y * virtual_CO2_FW_factor;

disp(['Estimated CO₂ emissions avoided by reusing SR1 instead of full FW: ', ...
    num2str(avoided_CO2_FW_in_SK1), ' kg per year']);
```

```
%% FW Only Cost (Annual Basis)
cost_freshwater = 0.73;         % €/m³
cost_pumping_fw_only = 0.14;    % €/m³
density_water = 1000;           % kg/m³
g = 9.81;                       % m/s²
pump_head = 30;                 % meters
efficiency_pump = 0.65;
co2_emission_factor = 0.22;     % kg CO₂/kWh

% Assume sk1_required_flow_rate is in m³/year
FW_flow_m3_per_y = sk1_required_flow_rate;

% Costs
% Freshwater purchase cost per year
cost_FW_only_per_y = FW_flow_m3_per_y * cost_freshwater;
disp(['Total freshwater supply cost to SK1 per year: ', num2str(cost_FW_only_per_y), ' €']);
```

5.3. Allocation Strategy Between Remain SR1 and SK2

Now that the analysis between Source 1 and Sink 1 has been completed, we proceed to evaluate the interaction between the remaining flow of SR1 and Sink 2.

In this section, the source to sink allocation algorithm focuses on determining how much of the available mass flow from the remaining portion of Source 1 can be used to satisfy the demand of Sink 2 . The matching process is governed by two critical parameters: the mass flow rate and the contaminant concentration of the streams involved.

The algorithm is structured to cover all possible scenarios through conditional statements, which evaluate the relationship between the contaminant concentrations and mass flow rates of Remain_SR1 and SK2. This comprehensive logic ensures that the program can adapt and correctly assign flow under varying input conditions, guaranteeing robustness and accuracy regardless of the specific plant data.

The following cases were implemented to describe and address all potential situations:

Case 1: Remain_SR1 concentration ≤ SK2 contaminant concentration required AND SK2 demand (m_SK2) > Remain_SR1 available mass flow

- In this case, Remain_SR1 cannot fully satisfy SK2 demand due to insufficient mass flow.
- The algorithm assigns all the remaining Remain_SR1 flow to SK2.
- The residual demand from SK2, after allocation from Remain_SR1, is supplied by Fresh Water (FW).
- The remaining mass flow in Remain_SR1 after supplying SK2 is calculated and reported.

Case 2: Remain_SR1 concentration ≤ SK2 contaminant concentration required AND SK2 demand ≤ Remain_SR1 available mass flow

- Here, Remain_SR1 is sufficiently clean and has enough mass flow to satisfy SK2 entire demand.
- SK2's full demand is supplied by Remain_SR1.
- There is no need for Fresh Water supplementation.
- The leftover mass flow in Remain_SR1 after allocation is updated accordingly.

Case 3: Remain_SR1 concentration > SK2 contaminant concentration required AND SK2 demand > Remain_SR1 available mass flow

- In this situation, Remain_SR1 contaminant concentration exceeds what SK2 can tolerate, so the supply must be adjusted based on concentration.
- The allocated mass flow from Remain_SR1 is calculated proportionally to the contaminant concentration limit required by SK2.
- SK2's remaining demand after this allocation is met with Fresh Water.
- The remaining mass flow in Remain_SR1 is recalculated and noted.

Case 4: Remain_SR1 concentration > SK2 contaminant concentration required AND SK2 demand ≤ Remain_SR1 available mass flow

- Although Remain_SR1 is more concentrated than SK2's requirement, its available mass flow is sufficient to cover SK2's demand.
- SK2 receives its full demand from Remain_SR1.
- Any additional mass flow left in Remain_SR1 is accounted for accordingly.

5.3.1 Explanation of the specific condition that applies to our plant

The following conditions were designed and implemented in my MATLAB code to cover all potential matching scenarios between water sources and sinks, based on mass flow rates and contaminant concentration levels. These generalized conditions ensure the model can handle any set of input data by classifying and processing the streams accordingly.

After the algorithm identified the specific condition for my plant, I will present the detailed calculations and explanations.

1.Plant Case Analysis

For our specific case:

- The mass flow demand of SK2, m_SK2 = 350 kg/y, is significantly less than the available mass flow in Remain_SR1, which is 1345 kg/y.
- The contaminant concentration in Remain_SR1 meets the requirement for SK2 (the concentration in SR1 is equal to or less than that required by SK2).

This condition corresponds to the case where the source (Remain_SR1) can fully satisfy the sink (SK2) demand without requiring additional supplementation from freshwater or other sources.

```
elseif sr1_concentration <= sk2_contaminant_concentration_required && m_sk2 <= SR1_remaining_mass_flow
   disp(['In this case we have that mSK2 which is ' num2str(m_sk2), ' is < than ' num2str(SR1_remaining_mass_flow), ' kg/y']);
sr1_mass_flow_rate_supplied_to_sk2 = m_sk2;

%% Display the value of sr1_flow_supplied
disp(['SR1 mass flow supplied: ', num2str(sr1_mass_flow_rate_supplied_to_sk2), ' kg/y']);


%% Calculate how much is the remaining mass flow requested by SK2 after being supplied by remain_sr1
disp('Now we are examining how much is the remaining mass flow rate needed by sk2 after being supplied by remain_sr1');
sk2_remaining_mass_flow_after_SR1 = m_sk2 - sr1_mass_flow_rate_supplied_to_sk2 ;  % Remaining flow needed

%% Seeing if the mass flow requested by SK2 is higher than zero
if sk2_remaining_mass_flow_after_SR1 > 0
   disp(['SK2 still have ', num2str(sk2_remaining_mass_flow_after_SR1), ' kg/y need to be supplied']);
m_FW_supplied_to_sk2 = sk2_remaining_mass_flow_after_SR1;
disp(' The rest of SK2 is supplied using FW');
disp([' The amount of FW supplied is ',num2str(m_FW_supplied_to_sk2),'kg/y' ]);
else
    disp('SK2 is satisfied');
end
```

2.Results and Interpretation

- SR1 mass flow supplied: The full SK2 demand of 350 kg/y is supplied from Remain_SR1.
- Remaining mass flow requested by SK2 after supply**:** Zero SK2 is fully satisfied by Remain_SR1.
- Remaining mass flow in Remain_SR1 after allocation: 995 kg/y remains available for allocation to other sinks or uses.

3.Implications

This outcome indicates an efficient source to sink allocation where:

- The available contaminated stream (Remain_SR1) is sufficient in both quantity and quality to fulfill SK2 requirements, avoiding the need for freshwater use.
- This reduces the operational cost and environmental footprint by maximizing reuse of existing streams.
- The surplus mass flow remaining in Remain_SR1 (995 kg/y) can potentially be allocated to additional sinks, improving overall water management within the system.

Flow Allocation

- SK2 demand: 7000 m³/year
- Supplied from remaining SR1: 5000 m³/year
- Supplied from freshwater (FW): 2000 m³/year
- Remaining flow in SR1 after supply: 8428.57 m³/year

```
elseif sr1_concentration <= sk2_contaminant_concentration_required && sk2_demand  <= SR1_remaining_flow
    disp(['Sk2 flow is ' num2str(sk2_demand), ' m^3/y that need to be supplied by remain SR1']);
   sr1_flow_supplied_to_sk2 =  sr1_mass_flow_rate_supplied_to_sk2 / (sr1_concentration / 1000);

%% Display the value of sr1_flow_supplied
disp(['SR1 flow supplied: ', num2str(sr1_flow_supplied_to_sk2), ' m^3/y']);
```

Interpretation:

About 71.43% of SK2's water needs are met by reusing SR1 water, which is a strong reuse rate, it was supplied using the following formula:

sr1_flow_supplied_to_sk2=sr1_mass_flow_rate_supplied_to_sk2 / (sr1_concentration / 1000)

Cost Analysis

- Pumping cost for SR1 → SK2: €700/year
- Pumping cost for FW → SK2**:** €280/year
- Freshwater blending cost: €1460/year
- Only freshwater supply cost to SK2: €5110/year
- Cost savings compared to FW-only supply: €4350/year

```
%% SR1 Pumping Cost

cost_pumping = 0.14;   % euro per m³
% sr1_flow_supplied_to_sk2 is in m³/y

% Pumping cost per year is just flow × cost per unit volume
pumping_cost_SR1_to_sk2_per_y = sr1_flow_supplied_to_sk2 * cost_pumping;

disp(['SR1 pumping cost to SK2 per year is: ', num2str(pumping_cost_SR1_to_sk2_per_y), ' euro']);
%% Environmental Study between SR1 and SK2: CO2 Emissions from Pumping (Padova, Italy)

% Input values
density_water = 1000;            % kg/m³
g = 9.81;                        % m/s²
pump_head = 30;                  % meters
efficiency_pump = 0.65;
co2_emission_factor = 0.22;      % kg CO2/kWh (Italy 2023 avg)

% Energy per m³ in kWh
energy_per_m3 = (density_water * g * pump_head) / (efficiency_pump * 3.6e6);  % kWh/m³

% CO₂ emissions per m³
co2_per_m3 = energy_per_m3 * co2_emission_factor;  % kg CO₂/m³

% Total CO₂ emissions per year
CO2_emissions_SR1_to_SK2 = co2_per_m3 * sr1_flow_supplied_to_sk2;  % kg CO₂/y

disp(['Estimated CO₂ emissions per year for SR1 to SK2 pumping: ', num2str(CO2_emissions_SR1_to_SK2), ' kg'])
```

Interpretation:

- Pumping cost for SR1 water is significantly higher than pumping FW, which suggests either SR1 is at a higher elevation or requires more energy to transport.
- Despite this, because using only freshwater itself is costly, the overall cost savings by using SR1 reuse is substantial (€4350 annually).
- Total freshwater supply cost (5110€) versus the savings (€4350) indicates that reusing SR1 water drastically reduces operational expenses.

Environmental Impact (CO_2 Emissions)

- CO_2 emissions for SR1 → SK2 pumping: 138.35 kg/year
- CO_2 emissions for FW → SK2 pumping: 55.34 kg/year
- Total CO_2 emissions for FW-only supply to SK2: 697,264.62 kg CO_2/year
- Estimated CO_2 avoided by reuse: 7500 kg/year
- Annual CO_2 reduction compared to FW-only supply: 697,126.27 kg/year

```
%% FW Cost for Blending - Annual Basis
cost_freshwater = 0.73;        % €/m³
cost_pumping = 0.14;           % €/m³

% FW_supplied is in m³/year
cost_FW_blending__per_y = FW_supplied_to_sk2 * cost_freshwater;
disp(['Total freshwater cost (blending) per year: €', num2str(cost_FW_blending__per_y )]);

pumping_cost_FW_per_y = FW_supplied_to_sk2 * cost_pumping;
disp(['Total pumping cost for FW (blending) per year: €', num2str(pumping_cost_FW_per_y)]);


%% Environmental Study between FW and SK2: CO₂ Emissions from Pumping (Padova, Italy)

% Parameters
efficiency_pump = 0.65;       % Pump + motor efficiency (decimal)
pump_head = 30;               % Head in meters
g = 9.81;                     % Gravitational acceleration (m/s²)
density_water = 1000;         % kg/m³
co2_emission_factor = 0.22;   % kg CO₂/kWh (Italy, 2023 avg)

% Convert yearly volume to total energy (in Wh)
% Total energy = (ρ × g × H × volume) / η
% Units: kg/m³ × m/s² × m × m³ = J; then convert to kWh
energy_J = FW_supplied_to_sk2 * density_water * g * pump_head / efficiency_pump;
energy_kWh_per_year = energy_J / 3.6e6;  % 1 kWh = 3.6e6 J

% CO₂ emissions (kg/year)
CO2_fw_to_SK2_yearly = energy_kWh_per_year * co2_emission_factor;

disp(['Estimated CO₂ emissions per year from FW to SK1 pumping: ', num2str(CO2_fw_to_SK2_yearly), ' kg']);
```

Interpretation:

- Pumping SR1 water emits more CO_2 per unit volume than pumping freshwater, probably due to higher pumping energy required.
- However, the huge reduction (~697,000 kg CO_2/year) when using SR1 compared to FW-only highlights the large carbon footprint of producing and sourcing freshwater, beyond just pumping.
- This CO_2 reduction is significant and shows the strong environmental benefit of water reuse in reducing greenhouse gas emissions.

Operational Efficiency & Sustainability

- Water reuse efficiency for SK2: 71.43%
- Remaining SR1 flow capacity: 8428.57 m³/year

```
%% Water Reuse Efficiency

total_flow_to_sk2 = sr1_flow_supplied_to_sk2 + FW_supplied_to_sk2;
reuse_efficiency_sk2 = (sr1_flow_supplied_to_sk2 / total_flow_to_sk2) * 100;
disp(['Water reuse efficiency for SK2 is: ', num2str(reuse_efficiency_sk2), '%']);

%% Environmental Benefit from Blending and Avoiding Full FW
% Virtual CO₂ emission factor for freshwater (based on embodied emissions)
virtual_CO2_FW_factor = 1.5;  % kg CO₂ per m³ of freshwater

% Flow avoided by using SR1 instead of FW (already in m³/year)
avoided_FW_m3_per_y = sr1_flow_supplied_to_sk2;

% CO₂ emissions avoided (kg/year)
avoided_CO2_FW_in_SK2 = avoided_FW_m3_per_y * virtual_CO2_FW_factor;

disp(['Estimated CO₂ emissions avoided by reusing SR1 instead of full FW: ', ...
    num2str(avoided_CO2_FW_in_SK2), ' kg per year']);
```

Interpretation:

- With over 70% reuse efficiency, SK2 relies heavily on internal water recycling, which reduces demand for costly and carbon-intensive freshwater.
- The substantial remaining SR1 flow (8428.57 m^3/year) suggests there is potential to further increase reuse or supply other sinks.
- Optimizing the use of this remaining SR1 water could lead to even more cost savings and emissions reductions.

This analyze clearly shows that reusing remaining SR1 water to supply SK2 is both economically and environmentally beneficial.

```
%% FW Only Cost (Annual Basis)
cost_freshwater = 0.73;        % €/m³
cost_pumping_fw_only = 0.14;   % €/m³
density_water = 1000;          % kg/m³
g = 9.81;                      % m/s²
pump_head = 30;                % meters
efficiency_pump = 0.65;
co2_emission_factor = 0.22;    % kg CO₂/kWh

% Assume sk2_required_flow_rate is in m³/year
FW_flow_m3_per_y = sk2_demand;

% Costs
% Freshwater purchase cost per year
cost_FW_only_per_y = FW_flow_m3_per_y * cost_freshwater;
disp(['Total freshwater supply cost to SK2 per year: ', num2str(cost_FW_only_per_y), ' €']);

% Pumping cost per year
pumping_cost_FW_only_per_y = FW_flow_m3_per_y * cost_pumping_fw_only;
disp(['Pumping cost of freshwater to SK2 per year: ', num2str(pumping_cost_FW_only_per_y), ' €']);

% Environmental Impact
% Power in Watts
power_fw_only_watt = (FW_flow_m3_per_y / (365*24*3600)) * density_water * g * pump_head / efficiency_pump;

% Convert to total annual kWh
power_fw_only_kWh_y = power_fw_only_watt * 3600 * 24 * 365 / 1e3;

% CO₂ emissions per year
CO2_fw_only_y = power_fw_only_kWh_y * co2_emission_factor;
disp(['Total CO₂ emissions for FW-only supply to SK2: ', num2str(CO2_fw_only_y), ' kg CO₂/year']);


%% Saving Cost through Blending (Annual Basis)

% Total annual costs
total_cost_FW_only = cost_FW_only_per_y + pumping_cost_FW_only_per_y;
total_cost_blend    = cost_FW_blending__per_y + pumping_cost_FW_per_y ;

% Cost savings per year
savings_cost_y = total_cost_FW_only - total_cost_blend;

% Total CO2 emissions
CO2_blend_y = CO2_fw_to_SK1_yearly + CO2_emissions_SR1_to_SK1;  % use your yearly vars
savings_co2_y = CO2_fw_only_y - CO2_blend_y;
```

5.4. Allocation Strategy Between Remain SR1 after SK2 and SK3

Now that the analysis between remain Source 1 and Sink 2 has been completed, we proceed to evaluate the interaction between the remaining flow of remain SR1 after sink 2 and Sink 3.

In this section, the source to sink allocation algorithm focuses on determining how much of the available mass flow from the remaining portion of Source 1 after sk2 can be used to satisfy the demand of Sink 3. The matching process is governed by two critical parameters: the mass flow rate and the contaminant concentration of the streams involved.

The algorithm is structured to cover all possible scenarios through conditional statements, which evaluate the relationship between the contaminant concentrations and mass flow rates of Remain_SR1 after SK2 and SK3. This comprehensive logic ensures that the program can adapt and correctly assign flow under varying input conditions, guaranteeing robustness and accuracy regardless of the specific plant data.

After analyzing the available data for SK3 and the remaining SR1 stream following supply to SK2, the following observations were made:

- The contaminant concentration in the remaining SR1 stream is lower than the required contaminant concentration for SK3. This indicates that the quality of SR1 water meets the purity requirements for SK3.
- However, the contaminant mass flow needed by SK3 (1,100 kg/year) exceeds the remaining contaminant mass flow available in SR1 after supplying SK2 (995 kg/year).

Based on these comparisons, the algorithm will proceed with the calculations according to the scenario defined by Condition 1.

If the contaminant concentration of SR1 is less than or equal to the contaminant concentration required by SK3, and the contaminant mass flow demand of SK3 exceeds the remaining contaminant mass flow available in SR1 after supplying SK2, then the mass flow rate of SR1 supplied to SK3 will be limited by the remaining available mass flow in SR1. In other words:

sr1_mass_flow_rate_supplied_to_sk3 = SR1_remaining_mass_flow_after_SK2;

This means SK3 will receive all the remaining flow from SR1, but additional sources or freshwater will be needed to meet its full demand.

Analysis of SR1 Remaining Flow after SK2 Supplying SK3 Results from MATLAB

After supplying SK2, the remaining SR1 contaminant mass flow available is 995 kg/year. However, the contaminant mass flow demand for SK3 is 1100 kg/year, which exceeds what SR1 can supply.

- SR1 mass flow supplied to SK3: 995 kg/year
- Remaining SK3 demand after SR1 supply: 1100 kg/year − 995 kg/year = 105 kg/year

Since SR1 cannot fully satisfy SK3's demand, the algorithm will look to the next available source to supply the remaining 105 kg/year. If no other source is available, this shortfall will be met using freshwater (FW).

- Remaining mass flow in SR1 after supplying SK3: 0 kg/year
  SR1 has been completely utilized and no longer holds any mass flow capacity.

Condition Check

The algorithm's condition for this case is:

if $sr1\_concentration \leq sk3\_contaminant\_concentration\_required \& m_{SK3} > m_{SR1,remain}$

Mass Flow Allocation

Since SR1 concentration meets SK3 requirements but the available mass flow in SR1 is insufficient, the algorithm limits the mass flow supplied to SK3 as:

$m_{SR1 \rightarrow SK3} = m_{SR1,remain} = 995 \text{ kg/year}$

This means SR1 will supply all of its remaining mass flow to SK3, but SK3 will still require an additional:

$m_{SK3,remaining} = m_{SK3} - m_{SR1 \rightarrow SK3} = 1100 - 995 = 105 \text{ kg/year}$

Flow Allocation

1. Supply Flow Matching

- **Total Demand of SK3**:
  SK3 requires a total of 22,000 m^3/year of water to meet its process needs.
- **Available Supply from SR1**:
  After supplying SK2, SR1 has 8,428.57 m^3/year of water available.
  This is not sufficient to fully meet SK3's needs.
- **SR1 Contribution to SK3**:
  - Flow Supplied: 8,428.5714 m^3/year
  - Mass Flow Supplied: Equivalent to the full remaining mass from SR1
  - This accounts for 38.3% of SK3 total flow demand.
- **Remaining Flow Requirement of SK3**:
  - SK3 still needs 13,571.4286 m^3/year to be covered, or about 61.7% of its demand.
  - This shortfall is handled using freshwater (FW) supply in the form of blending.

2. Cost Analysis

Costs Incurred for SR1-to-SK3 Reuse:

- Pumping Cost (SR1 → SK3): €1,180 per year

Freshwater Usage for Remaining SK3 Demand:

- Freshwater Supplied: 13,571.43 m^3/year
- Freshwater Cost (Blending): €9,907.14/year
- FW Pumping Cost: €280/year

FW-Only Scenario (No Reuse):

- If the full 22,000 m^3/year had been supplied using freshwater only:
  - FW Cost: €16,060/year
  - FW Pumping Cost**:** €3,080/year

3. Cost Savings

Using partial reuse of SR1 for SK3 instead of full FW supply results in:

- Total Annual Cost Savings**:**
  €16,060 (FW-only) – (€9,907.14 + €280 + €1,180) = €8,952.86 saved per year

This reflects a 55.8% cost reduction compared to full freshwater reliance a significant economic benefit of integrating reuse.

4. Environmental Impact: CO_2 Emissions

Reuse Emissions (SR1 → SK3):

- Pumping Emissions**:** 233.21 kg CO_2/year

FW Emissions (13,571.43 m^3 only):

- Pumping Emissions**:** 375.51 kg CO_2/year

FW-Only Scenario Emissions:

- Total Emissions**:** 2,191,403.08 kg CO_2/year

CO_2 Avoidance and Reduction

- CO_2 Emissions Avoided by reusing SR1 instead of using FW for the same flow: 12,642.86 kg CO_2/year
- Total Annual Emissions Reduction Compared to FW-only scenario**:** 2,190,794.35 kg CO_2/year

This is a 99.98% reduction in emissions a massive sustainability impact from partial reuse implementation.

5. Water Reuse Efficiency

- Water Reuse Efficiency for SK3 is more than 70% of SK3's needs were met through reuse, drastically reducing the burden on freshwater systems.

Even partial reuse of SR1 for SK3 brings significant economic and environmental benefits, demonstrating the power of optimized water reuse strategies.

The reuse strategy allowed a reduction in CO_2 emissions by over 2 million kg per year, which is equivalent to removing more than 470 passenger cars from the road annually.

Additionally, the financial savings make it attractive from an investment and operational perspective, especially in large industrial processes or utilities. This analysis reinforces the importance of Source-Sink Matching with blending strategies.

5.5. Allocation Strategy Between SR2 and Remain SK3

Now that the analysis with SR1 has been completed, we proceed to evaluate the interaction between SR2 and remain Sink 3.

In this section, the source to sink allocation algorithm focuses on determining how much of the available mass flow from Source 2 can be used to satisfy the demand of remain_Sink 3. The matching process is governed by two critical parameters: the mass flow rate and the contaminant concentration of the streams involved.

The algorithm is structured to cover all possible scenarios through conditional statements, which evaluate the relationship between the contaminant concentrations and mass flow rates of SR2 and remain SK3. This comprehensive logic ensures that the program can adapt and correctly assign flow under varying input conditions, guaranteeing robustness and accuracy regardless of the specific plant data.

After analyzing the available data for the remaining SK3 demand and the SR2 stream, the following observations were made:

- The contaminant concentration in SR2 is higher than the contaminant concentration required by SK3. This indicates that SR2 water is more concentrated than needed and can be blended to meet the SK3 specifications.
- The contaminant mass flow still required by SK3 after partial supply is less than the total contaminant mass flow available in SR2. This means SR2 has sufficient contaminant capacity to fully satisfy the remaining demand of SK3.

Based on these comparisons, the algorithm proceeds with the calculations according to the scenario defined by Condition 3.

If the contaminant concentration of SR2 is greater than the contaminant concentration required by SK3, and the remaining contaminant mass flow demand of SK3 is less than or equal to the contaminant mass available in SR2, then the contaminant mass supplied by SR2 to SK3 will be exactly equal to the remaining mass demand of SK3. In other words:

sr2_mass_flow_rate_supplied_to_sk3 = sk3_remaining_mass_flow_after_SR1;

This implies that SR2 will supply 105 kg/year of contaminants to SK3.

As a result, the entire remaining demand of SK3 is successfully covered by SR2 without requiring any additional freshwater input. The excess capacity in SR2 remains available for potential use in other sink streams.

1. Mass Flow Allocation

- SR2 Available Contaminant Mass Flow: 350 kg/year
- SK3 Remaining Mass Demand: 105 kg/year
- Condition Met: SR2 concentration > SK3 requirement, and SR2 mass flow is greater than SK3's remaining demand.

Mass Flow Supplied from SR2 to SK3:

- $m_{SR2 \rightarrow SK3} = 105$ kg/year
- Remaining mass in SR2 after SK3 supply: $m_{SR2,remain} = 350 - 105 = 245$ kg/year

Flow Allocation and Economic-Environmental Analysis: SR2 → Remaining SK3

1. Supply Flow Matching

- Total Remaining Demand of SK3:
  SK3 needs 13,571.43 m³/year total. After partial supply from SR2, the remaining flow needed by SK3 is 12,521.43 m³/year.
- Available Supply from SR2:
  SR2 has 2,500 m³/year of flow available in total, of which 1,050 m³/year will be supplied to SK3.
  The remaining SR2 flow available is 1,450 m³/year will be supplied partially by the next available source below the pinch, source 3 and the rest using FW.

2. Cost Analysis

- Pumping Cost for SR2: €147/year for 1,050 m³ pumped

3. Environmental Analysis

- Estimated CO_2 emissions per year from SR2 to SK3 pumping: 29.0527 kg

After the partial supply of SK3 water demand by SR2, which provided a flow of 1,050 m^3/year, the remaining flow requirement for SK3 still amounts to 12,521.43 m^3/year. This shortfall necessitates the utilization of additional sources to meet the process water demand. The subsequent step involves evaluating the availability and suitability of the next potential source to partially or fully supply this remaining volume, while ensuring that water quality and blending constraints are respected.

5.6. Allocation Strategy Between SR3 and Remain SK3 after SK2

In this part, trying to treat water from SR3 (contaminated at 140 ppm) to supply SK3, which requires 0 ppm contain an issue because:

- SK3 remaining mass need after SR2 is equal to 0 kg/year meaning it is been already satisfied
- So when you doing treatable flow = m / (C / 1000) will get a zero, making it impossible to calculate how much flow from SR3 can be reused.
- But this is misleading because flow from SR3 can be used, as long as it is treated to 0 ppm.

Correct Approach:

Since the mass to match is equal zero, the logic will be reversed by searching what is the maximum volume of water that can be treated from SR3 to reach 0 ppm and supply to SK3

That is:

- No longer mass limitation
- Flow-limited, based on how much SK3 still needs.

By using the following formula: treatable_volume = min(sr3_available_flow, sk3_remaining_flow_demand)

- Any flow from SR3 can be treated to bring it to 0 ppm
- The only limit is:
    - How much SR3 has
    - How much flow SK3 still needs

So this part could be explained in the following:
Given that the SK3 sink requires water at 0 ppm contaminant concentration, the mass flow requirement after being partially supplied by SR2 is effectively zero. This means that a direct mass based allocation from SR3 is not applicable, as it leads to undefined or zero treatable flow calculations. However, since SK3 still has a remaining demand of 12,521.43 m³/year, the allocation strategy must be reoriented to focus on flow rather than contaminant mass.

In this context, a portion of the available flow from SR3 can be treated to meet the 0 ppm requirement of SK3. The decision is therefore based on determining the maximum amount of water that can be treated from SR3 and reused by SK3, rather than attempting to match a non-existent contaminant mass flow. The treatable flow is limited by the lesser of SR3 available flow and SK3 remaining flow demand. Accordingly, 12,521.43 m³/year of water is identified from SR3, assumed to be fully treated to remove contaminants before being reused to fulfill SK3 remaining water demand. This strategy not only eliminates the need for additional freshwater but also enhances the reuse efficiency by leveraging treatment processes for higher-contaminant sources.

Water Reuse Analysis: Source 3 (SR3) → Sink 3 (SK3)

1. Supply Flow Matching and Treatment Decision

- Total Remaining Demand of SK3: After partial supply from SR2, SK3 still requires 12,521.43 m³/year of water.
- Contaminant Requirement: SK3 requires ultra-pure water at 0 ppm contaminant concentration. Since SR3 has a concentration of 140 ppm, direct use is not possible. Instead, a treatment process is initiated to bring the contaminant level from 140 ppm to 0 ppm.
- Available from SR3:
    - Total Flow Available: 42,187.00 m³/year
    - Mass Flow Available: 7,593.6 kg/year
- Allocated for Treatment and Reuse:
    - Treated Flow from SR3: 12,521.43 m³/year (supplied to SK3)
    - Contaminant Removed During Treatment**:** 89,438,775.51 kg/year, demonstrating the scale of the purification required.
- Post-Treatment: SK3's remaining demand is fully satisfied after treatment.
    - Remaining SR3 Flow**:** 29,665.57 m³/year still available.
    - Remaining SR3 Mass Flow**:** Unconsumed mass remains usable for other sinks or processes**.**

2. Economic Analysis

Reuse Costs from SR3:

- Water Treatment Cost**:** €6,010.29/year
- Pumping Cost from SR3 to SK3: €1,753/year
- Total Cost of Reuse**:** €7,763.29/year

FW-Only Scenario (Without Reuse):

- Total Cost of Supplying SK3 Fully with FW**:** €16,060/year
- FW Pumping Cost**:** €3,080/year
- Total Cost**:** €19,140/year

Annual Cost Savings**:**

By partially reusing SR3 and minimizing freshwater use:

- Total Savings**:**
  €19,140 – (€7,763.29 + €11,807.14) = €7332.86/year
- Cost Reduction**:** ~38.3% over FW-only scenario.

3. Environmental Impact: CO_2 Emissions

Emissions from Reuse Strategy:

- CO_2 from SR3 Treatment & Pumping: 25,042.86 kg CO_2/year
- CO_2 from FW Pumping (for remaining SK3 demand): 375.511 kg CO_2/year
- Total Emissions with Reuse**:** 25,418.37 kg CO_2/year

FW-Only Scenario:

- Total Emissions (Full FW Supply to SK3)**:** 2,191,403.08 kg CO_2/year

Annual CO_2 Emissions Reduction**:**

- **Avoided Emissions**:
  2,191,403.08 – 25,418.37 = 2,166,984.71 kg CO_2/year
- Reduction Percentage**:** > 99%, a massive drop in environmental burden.

4. Water Reuse Efficiency

- Water Reuse Efficiency for SK3: 47.99%
- This indicates that nearly half of SK3's water needs were met via internal reuse, significantly reducing dependency on freshwater sources.

5. Summary of Benefits

- **SK3 Fully Satisfied**: With treated water and blended freshwater.
- **Cost Savings**: Over €7,300 saved annually.
- **CO_2 Emissions Reduced**: By more than 2.16 million kg per year.
- **Reuse Efficiency**: Nearly 48% of SK3's flow supplied through reuse.
- **Circular Water Use Strategy**: Demonstrates a clear case for reuse + treatment over full freshwater reliance.

6. Source and Sink Allocation – Region Above the Pinch Point

6.1. Allocation Strategy Between SR4 and Sink4

Now that the analysis between other streams has been conducted, we evaluate the potential for reuse between Source SR4 and Sink4 in the above the pinch region.

This region includes sinks that can tolerate higher contaminant concentrations, hence offering flexibility for internal water reuse. However, freshwater is prohibited in this region to avoid inefficiencies.

This section applies the source-to-sink allocation algorithm, determining how much of the available mass flow in SR4 can be reused to satisfy the water demand of Sink4, based on both contaminant concentration compatibility and mass flow balance.

The Following Cases Were Considered:

Case 1: SR4 concentration ≤ Sink4 requirement AND Sink4 demand > SR4 available mass flow
• SR4 water is sufficiently clean for Sink4.
• But the mass flow in SR4 (5,175 kg/y) is less than Sink4's demand (4,900 kg/y) → Not true (SR4 > Sink4).

Case 2: SR4 concentration ≤ Sink4 requirement AND Sink4 demand ≤ SR4 available mass flow
Applicable in my case.
• Contaminant concentration in SR4 is 190 ppm, which is higher than Sink4's requirement of < 140 ppm, so this case is not valid.

Case 3: SR4 concentration > Sink4 requirement AND Sink4 demand > SR4 available mass flow
• Not valid because Sink4 demand (4,900 kg/y) is less than SR4 available mass flow (5,175 kg/y).

Case 4: SR4 concentration > Sink4 requirement AND Sink4 demand ≤ SR4 available mass flow
This is the condition that applies to my plant.
• SR4 concentration (190 ppm) exceeds Sink4 limit (140 ppm).
• Despite that, the available mass flow in SR4 (5,175 kg/y) is sufficient to meet Sink4 demand (4,900 kg/y).
• So, we partially allocate SR4 to Sink4 based on the maximum allowable contaminant load, ensuring not to exceed the limit.

6.2 Plant-Specific Case Summary:

- Source SR4: 5,175 kg/y at 190 ppm
- Sink4 requirement: 4,900 kg/y at <140 ppm

Since SR4 exceeds the contaminant concentration limit of Sink4, only a portion of SR4 can be allocated. The allowable mass flow (Q) from SR4 to Sink4 is calculated using:

Q = Cmax×Vsink / Csource =140×35,000190 = 25,789.47 m3/y

But SR4 is only 22,500 m^3/y, so:

Mass Flow from SR4=22,500×1901,000,000=4,275 kg/y<4,900 kg/y

Hence, SR4 can partially satisfy Sink4, SR4 must be sent to discharge

Q = Cmax×Mallowed / Csource =140×4900/190 = 3610.53 m3/y

6.3 Economic and environmental analysis between Source SR4 and Sink SK4

Reuse Costs from SR4:

- Water Treatment Cost**:** €4,900.00/year
- Pumping Cost from SR4 to SK4**:** €1,260.00/year
- Total Cost of Reuse**:** €6,160.00/year

FW-Only Scenario (Without Reuse):

- Total Cost of Supplying SK4 Fully with FW**:** €14,700.00/year
- FW Pumping Cost**:** €2,050.00/year
- Total Cost**:** €16,750.00/year

Annual Cost Savings**:**

By partially reusing SR4 and minimizing freshwater use:

- Total Savings**:**

  16,750 – (6,160 + 12,330) = €2,260.00/year

- Cost Reduction**:** 13.5%

Environmental Impact: CO_2 Emissions

Emissions from Reuse Strategy:

- CO_2 from SR4 Treatment & Pumping**:** 18,550.00 kg CO_2/year

FW-Only Scenario:

- Total Emissions (Full FW Supply to SK4)**:** 1,644,000.00 kg CO_2/year

Annual CO_2 Emissions Reduction:

- Avoided Emissions**:**

  1,644,000–18,862.50 = 1,625,450.00 kg CO_2/year

- High Reduction Percentage showing major environmental improvement.

Water Reuse Efficiency

- Water Reuse Efficiency for SK4**:** 30.85%
- This means that nearly one-third of SK4 water needs were met via treated internal reuse, cutting down on freshwater dependency.

Summary of Benefits (SR4 → SK4)

- Cost Savings: Over €2,260 saved annually**.**
- Reuse Efficiency**:** About 31% of SK4's demand met internally.
- Sustainable Water Strategy**:** Strong case for combining reuse to optimize cost and environmental performance.

6.Key Accomplishments and Novel Contributions and Innovative Contributions to Water Reuse Optimization

I chose the blending strategy because it provides the most cost-effective and feasible solution. While treatment seems slightly cheaper per second, it comes with significant infrastructure and operational costs. And using only fresh water is both environmentally and economically inefficient. Blending allows for reuse, keeps concentrations within limits, and minimizes operational costs making it the most efficient and sustainable approach.

In my thesis, I did not just applied blending techniques, instead i optimized, enhanced, and extended it creatively by performing the followings:

Proposing Smart Innovations

1. Dynamic Blending Algorithm (with MATLAB)

Instead of using static proportions (e.g., always 50/50), I built a dynamic algorithm in MATLAB that selects the optimal SR/FW ratio in real time based on:

- availability of sources
- target sink concentration
- cost per m^3
- pumping distances and energy use
- environmental impact
- CO2 reductions
- Water reuse efficiency
- Cost reduction

2. Cost-Weighted Optimization Function

I created an optimization model that minimizes total cost by blending in such a way that satisfies constraints (concentration, flow, etc.) while also accounting for pumping energy. This is more advanced than typical fixed blending.

3. Multi-Sink Network with Source Allocation Curves (SSAC)

I extended the idea by integrating blending into a multi sink network. I used Source and Sink Allocation to visualize and select the most cost-effective blending paths across the entire water network.

4. Sensitivity Analysis: Cost vs. Concentration Trade-Off

I conducted a sensitivity analysis to show how the cost varies with stricter concentration limits, source availability, or varying prices allowing decision-makers to choose best operating points.″

5. Environmental and Sustainability Benefit Quantification

In addition to cost, I calculated the freshwater savings (m^3/h) and CO_2 emissions avoided by reducing freshwater pumping and treatment. So not only blending but measuring the environmental impact, which is essential today. Adding a CO_2 footprint comparison per option.

6. Public, modular, and cost-optimized blending tools in MATLAB

Most of the work in the literature:

- Focuses on mathematical models (equations and graphs),
- Not fully implemented dynamic simulation tools,
- If there's code, it's often not shared,
- Rarely includes real-time cost analysis or adaptive allocation.
- Few have built a full, dynamic, source-sink blending engine with economic objectives and real-time adaptability
- Whole code was done by myself

To the best of my knowledge, while blending has been theoretically studied, there are no accessible, dynamic, and cost-based MATLAB tools that implement it for industrial reuse scenarios. I created this engine from scratch to fill that gap, making it flexible, automated, and scalable and applied it for the Waste-to-Energy plant "San Lazzaro" of Padova. This can be used as a base for industries to build smart reuse planners integrated with sensors, bridging academic theory and real time engineering.

Conclusion Part 2: Water Treatment through Water Pinch Analysis and Reuse Optimization

This second part of the study has focused on applying Water Pinch Analysis (WPA) to enhance the water management strategy of the San Lazzaro Waste-to-Energy (WtE) plant, aiming to reduce both freshwater consumption and wastewater discharge. Through a structured and systematic approach, all significant water sources and sinks within the facility were identified, characterized, and analyzed based on flowrate and quality requirements.

Water enters the San Lazzaro plant from three main sources: the municipal public grid (providing treated water), the Piovego Canal (supplying raw surface water), and rainfall (collected as a supplementary input). These are distributed across various operations such as boiler feedwater conditioning, equipment and yard washing, ash quenching, and cooling circuits. Post-usage, the water exits as wastewater from processes like boiler blowdown, cooling loop discharge, ash quenching, cleaning activities, and the initial runoff from rain (first-flush water). Despite being contaminated, many of these wastewater streams still hold reuse potential in less purity-sensitive processes.

By implementing WPA, strategic internal reuse opportunities were uncovered between selected sources and sinks. Notably, the reuse strategy demonstrated a clear technical and environmental advantage. Through this reuse strategy, water needs were satisfied internally, reducing its reliance on freshwater. Economically, the partial reuse scenario resulted in annual cost savings, reflecting a reduction compared to the freshwater only scenario. Environmentally, the impact was even more significant where annual CO_2 emissions were reduced representing a cut in emissions from avoided freshwater extraction and pumping.

The WPA framework revealed that streams such as SRC1, SRC2, and SRC3 can be paired with corresponding sinks (SINK1, SINK2, SINK3), laying the foundation for a fully integrated water reuse network. While high-purity demands like boiler feedwater still require treated freshwater, lower-quality processes such as cleaning and cooling can be reliably served through treated wastewater. This selective targeting and cascading use of water flows enables circularity and resource optimization within the plant.

In summary, this part of the study confirms that WPA is a powerful tool for improving water sustainability in complex industrial operations. When combined with practical reuse infrastructure and quality matching strategies, it enables significant cost savings, operational efficiency, and environmental benefits. The San Lazzaro WtE plant serves as a compelling example of how targeted water reuse can transform a linear water system into a circular and resilient one.

References

[1]
Klemeš, J.J., Varbanov, P.S., Wan Alwi, S.R., & Manan, Z.A. (2013). Process Integration and

Intensification: Saving Energy, Water and Resources. De Gruyter Graduate. file:///C:/Users/USER/Downloads/process-integration-and-intensification-saving-energy-water-and-resources-9783110306859_compress.pdf

[2]

Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy" by Bodo Linnhoff et al. (1982): file:///C:/Users/USER/Downloads/Pinch_Analysis_and_Process_Integration_1.pdf

[3]

Process Integration: A Comprehensive Approach to Energy, Mass, and Water Minimization" by El-Halwagi (2006): file:///C:/Users/USER/Downloads/Process_Integration.pdf

[4]

Handbook of Process Integration (PI)" edited by Janusz K. Klemeš file:///C:/Users/USER/Downloads/34.pdf

[5]

Sustainable Design through Process Integration" by El-Halwagi (2012)

https://archive.org/details/sustainabledesig0000elha/page/n3/mode/2up

[6]

Prof.Lazzaretto, Andrea. *Pinch Technology: Composite Curves and Minimum Energy Exchange with the External Utilities*. Corso di Sistemi Energetici, University of Padua, STEM eLearning, https://stem.elearning.unipd.it/pluginfile.php/722621/mod_resource/content/1/20%20Pinch%20Technology_%20Curve%20Composite%20e%20utility.pdf.

[7]

Prof. Lazzaretto, Andrea. *Pinch Technology: Grand Composite Curves and Construction of the Heat Exchanger Networks (HENs)*. *Energy Systems Course*, University of Padua, STEM eLearning, https://stem.elearning.unipd.it/pluginfile.php/727092/mod_resource/content/1/24%20Pinch%20Technology_%20GCC_HEN%20MER_for%20students.pdf

[8]

San Lazzaro Waste-to-Energy Plant. (2025). *Process and wastewater data spreadsheet* [Unpublished Excel file]. Provided by plant engineers during thesis collaboration.

[9]

Piacenza, E. (2022). *Analysis and optimization of the processes in a physical-chemical wastewater treatment plant serving a waste-to-energy plant* (Master's thesis). University of Padua. *(Unpublished manuscript)*

[10]

Waste-to-Energy Plant in Padua*. Gruppo Hera:*

https://ha.gruppohera.it/plants-list/waste-to-energy-plant-in-padua1.

[11]

Klemeš, J.J., Varbanov, P.S., Wan Alwi, S.R., & Manan, Z.A. (2013). *Process Integration and Intensification: Saving Energy, Water and Resources*. De Gruyter Graduate.

[12]

- **El-Halwagi, M.M. and Manousiouthakis, V. (1989)**. *Synthesis of mass-exchange networks, AIChE Journal, 35 (8), 1233–1244*. DOI: 10.1002/aic.690350802.

[13]

- **Dhole, V.R., Ramchandani, N., Tainsh, R.A. and Wasilewski, M. (1996)**. *Make your process water pay for itself, Chemical Engineering, 103, 100–103*.

[14]

- **Foo, D.C.Y. (2009)**. *State-of-the-art review of Pinch Analysis techniques for water network synthesis, Industrial and Engineering Chemistry Research, 48 (11), 5125–5159*

[15]

- Reay, D., Ramshaw, C., & Harvey, A. (2008). *Process intensification: Engineering for efficiency, sustainability and flexibility* (2nd ed.). Butterworth-Heinemann.