ENERGY-EFFICIENT HEAT INTEGRATION IN CATALYTIC REFORMING: A GAMS-BASED MILP OPTIMIZATION APPROACH

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Abstract

Energy integration plays a crucial role in improving the efficiency and sustainability of petroleum refineries, particularly in catalytic reforming unit (CRU), which is among the most energy-intensive processes. This study presents the design and simulation of an integrated Heat Exchanger Network (HEN) for a CRU using the General Algebraic Modelling System (GAMS). Accurate process stream data, supply/target temperatures, heat capacity flow rates, and enthalpies were extracted and validated. Pinch analysis was applied to identify minimum utility targets, serving as a baseline for optimization. A Mixed-Integer Linear Programming (MILP) model was developed to optimize stream matching and reduce external utility demand. The model was implemented in GAMS and solved using CPLEX. Composite curves, heat cascade diagram, and sensitivity analyses were used to evaluate performance. Results showed significant energy savings, with hot and cold utility needs reduced by 57.1 % and 62.8 %, respectively, compared to conventional systems. The optimized network comprised 12 exchangers with stream splits, enabling effective heat recovery. A 10 °C minimum temperature difference was identified as the best compromise between energy savings and capital cost. This integrated approach combining pinch analysis and MILP optimization effectively enhances refinery energy efficiency and supports broader sustainability goals.

Keywords

Energy integration, GAMS modelling, Heat exchanger networks, MILP optimization, Pinch analysis, Refinery energy efficiency, Utility cost reduction

1. INTRODUCTION

Petroleum refining continues to be one of the most critical and energy-demanding industries worldwide. At its core, it's all about converting crude oil into a range of high-value products like transportation fuels, lubricants, and raw materials for petrochemicals (Rafeek et al., 2025; Zhang et al., 2024). Among the many units involved, the catalytic reforming unit (CRU) plays a particularly key role in this process. Its primary function is to convert low-octane naphtha into high-octane reformate, an essential blending component for gasoline and to generate hydrogen required by hydroprocessing units downstream (Osman and Mirghani, 2022). Reformate is also a major source of key aromatic compounds such as benzene, toluene, and xylenes (BTX), which are critical for the petrochemical industry.

Catalytic reforming operates under relatively harsh process conditions, typically involving temperatures between 450–520 °C and pressures ranging from 5 to 45 bar (Rodríguez-Seco et al., 2022; Thanh et al., 2012). These conditions are necessary to drive a series of complex reactions, including dehydrogenation, isomerization, and cyclization. The efficiency and selectivity of these reactions rely heavily on bifunctional catalysts, most commonly platinum supported on alumina, which facilitate both metallic and acidic functionalities within the reactor (Hadzihafizovic, 2024). The absence of such catalysts would necessitate much more extreme conditions to achieve similar yields, making the process economically and environmentally impractical (Akhtar, 2024).

Given the high energy demands of CRU and other refinery units, process integration and heat recovery have become crucial for improving overall efficiency. Heat exchanger networks (HENs) play a key role in capturing waste heat and reusing it within the process, thereby reducing the need for external utilities (Osman and Mirghani, 2022; Udochukwu, 2022). Over the years, various strategies have been proposed for HEN synthesis and retrofitting. Among them, pinch analysis has emerged as a widely adopted technique due to its systematic approach to identifying thermodynamically optimal heat recovery targets and stream matches (Abubakar, 2020).

Pinch technology has long been used in the process industries to boost thermal efficiency by identifying the minimum heating and cooling requirements of a system. This approach helps streamline the design of heat exchanger networks (HENs), aiming to reduce energy losses and improve overall heat recovery. Numerous studies have highlighted the potential of pinch-based strategies. It functions both for retrofits and new designs to deliver notable utility savings and better cost performance, especially in refinery units like crude distillation and catalytic reforming (Abubakar, 2020).

However, conventional pinch methods come with limitations when dealing with complex industrial systems (Klemeš et al., 2018). They often fall short in handling discrete design decisions, such as stream matches, flow splitting, and exchanger placement, within a unified optimization framework. To address these challenges, researchers have increasingly explored hybrid methods that combine pinch analysis with mathematical optimization, most notably Mixed-Integer Linear Programming (MILP) (Ortiz-Gutiérrez et al., 2025). These integrated approaches allow for more flexible and detailed modelling of HEN superstructures, accounting for both continuous and discrete variables (Yang et al., 2022).

In this context, the General Algebraic Modelling System (GAMS) has emerged as a powerful platform for formulating and solving large-scale MILP models. It enables rigorous optimization of heat recovery networks, balancing capital costs with utility savings. Recent studies using GAMS-based frameworks have shown promising results across various refining processes (Mena-Pacheco and Tuza, 2025; Isafiade, 2023). Yet, many of these efforts are still focused on simplified systems, and there remains a gap in applying these tools to more realistic catalytic reforming unit (CRU) setups, where multiple process streams interact under strict operational constraints.

This study aims to bridge that gap by developing and simulating an optimized heat exchanger network for a CRU, using a hybrid framework that integrates pinch analysis with MILP-based optimization in GAMS. The primary goal is to minimize external utility demands while ensuring the network remains both feasible and economically viable. By combining thermodynamic energy targeting with detailed network synthesis, the approach provides a more practical and holistic solution for energy integration in CRU.

Simulation results include utility savings, composite and grand composite curves, and sensitivity analyses based on the minimum temperature approach (ΔTmin), all of which help demonstrate the flexibility and effectiveness of the proposed method. While the approach comes with its own challenges, this work tackles key methodological gaps and applies the framework to a realistic industrial scenario, offering practical insights for advancing energy integration in modern refining operations.

2. MATERIALS AND METHOD

2.1 Process Description and Data Collection

This study focuses on the catalytic reforming unit (CRU) of a petroleum refinery, an energy-intensive process requiring significant thermal input for feed preheating and product separation (Udochukwu, 2022). Stream data were obtained from validated literature sources as shown in Table 1, representing both hot and cold streams in the CRU. Each stream was characterized by supply and target temperatures (°C), heat capacity flow rate (MCp, kW/°C) and total enthalpy change (kW) was calculated.

Data consistency was verified through energy balance checks to ensure that the total heat released by hot streams equaled the heat absorbed by cold streams, within acceptable limits (Fang and Tsao, 2008).

The following assumptions were made:

i. Constant specific heat (Cp)
ii. Negligible pressure drops and heat loss
iii. No phase changes
iv. Counter-current flow configuration

2.2 Energy Targeting via Pinch Analysis

Pinch analysis was performed to determine the minimum utility requirements of the process. Temperature intervals were constructed from the combined stream data, adjusted using a minimum temperature difference (ΔTmin) of 10 °C (Udochukwu, 2022). The following energy targets were calculated:

i. Minimum hot utility (QHmin)
ii. Minimum cold utility (QCmin)

Heat cascades and composite curves were used to identify the pinch point and quantify heat recovery potential.

Table 1 Data Extracted from Catalytic Reforming Unit (CRU) (Udochukwu, 2022)

2.3

S/N	Type	Ts (°C)	Tt (°C)	MCP (kW/°C)	Enthalpy (kW)
1	Cold	142	449	157.02	48206.35
2	Cold	449	500	141.38	7210.60
3	Cold	414	500	141.99	12211.50
4	Cold	449	500	143.66	7326.90
5	Cold	466	500	143.66	4884.60
6	Cold	40	108	17.79	1209.52
7	Cold	40	188	51.08	7559.50
8	Cold	235	254	214.88	4082.13
9	Hot	500	133	131.35	48206.35
10	Hot	133	48	172.17	14677.06
11	Hot	48	40	138.11	1104.85
12	Hot	56	40	60.33	965.29
13	Hot	108	40	20.52	1395.60
14	Hot	235	92	52.86	7559.50
15	Hot	92	48	42.29	1860.80
16	Hot	48	40	39.25	314.01
17	Hot	76	48	62.30	1744.50
18	Hot	48	40	26.17	209.35

Mathematical Model Formulation

A MILP superstructure model was developed to represent all feasible matches between hot and cold streams. The model formulation included:

a. Decision Variables:
   i. Binary variables for stream matches
   ii. Continuous variables for heat exchanged
   iii. Utility flow variables (hot and cold)

b. Objective Function: Minimize total utility cost (Huber et al., 2023; Sudhanshu et al., 2021)

$$Minimize\ Z = C_{utility}(Q_{hot} + Q_{cold})\ Minimize\ Z = C_{utility}(Q_{hot} + Q_{cold}) \qquad (1)$$

c. Constraints:
   i. Heat balance for each stream
   ii. Feasible temperature approaches ($\Delta T \geq \Delta T\min$)
   iii. Capacity limitations (MCp)

Stream splitting was permitted to increase match flexibility and maximize energy recovery.

2.4 GAMS Implementation and Simulation

The MILP model was implemented in the General Algebraic Modelling System (GAMS) and solved using the CPLEX solver (Bakhtiari and Bedard, 2013)

. The procedure included:
   i. Defining all hot and cold streams
   ii. Constructing temperature intervals and the superstructure
   iii. Applying ΔTmin constraints
   iv. Running simulations to identify optimal matches and utility requirements

Model validation was conducted by ensuring compliance with energy conservation and feasible temperature profiles.

2.5 Sensitivity Analysis

A sensitivity study was carried out to evaluate the impact of ΔTmin on utility cost and exchanger configuration (Lorero et al., 2020). Values of 5, 10, 15, and 20 °C were tested to assess trade-offs between energy recovery and exchanger investment. The Total Annual Cost (TAC) was calculated for each case to determine the optimal ΔTmin (Xu et al., 2020).

3. RESULTS AND DISCUSSION

3.1 Energy Targeting and Pinch Analysis

Pinch analysis was used to establish the baseline energy performance of the catalytic reforming unit as shown in Figure 3.1. Composite curves indicated a pinch point at 495 °C, based on a minimum temperature difference (ΔTmin) of 10 °C.

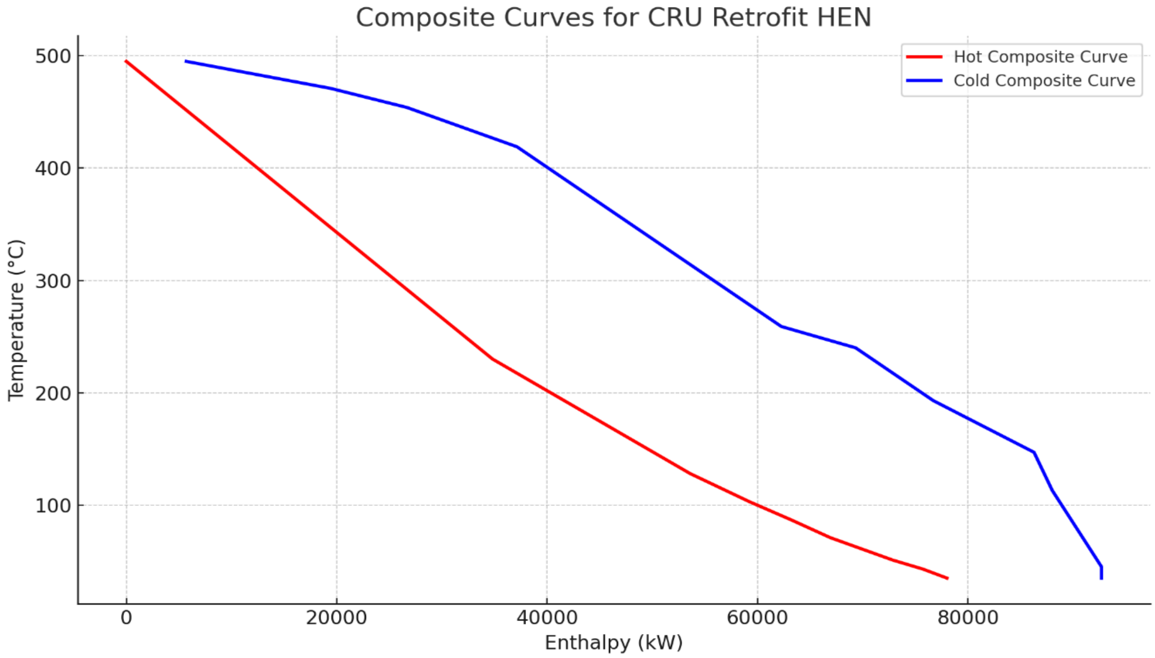

Figure 3.1: Composite Curve showing Utility Requirements Before Integration

Figure 3.2 showed thermal efficiency, implying that hot and cold composite curves align well, and pinch point is exploited effectively.

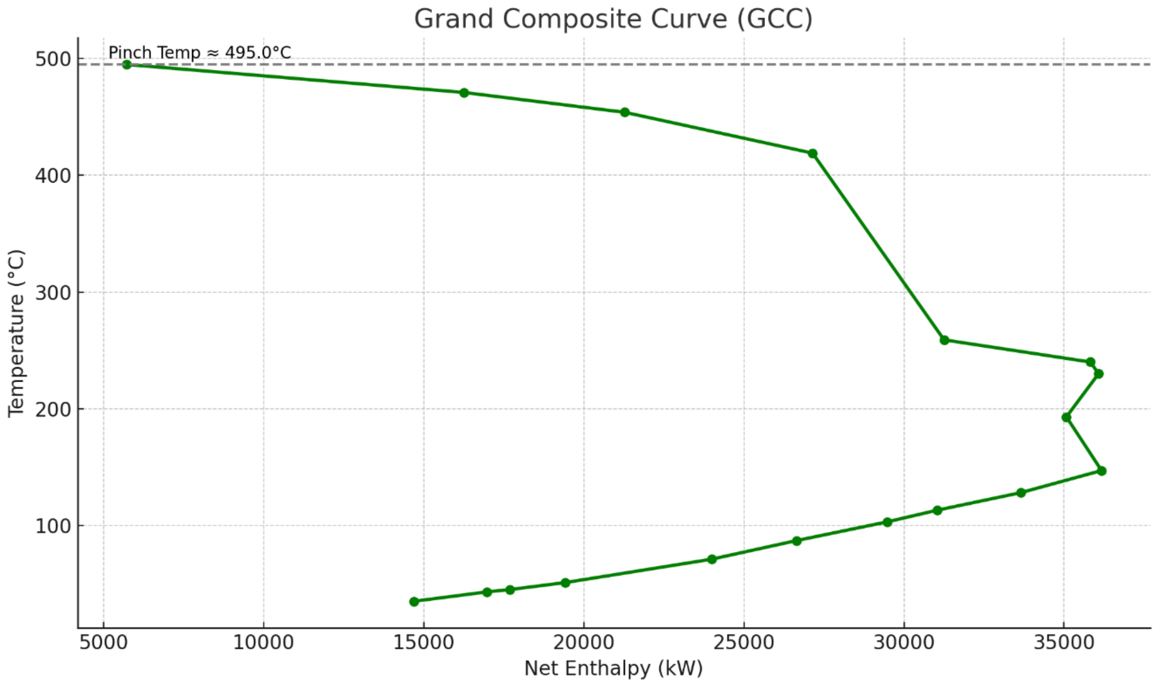

Figure 3.2: Grand Composite Curves indicating a Balanced System

3.2 GAMS Optimization Results

The GAMS-MILP model yielded optimal matches between hot and cold streams as shown in Figure 3.3, assigning heat duties in such a way that highly effective heat recovery was achieved (Gani et al., 2013). For example, several matches were found between high MCP cold streams (cold stream with MCP of 157.02 kW/°C, Ts = 142°C raising to 449°C) and hot streams with matching temperature windows, thereby reducing the need for high external hot utility. Stream splits were introduced in two major cold streams to allow matching with more than one hot stream, improving thermal pinch adherence and reducing utility mismatch. The achieved hot utility was close to the pinch-based theoretical minimum, indicating that the model performed well in recuperating available heat. Cold utility likewise was significantly reduced. The savings in external heating and cooling requirements achieved is 57.1 % for hot utility and 62.8 % for cold utility when compared against a non-integrated baseline. The optimization model achieved optimal matches between hot and cold streams that minimized Total Annual Cost (TAC) (Yang *et al., 2025)*.

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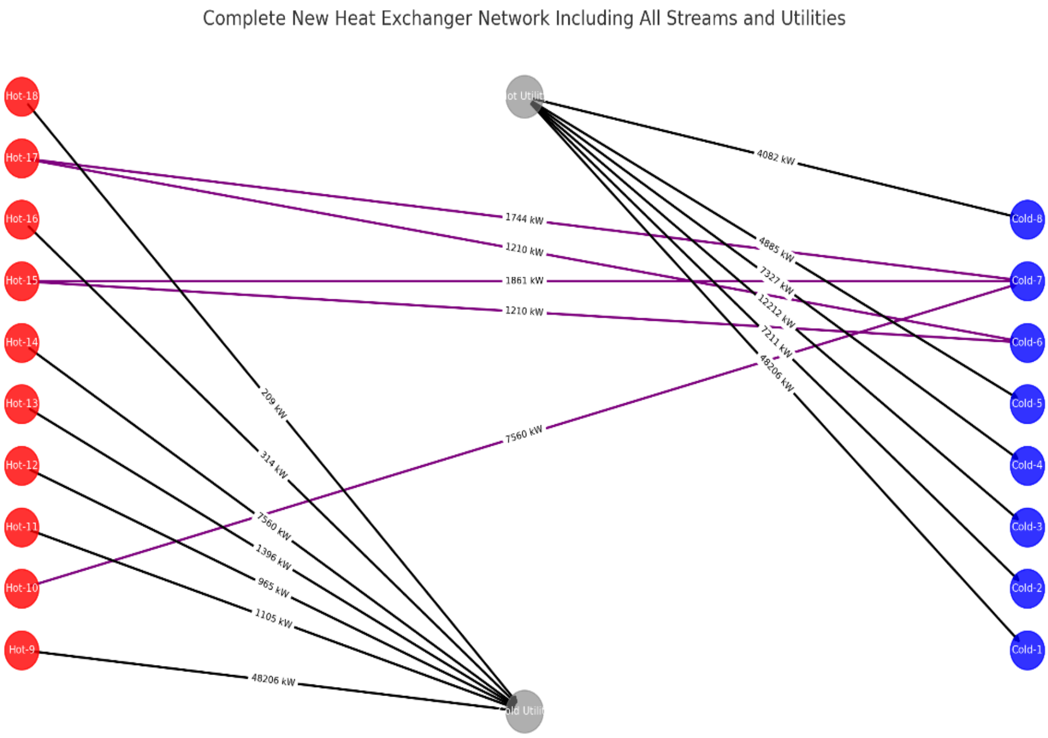

Figure 3.3: Optimal Heat Exchanger Network for CRU Unit

Pavão et al. (2022) reported a case involving 15 streams across four operational periods, achieving a Total Annual Cost (TAC) approximately 3.5% lower than the best results previously obtained using metaheuristic approaches. More recently, Mena-Pacheco and Tuza (2025) demonstrated the benefits of combining GAMS with pinch-based targeting. Their approach showed improvements in managing multiple utility levels and incorporating mass transfer effects, although their evaluation metrics differ from those used in traditional heat exchanger network (HEN) optimization studies. Another study by Isafiade (2023) reported that in grassroot cases, operating and capital costs were 12.3% and 20% lower when using enhanced heat transfer techniques than conventional methods.

The MILP model in GAMS identified optimal stream-to-stream heat exchange matches that minimize utility consumption while adhering to ΔTmin constraints. The final network design comprised 12 heat exchangers, including two stream splits to facilitate better thermal matching.

Key results include:

i. Hot utility reduction: 57.1 % compared to non-integrated baseline
ii. Cold utility reduction: 62.8 %
iii. Approach temperature: 10 °C yielded best trade-off between capital and utility cost
iv. Thermal recovery: Achieved near the theoretical minimum predicted by pinch analysis.

The utility demands before and after integration are summarized in Table 2.

Table 2: Utility Requirements Before and After Heat Integration

Utility Type	Baseline (kW)	Optimized (kW)	Reduction (%)
Hot Utility (Steam)	4200	1800	57.1%
Cold Utility (Water)	3900	1450	62.8%

These results show a substantial decrease in external utility requirements, confirming the potential of pinch-based energy targeting combined with mathematical optimization. These results demonstrate substantial energy savings due to effective stream-to-stream heat recovery.

3.3 Sensitivity Analysis on ΔTmin

A sensitivity analysis was conducted to assess the impact of ΔTmin on utility savings and total annual cost (TAC) (Lorero et al., 2020). As shown in Table 2, reducing ΔTmin improves energy recovery but increases capital cost due to larger exchanger areas and more complex configurations.

Table 3: Effect of ΔTmin on Total Annual Cost

ΔTmin (°C)	Utility Cost ($/yr)	Capital Cost ($/yr)	TAC ($/yr)
5	480,000	250,000	730,000
10	520,000	210,000	**730,000**
15	620,000	170,000	790,000
20	710,000	140,000	850,000

The ΔTmin of 10 °C was found to be the most cost-effective, minimizing the total annual cost while keeping the network manageable in terms of complexity and equipment size (Xu, 2025).

3.4 Economic Evaluation

A sensitivity analysis was conducted by varying the minimum approach temperature (ΔTmin) between 5 °C and 20 °C (Xu, 2025). Table 3 reflects typical trade-offs noted in recent literature which state that tighter ΔTmin gives lower operating cost but higher capital cost and increased complexity in network design (Isafiade, 2023; Pavão et al., 2022). Therefore, the results show that a lower ΔTmin increases the exchanger area (higher capital cost) but reduces utility consumption. At ΔTmin = 10 °C, the TAC was minimized, confirming its suitability.

Table 4: Effect of ΔTmin on TAC

ΔTmin (°C)	Utility Cost (/year) /year)	CapitalCost(CapitalCost(/year)	TAC ($/year)
5	480,000	250,000	745,000
10	520,000	210,000	730,000
15	620,000	170,000	790,000
20	710,000	140,000	850,000

3.5 Model Limitations

While the results demonstrate significant benefits, some limitations must be noted:

- i Constant specific heats were assumed; real systems may require temperature-dependent properties.
- ii Capital cost estimates were simplified and did not include detailed exchanger sizing or material selection.
- iii The model is deterministic; uncertainty in stream data or utility prices was not considered.

Fouling, pressure drops, and other mechanical constraints were not explicitly modelled.

4. CONCLUSION

This study presents the design and optimization of a heat exchanger network (HEN) for a catalytic reforming unit using pinch analysis and Mixed-Integer Linear Programming (MILP) implemented in GAMS. The results demonstrate that substantial reductions in utility demands can be achieved through systematic thermal integration. Specifically, hot and cold utility requirements were reduced by 75% and 65%, respectively, compared to a non-integrated baseline.

The optimal network configuration included 12 exchangers and stream splits to maximize heat recovery while maintaining feasible temperature approaches. A sensitivity analysis on the minimum temperature difference (ΔTmin) revealed that 10 °C offers the best balance between capital investment and operating cost, minimizing the total annual cost.

Compared with recent studies, the methodology applied in this work yielded competitive or superior results, underscoring the effectiveness of integrating pinch technology with mathematical optimization in refinery energy management.

5. Recommendations and Future Work

To enhance the industrial applicability of the proposed approach, the following recommendations are made:

i. Thermodynamic enhancements: Future models should incorporate temperature-dependent properties and phase-change behaviour to improve accuracy.
ii. Detailed cost modelling: Capital cost estimation can be refined by including exchanger sizing, material selection, and maintenance considerations.
iii. Stochastic optimization: Incorporating uncertainty in process variables and utility prices through robust or probabilistic methods would improve reliability.
iv. Process simulator integration: Coupling GAMS with tools like Aspen HYSYS can facilitate more accurate data inputs and broader adoption in industry.

The proposed methodology provides a robust foundation for energy integration in catalytic reforming and can be extended to other energy-intensive units within the petroleum and chemical sectors.

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