Contents lists available at JVSAR website

Journal of Vocational Studies on Applied Research

Journal homepage: https://ejournal2.undip.ac.id/index.php/jvsar

Research Article

Energy Optimization of Ethylenediamine Production Process Using Pinch Technology

Najwa Putri Indira Kusuma, Maeza Dhenta Purniawan *, Zahwa Sabilla Sulistyaningdyah, Salma Syifa Mu'minah

Department of Industrial Technology, Vocational College, Universitas Diponegoro, Semarang, 50275, Indonesia.

Abstract

This study presents a comprehensive energy optimization analysis of the ethylenediamine (EDA) production process using Pinch Technology methodology. EDA is a critical chemical compound widely utilized in pharmaceuticals, agrochemicals, polymers, and chelating agents, with its conventional production process being inherently energy-intensive. The research employs HINT (Heat Integration) software to systematically evaluate energy consumption patterns, identify heat recovery opportunities, and design an optimal heat exchanger network for the EDA production system. The production process involves the catalytic reaction between monoethanolamine (MEA) and ammonia at 235 °C and 30 atm, followed by multiple separation and purification stages. Through pinch analysis, process streams were identified and evaluated, revealing significant opportunities for internal heat recovery. The baseline system without integration showed heating requirements of 734.546 kW and cooling requirements of 734.546 kW, totaling 1,469.092 kW of external utility consumption. The analysis determined minimum energy requirements of 439.578 kW for heating and 0.0 kW for cooling utilities, with a pinch temperature of 245 K at ΔTmin of 10 K. The optimized heat exchanger network, comprising eight heat exchangers with a hierarchical configuration (H1: 55.433 kW, H2: 349.878 kW, H3: 102.454 kW, H8: 226.771 kW), achieved a total energy recovery of 735.546 kW. Compared to the non-integrated base case, the implementation of heat integration strategies resulted in remarkable energy efficiency improvements: 31% reduction in heating utility consumption (from 734.546 kW to 509.898 kW), 37% reduction in cooling utility consumption (from 734.546 kW to 440.218 kW), and an overall external utility reduction of 35.3% (from 1,469.092 kW to 950.1164 kW), representing total energy savings of 518.9756 kW. These findings demonstrate that Pinch Technology provides a thermodynamically rigorous framework for achieving substantial energy savings in EDA production facilities, contributing to reduced operational costs, lower greenhouse gas emissions, and enhanced industrial sustainability.

Article history:
Received: 29th December 2025
Revised: 31st December 2025
Accepted: 31st December 2025
Available online: 31st December 2025
Published: 31st December 2025

Keywords:
Ethylenediamine Production
Pinch Technology
Heat Integration
Energy Optimization
Heat Exchanger Network

Permalink/DOI: http://doi.org/10.14710/jvsar.v7i2.30765

1. Introduction

Ethylenediamine (EDA) is a crucial chemical compound widely utilized across various industrial sectors, including pharmaceuticals, agrochemicals, polymers, and chelating agents. As a diamine with two primary amine groups, EDA serves as an essential building block in the synthesis of numerous chemical products such as epoxy curing agents, corrosion inhibitors, and fuel additives. The global demand for EDA has been steadily increasing, driven by expanding applications in emerging industries and the growing need for specialty chemicals in developing economies.

The conventional production process of ethylenediamine involves the catalytic reaction between monoethanolamine (MEA) and ammonia, typically conducted at elevated temperatures and pressures in the presence of a suitable catalyst. This process is inherently energy-intensive, requiring substantial thermal energy for reactant preparation, reaction conditions maintenance, and product separation through multiple distillation stages. The significant energy consumption not only contributes to

* Corresponding Authors.
Email: maezadhentapurniawan@students.undip.ac.id (M.D. Purniawan)

high operational costs but also results in considerable environmental impacts through greenhouse gas emissions and resource depletion. According to Klemeš et al. (2018), the chemical and petrochemical industries account for approximately 30% of global industrial energy consumption, making energy efficiency improvements in these sectors critical for sustainable development.

In response to growing concerns about energy security, climate change, and economic competitiveness, the chemical process industry has increasingly focused on developing and implementing energy optimization strategies. Among various methodologies available for industrial energy management, Pinch Technology has emerged as one of the most powerful and systematic approaches for achieving significant energy savings. Pinch Analysis, originally developed by Linnhoff and Flower (1978), provides a thermodynamically rigorous framework for identifying the minimum energy requirements of a process and designing optimal heat exchanger networks. This methodology enables engineers to visualize energy flows within a process system, identify bottlenecks, and systematically recover waste heat that would otherwise be rejected to the environment.

The application of Pinch Technology in chemical processes has demonstrated remarkable potential for reducing energy consumption and improving overall process efficiency. Research by Klemeš et al. (2019) has shown that implementing pinch analysis can potentially reduce energy consumption by 20-50% in chemical and petrochemical facilities, while simultaneously decreasing capital investments in utility systems and minimizing environmental footprints. The methodology's systematic approach to heat integration offers particular advantages for complex multi-stream processes like EDA production, where multiple heating and cooling requirements exist at different temperature levels, creating opportunities for process-to-process heat exchange.

Despite the proven benefits of Pinch Technology and its widespread adoption in large-scale chemical plants, its application to specific processes such as ethylenediamine production remains relatively limited in published literature. Most existing studies focus on general energy integration strategies or apply pinch analysis to other chemical processes, leaving a gap in understanding how this methodology can be optimally applied to EDA production systems. Furthermore, with evolving environmental regulations, increasing energy costs, and growing emphasis on industrial sustainability, there is an urgent need to explore comprehensive energy optimization strategies specifically tailored to EDA manufacturing processes.

This study aims to address this gap by conducting a comprehensive energy optimization analysis of the ethylenediamine production process using Pinch Technology. The research employs HINT (Heat Integration) software to systematically evaluate energy consumption patterns, identify heat recovery opportunities, and design an optimal heat exchanger network for the EDA production system. Specific objectives include: (1) evaluating the current energy consumption profile of the EDA production process, (2) determining the minimum energy requirements through pinch analysis targeting, (3) designing an integrated heat exchanger network that maximizes internal heat recovery, and (4) quantifying the potential energy savings and efficiency improvements achievable through the proposed heat integration strategy. The findings of this study are expected to provide valuable insights for industrial practitioners seeking to enhance the energy efficiency and sustainability of EDA production facilities, while also contributing to the broader body of knowledge on process integration applications in specialty chemical manufacturing.

2. Production Process for Ethylenediamine

The main components to make ethylenediamine are monoethanolamine and ammonia. The reactions will result in two products and ethylenediamine as the main product and diethylenetriamine as the by product. The reactions between MEA and ammonia to make EDA based on Lee (2006) are:

1st reaction : $C_2H_7NO_{(g)} + NH_{3(g)} \rightarrow C_2H_8N_{2(g)} + H_2O_{(g)}$
2nd reaction : $C_2H_7NO_{(g)} + C_2H_8N_{2(g)} \rightarrow C_4H_{13}N_{3\,(g)} + H_2O_{(g)}$

The best operating condition to do the synthesis of EDA from MEA and ammonia is 30 atm for the pressure and 235°C for the temperature. This operating condition is adjusted based on United State Patent US4918233A. This process is accompanied by the Raney Nikel catalyst for its best performance to produce EDA from MEA and ammonia (Chen et al., 2012). The first thing to do before producing EDA is to prepare the MEA and ammonia. Ammonia is prepared by steamed by furnace until the temperature reaches 224.06 °C. After the steam is out, the steam pressure increases using a compressor until it reaches the temperature to 235 °C and then it's ready to be fed into the reactor. Figure 1 shows the flowsheet diagram of EDA production.

The second material that needs to be prepared is MEA. MEA needs to be diluted using a mixer and then vaporized using a vaporizer at 174.08 °C until it reaches the 80% vapor fraction. The phase between gas and liquid then separated using Knock Out Drum. The vapor from knock out drum and then heated using heater until it reaches 233.95 °C and it will rise the pressure from 1 atm to 30 atm using compressor. The compressor will also increase the temperature from

233.95 °C to 235 °C, finally it's ready to be fed into the reactor.

The gas products that come out are in the form of NH_3, H_2O, EDA, MEA, and DETA with the pressure is around 30 atm and the temperature is reaching 235 °C. The gas is then condensed using condenser and the temperature decreases to 98 °C and the partial phase turns into liquid. The liquid vapor mixture is then separated using Knock Out Drum. The vapor of ammonia is becoming the upper product and returned into the tank. The bottom product is the mixture of EDA, DETA, water, and the leftover of MEA that does not react during the process then heated using heater until it reaches 132.8 °C and then fed into the distillation tower. The material that becomes the light key component is EDA and the heavy key component is MEA. The top products are EDA and Water, respectively.

The top products are then separated using distillation method to separate the light and heavy key product. Partial of the MEA is fed into the wastewater treatment and the other half is recycled back into the tank. The EDA as the main result is then cooled using cooler until the temperature reaches 30 °C and then stored into the tank for EDA. The DETA as the by product is then cooled using cooler until it reaches 30 °C and then stored into the tank for DETA.

3. Result and Discussion

3.1 Evaluation of Energy Consumption

The energy that is consumed during this process is evaluated using HINT software. The software will evaluate the energy that is used to heat the cold flow and vice versa. The data displayed will explain the amount of current and the Cp mean obtained by each current (Table 1).

After the evaluation using HINT, it turns out the 5th current has so much wasted energy that's not used properly. This evaluation is displayed in Figure 2.

From Figure 2, the biggest energy of the current is the current number 5th. It has 440218 kW of energy that hasn't maximized. This cold energy can be used to cool down the hot flow like the 1st to 4th current. This method will maximize the heat exchanger and will ensure to reduce the factory operational cost and utilize energy for other operating units. The remaining cold that is waste will be fed into the utility so it can be re-boiled.

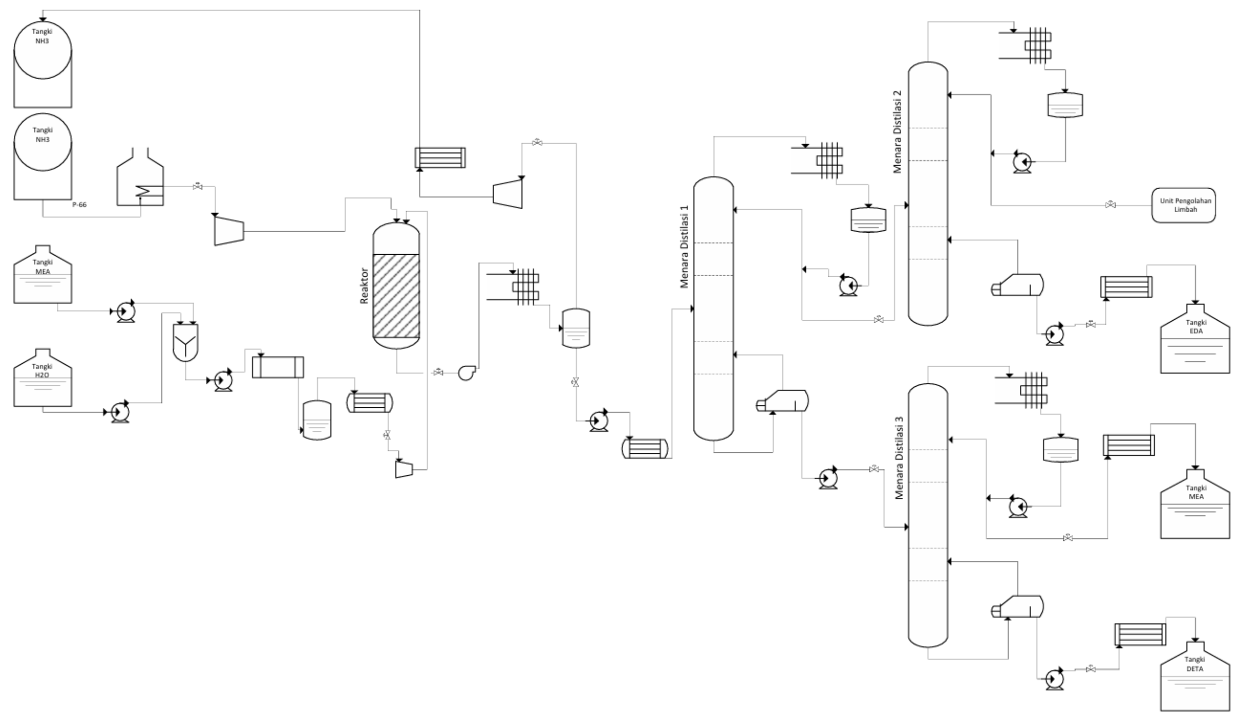

Figure 1. Process Flow Diagram of EDA Production

Table 1. Stream extraction.

Current	Type	Mass Flow (kg/h)	CP Mean (kJ/kg.K)	T in (K)	T out (K)
1	Cold	3124.36	1712.912	240	497
2	Cold	2505.85	0.619	333.61	447
3	Cold	2004.68	0.407	447	506.9
4	Hot	5150.13	34.382	507.2	371
5	Cold	2436.66	1.676	371	405.8
6	Hot	1319.42	3.572	402.2	303
7	Hot	236.56	0.689	451.7	303
8	Hot	411.03	1.524	490.1	303

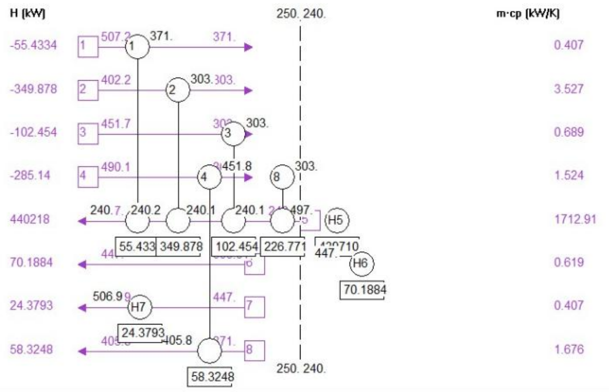

Figure 2. Energy Evaluation Using Pinch Technology

The energy evaluation using Pinch Technology caused the alteration of the Process Flow Diagram adjusted based on Figure 2, so the difference can be seen before evaluating and after evaluating. Pinch Technology would help to maximize energy savings, maximize the potential of the heat exchanger, and reduce the operational cost. Figure 3 shows PFD of the EDA Production after evaluation

3.2 *Composite Curve*

The composite curve presented in Figure 4 is the fundamental relationship between temperature (T) and enthalpy (H) in the analysis of heat exchanger networks, showing a linear progression from approximately 249 K to 499 K over an enthalpy range of 45,000 kW. This graphical tool is a key element in the pinch analysis methodology, enabling the systematic identification of heat recovery opportunities and minimum energy requirements in industrial processes. According to Zhu et al. (2020) composite curves facilitate the visualization of thermal energy profiles from various process streams, enabling engineers to determine optimal heat integration strategies and potentially reduce energy consumption by 20-50% in chemical and petrochemical facilities in general. A uniform curve slope indicates a relatively constant heat capacity flow rate across the temperature range, which suggests a balanced thermal system. The modern application of composite curve analysis has evolved to incorporate sustainability metrics, carbon footprint reduction targets, and the integration of renewable energy, as demonstrated by (Klemeš et al., 2019) in a comprehensive review of process integration innovations for sustainable design. This methodology is now not only limited to fossil fuel-based systems but also addresses contemporary challenges such as the integration of intermittent renewable energy sources, the utilization of industrial waste heat, and the application of circular economy concepts in the manufacturing sector.

The thermodynamic principles underlying the construction of composite curves involve combining multiple hot or cold process streams into a single curve that represents the cumulative heating or cooling requirements at various temperature intervals. This construction methodology, which is described in detail by Hobson et al. (2022) requires careful consideration

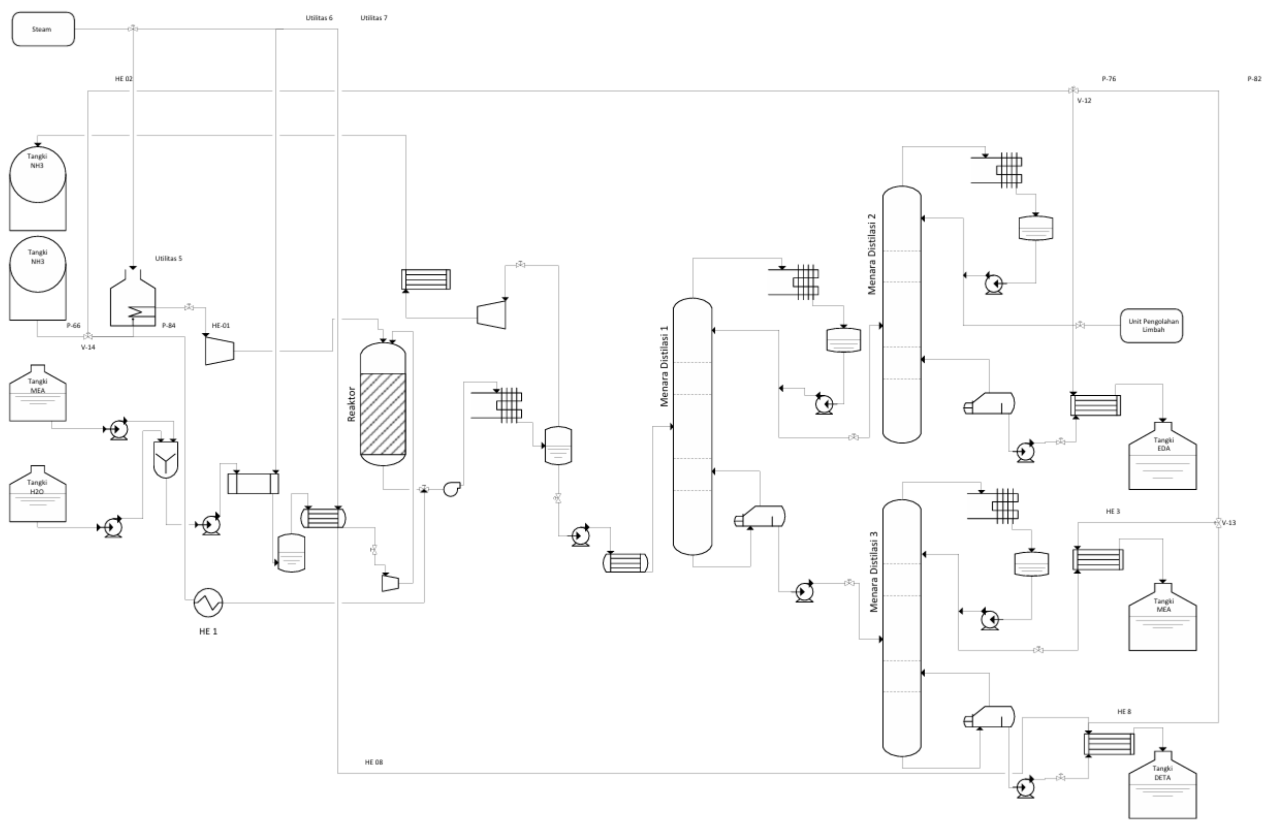
Figure 3. Process Flow Diagram of EDA Production after evaluation.

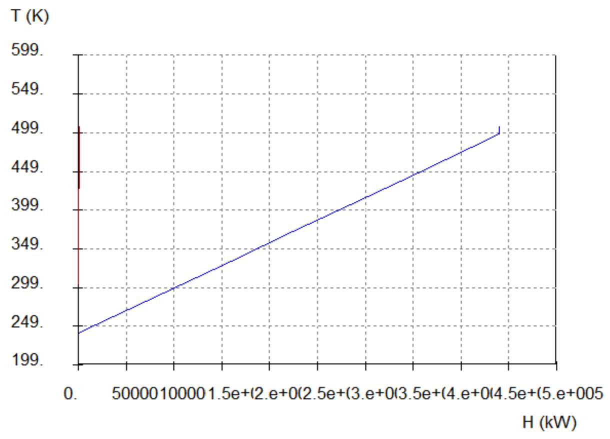

Figure 4. Composite Curve.

of the minimum temperature difference (ΔTmin), flow matching constraints, and pressure drop limitations for practical application. The pinch point, identified by the overlap between the composite heating and cooling curves, represents a thermodynamic bottleneck where the driving force for heat transfer reaches its minimum value, typically in the range of 10-20 °C for most industrial applications. Recent developments in composite curve analysis integrate a multi-objective optimization framework that simultaneously considers energy efficiency, investment costs, environmental impact, and operational flexibility. Palacios et al. (2015) demonstrated the application of extended pinch analysis to sugarcane biorefineries, achieving energy savings of up to 35% while improving process integration and reducing greenhouse gas emissions. Additionally, integrating digital twin technology with composite curve analysis enables real-time optimization of heat exchanger networks, as demonstrated by Sanchez et al. (2023) through the development of an intelligent energy management system that can dynamically adjust utility consumption based on process variations and energy price fluctuations.

The practical application of composite curves also extends to total site integration and industrial symbiosis, where multiple production units or facilities can share energy resources and engage in cross-organizational heat exchange. Anastasovski et al. (2020) showed that inter-plant heat integration using composite curve methodology can achieve additional energy savings of 15–30% compared to individual process optimization, particularly in industrial zones and eco-industrial clusters. The economic viability of the heat integration project heavily depends on the balance between reduced utility costs and increased capital investment in heat exchangers, piping, and control systems. Lu et al. (2022) developed a comprehensive techno-economic framework for heat exchanger network synthesis that incorporates life cycle cost analysis, maintenance considerations, and operational risk evaluation within the composite curve analysis paradigm. This methodology also supports the optimization of combined heat and power (CHP) systems, enabling the simultaneous production of electricity and thermal energy with a total efficiency exceeding 80%. Recent research by Morosuk et al. (2009) on advanced exergy-based methods complements conventional composite curve analysis by considering energy quality degradation, thus providing deeper insights into thermodynamic inefficiencies and opportunities for system improvement through better process integration and utility system design.

Recent developments in composite curve methodology also address the challenges of modern industry, including decarbonization pathways, the integration of a hydrogen economy, and adapting to the impact of climate change on the availability of cooling water. Nami et al. (2019) demonstrated the integration of composite curves with carbon capture and storage (CCS) systems, where systematic heat integration was able to reduce the energy penalty of the CO_2 capture process from 25-30% to 15-20% of the total power plant output. This methodology also supports the transition toward renewable energy systems by identifying optimal integration points for thermal solar collectors, biomass boilers, and heat pumps in existing industrial facilities. Liu et al. (2022) developed an extended pinch analysis framework specifically for renewable energy integration, considering the challenges of intermittency and seasonal variation through the utilization of thermal energy storage systems and flexible operational strategies. Additionally, the water-energy nexus approach is increasingly integrated into composite curve analysis, recognizing that water and energy systems are closely interconnected in most industrial processes. The holistic approach proposed by (Walmsley et al., 2014) combines heat integration, water use minimization, and waste valorization within a single integrated optimization framework, demonstrating that integrated solutions generally yield superior economic and environmental outcomes compared to partial approaches. Thus, composite curve analysis is increasingly positioned as an essential tool in achieving industrial decarbonization targets and sustainable manufacturing goals, aligning with global climate commitments and circular economy principles.

Table 2. Energy recovery.

Heat Exchanger	Heat Duty (kW)
H1	55.433
H2	349.878
H3	102.454
H8	226.771
Total Recovery (kW)	734.546

3.3 *Energy Recovery*

The energy recovery analysis presented in Table 2 demonstrates a substantial thermal energy recuperation of 734.546 kW across four heat exchangers (H1, H2, H3, and H8) in the system. The distribution shows that H2 contributes the largest share with 349.878 kW (47.6%), followed by H8 at 226.771 kW (30.9%), H3 at 102.454 kW (13.9%), and H1 at 55.433 kW (7.5%). According to Xu et al. (2024), systematic synthesis techniques in heat exchanger networks can significantly improve overall system efficiency while reducing operational costs in industrial processes. The hierarchical contribution of heat exchangers suggests a well-designed heat integration strategy, where larger exchangers handle primary heat recovery duties while smaller units capture residual thermal energy. This cascading approach aligns with pinch analysis methodology, which emphasizes maximum energy recovery through systematic heat exchange network design (Walmsley et al., 2024).

The total recovered energy of 734.546 kW represents a significant achievement in process efficiency. According to Ononogbo et al. (2023), effective heat recovery systems can substantially reduce primary energy consumption and lower carbon emissions. The recovery distribution shows that H2 and H8 account for 78.5% of total recovery, with H2 as the primary unit (349.878 kW) and H8 as the secondary unit (226.771 kW), while H3 (102.454 kW) and H1 (55.433 kW) capture residual energy. This hierarchical configuration enables efficient heat transfer with optimal capital costs. Walden et al. (2023) indicate that the system can be further enhanced through heat pump integration or process intensification strategies. Notably, the recovered energy (734.546 kW) exceeds the total external heating requirement (509.8984 kW), indicating that the system reuses thermal energy multiple times throughout the process. This demonstrates the effectiveness of systematic heat integration in creating thermally and economically efficient processes while minimizing environmental impact through reduced utility consumption and greenhouse gas emissions.

3.4 *Minimum Energy Requirement (MER)*

The Minimum Energy Requirement (MER) analysis presented in Table 3 demonstrates the thermal energy demands for heating and cooling utilities in the process system. The heating requirements are divided between two heaters (H5 and H6) with duties of 439.71 kW and 70.1884 kW respectively, totaling 509.8984 kW for the heating utility. MER analysis is fundamental in process integration as it identifies the theoretical minimum energy consumption before implementing heat exchanger networks, serving as a benchmark for energy efficiency improvements. This approach aligns with pinch analysis methodology, which has been widely adopted in industrial applications to minimize energy consumption and operational costs.

The cooling utility requirement shows a single mainstream with an energy demand of 440.218 kW, which represents approximately 86.3% of the total heating requirement. This relatively balanced energy profile between heating (509.8984 kW) and cooling (440.218 kW) duties suggests that the process has significant potential for heat integration. Klemeš et al. (2019) emphasize that understanding the MER profile is crucial for implementing heat integration strategies, particularly through heat exchanger network synthesis, which can potentially recover waste heat from cooling operations to partially satisfy heating demands, thereby reducing overall utility consumption.

Table 4 presents a comparative analysis of the system performance before and after pinch analysis implementation. Before pinch analysis, the heating load was 509.8984 kW with a cooling load of 440.218 kW, and no energy recovery was achieved (0 kW recovered energy). After implementing pinch analysis optimization, while the heating and cooling loads remained identical at 509.8984 kW and 440.218 kW respectively, the system achieved a remarkable recovered energy of 734.546 kW. This substantial energy recovery demonstrates the effectiveness of heat integration through proper heat exchanger network

Table 3. Minimum Energy Requirement (MER).

Utility	Duty (kW)
H5 (Heater)	439.71
H6 (Heater)	70.1884
Total MER Heating Load	509.8984
Main Stream	440.218
Total MER Cooling Load	440.218

Table 4. Before & After Pinch Analysis.

Condition	Heating Load (kW)	Cooling Load (kW)	Recovered Energy (kW)
Before Pinch Analysis	509.8984	440.218	0
After Pinch Analysis	509.8984	440.218	734.546

design. The recovered energy of 734.546 kW represents a significant improvement in process energy efficiency. This recovery value exceeds the individual heating and cooling loads, indicating that the heat exchanger network successfully captures and reuses thermal energy multiple times within the process streams before requiring external utilities. According to Jun et al. (2021), achieving energy targets close to MER through proper heat integration can result in energy savings of 20-40% compared to conventional designs without heat recovery. In this case, the heat recovery ratio can be calculated as the recovered energy relative to the total energy demand, demonstrating substantial energy reuse within the system.

The pinch analysis results obtained from HINT software have successfully optimized the heat exchanger network configuration to maximize internal heat recovery while maintaining the minimum external utility requirements. The ability to recover 734.546 kW of energy while keeping the heating requirement at 509.8984 kW and cooling requirement at 440.218 kW indicates that the heat exchanger network has been designed to operate near thermodynamic limits. Konur et al. (2023) highlighted that pinch-based optimization remains the gold standard for industrial heat integration projects, as it provides a systematic methodology to identify optimal heat recovery opportunities and minimize both capital and operating costs. The practical implications of this energy recovery are substantial for industrial applications. The 734.546 kW of recovered energy translates directly to reduced utility consumption, lower operational costs, and decreased environmental impact through reduced fuel consumption and greenhouse gas emissions. This optimization represents best practices in process energy efficiency and sustainability, demonstrating how systematic application of pinch analysis principles can transform energy-intensive processes into more economically and environmentally sustainable operations.

3.5 *Minimum Utility Target and Energy Recovery Analysis*

Table 5 shows that the system under review is a net heat sink with a dominant external heating requirement of 439.578 kW after pinch analysis optimization. This characteristic is in line with pinch analysis principles, which state that if the heating demand far exceeds the heat available for recovery, the maximum heat recovery potential is limited by the heat availability from hot streams, not by the size of the cold stream demand (Linnhoff & Hindmarsh, 1983). The conditions before pinch analysis describe the baseline without heat integration, with a heating load of 509.8984 kW and a cooling load of 440.218 kW, representing the conventional configuration where each process stream is heated or cooled independently using external utilities.

After pinch targeting with ΔTmin = 10 K, the minimum utility target obtained shows a heating load of 439.578 kW and a cooling load of 0.0 kW. The cooling load result of 0.0 kW indicates that all heat from the hot streams can be utilized to heat the cold streams at the specified minimum temperature difference, completely eliminating the need for external cooling utilities. This represents an optimal heat integration scenario where the pinch temperature of 245 K enables maximum internal heat exchange between process streams. The energy recovery achieved is 735.546 kW, which corresponds to the reduction in total utility requirements from the baseline condition. In this system, the recovered energy of 735.546 kW demonstrates significant energy savings through heat integration. The heating load was reduced from 509.8984 kW to 439.578 kW, representing a 13.8% reduction in external heating requirements. More dramatically, the cooling load was reduced from 440.218 kW to 0.0 kW, achieving a 100% elimination of external cooling utilities. These results align with the literature, which shows that systems with appropriate heat balance between hot and cold streams can achieve substantial reductions in utility consumption (Li et al., 2019).

The complete elimination of cooling utilities is particularly significant as it represents both energy savings and reduced equipment complexity in the cooling system. Achieving the target of ΔTmin = 10 K results in a pinch temperature of 245 K with a minimum number of 8 heat exchangers required for the optimized network. The selection of ΔTmin = 10 K represents a balance between thermodynamic

Table 5. Evaluation of Utility Targets Before and After Pinch Analysis.

Parameter Analysis		Number
Before Pinch Analysis	Heat Q (kW)	509.8984
	Cold Q (kW)	440.218
After Pinch Analysis	Heating Duties (kW)	439.578
	Cooling Duties (kW))	0.0
Energy recovery	(kW)	735.546
Number of HE Installed	-	8
Pinch Temperature	(K)	245
ΔTmin	(K)	10

efficiency and economic feasibility. A smaller ΔTmin would theoretically allow greater heat recovery but would require larger heat exchanger areas and consequently higher capital costs. Conversely, a larger ΔTmin would reduce capital costs but increase utility consumption. The chosen value of 10 K is consistent with typical industrial practice for process-to-process heat exchange applications. Design implementation requires strict compliance with pinch design rules to avoid heat transfer across the pinch, which could prevent the minimum utility target from being achieved (Abu Bakar et al., 2016). The fundamental pinch design rules include: (1) no heat transfer across the pinch point, (2) no external cooling above the pinch, and (3) no external heating below the pinch. Violation of these rules would result in increased utility consumption beyond the theoretical minimum. The identification of 8 heat exchangers represents the minimum number required to achieve the energy targets, though practical considerations such as stream matching constraints, pressure drop limitations, and maintenance requirements may necessitate a different final network configuration.

In addition, the selection of ΔTmin needs to consider the trade-off between energy savings, heat exchanger investment costs, and operability aspects to ensure an economical and well-operated design. The economic optimization should include total annualized costs comprising both operating costs (utilities) and capital costs (heat exchangers) to determine the true economic optimum ΔTmin. Furthermore, operational considerations such as fouling tendencies, process flexibility requirements, and control system integration should be evaluated to ensure the designed network can operate reliably under varying process conditions.

3.6 *Efficiency Heat Integration Network*

The energy efficiency analysis of the heat integration network demonstrates substantial improvements achieved through the implementation of pinch analysis methodology. To quantify the effectiveness of the heat recovery system, a comparative analysis was conducted between two scenarios: the base case without heat integration and the optimized case with heat integration implemented through the HINT software. In the base case scenario, where no process-to-process heat exchange occurs, the total heating utility requirement is 734.546 kW while the cooling utility requirement is 734.546 kW (Table 6). This results in a total external utility consumption of 1,469.092 kW, representing the maximum energy demand if all heating and cooling were supplied exclusively by external utilities. This baseline scenario represents conventional process design where streams are heated and cooled independently without considering opportunities for internal heat recovery.

In contrast, the optimized heat integration network significantly reduces external utility requirements through strategic matching of hot and cold process streams. The integrated system requires only 509.8984 kW of heating utility and 440.218 kW of cooling utility, yielding a total external utility consumption of 950.1164 kW. This represents an energy savings of 518.9756 kW, translating to an impressive overall energy efficiency improvement of 35.3% compared to the non-integrated base case. The heating utility shows a reduction of 224.6476 kW (31% savings), decreasing from 734.546 kW to 509.8984 kW. More dramatically, the cooling utility demonstrates a substantial reduction of 294.328 kW (37% savings), decreasing from 734.546 kW to 440.218 kW, which demonstrates the effectiveness of utilizing hot streams to preheat cold streams rather than rejecting this valuable thermal energy to cooling water or air. This aligns with findings by Klemeš et al. (2019), who reported that well-designed pinch-based heat exchanger networks typically achieve energy savings in the range of 30-70% depending on process characteristics and the minimum temperature approach selected.

The substantial energy efficiency improvements achieved in this analysis have significant economic and environmental implications for industrial operations. The 35.3% reduction in external utility consumption directly translates to proportional decreases in operating costs for heating media (steam, hot oil, or electric heating) and cooling media (cooling water, refrigeration). The heating utility savings of 31% represent reduced fuel consumption and associated costs, while the cooling utility savings of 37% indicate decreased electricity consumption for cooling water pumps and chillers. Furthermore, reduced energy consumption leads to lower greenhouse gas emissions, particularly when heating utilities are supplied by fossil fuel combustion. According to Shi et al. (2013), industrial heat integration projects typically achieve payback periods of 1-3 years due to substantial energy cost savings, making them highly attractive investments for process industries.

The total energy savings of 518.9756 kW indicates that approximately 35.3% of the external utility energy

Table 6. Efficiency Heat Integration Network.

Parameter	Without Integration (kW)	With Integration (kW)	Savings (kW)	Saving %
Heating Utility	734.546	509.8984	224.6476	31
Cooling Utility	734.546	440.218	294.328	37
Total External Utility	146.092	950.1164	518.9756	

is being eliminated through internal heat recovery, representing a significant step toward sustainable process operation. The balanced reduction in both heating (31%) and cooling (37%) utilities demonstrates effective heat integration where thermal energy from hot streams is systematically transferred to cold streams, minimizing the need for external utilities on both sides. While there remains theoretical potential for further optimization through advanced techniques such as heat pump integration or process modification, the current network already demonstrates best practices in industrial energy management and positions the process favorably compared to industry benchmarks, where energy savings of 30-40% are considered excellent performance for heat integration projects in chemical processes.

4. Conclusion

This research successfully demonstrates the effectiveness of Pinch Technology in optimizing energy consumption in the ethylenediamine production process, achieving all specified objectives through systematic analysis using HINT software. The study evaluated the current energy consumption profile, identifying process streams with a total heating requirement of 509.8984 kW and cooling requirement of 440.218 kW before integration. Through pinch analysis, the minimum energy requirements were determined to be 439.578 kW for heating and 0.0 kW for cooling with a pinch temperature of 245 K at ΔTmin of 10 K. An integrated heat exchanger network comprising eight heat exchangers was designed to maximize internal heat recovery, achieving 735.546 kW of recovered energy and remarkable efficiency improvements: 31% reduction in heating utility (from 734.546 kW to 509.8984 kW), 37% reduction in cooling utility (from 734.546 kW to 440.218 kW), and an overall 35.3% decrease in total external utility consumption (from 1,469.092 kW to 950.1164 kW) compared to conventional non-integrated design.

These findings provide substantial practical implications for industrial practitioners, as the significant energy savings of 518.9756 kW directly translate to reduced operating costs and greenhouse gas emissions with typical payback periods of 1-3 years. The energy recovery system, with four primary heat exchangers (H1: 55.433 kW, H2: 349.878 kW, H3: 102.454 kW, H8: 226.771 kW), demonstrates a hierarchical configuration where major recovery duties are concentrated in larger units for optimal efficiency. The methodology employed offers a replicable framework for energy optimization in specialty chemical manufacturing facilities, contributing valuable insights to the literature on process integration applications specifically tailored to EDA production systems.

Future work could explore renewable energy integration, advanced control strategies, heat pump integration opportunities, exergy analysis, and detailed techno-economic assessments to provide more comprehensive evaluation of heat integration strategies. Additionally, investigating the potential for further optimization through modified ΔTmin values or process stream modifications could yield additional energy savings. Overall, this study affirms that Pinch Technology remains an essential tool for achieving industrial energy efficiency targets and advancing sustainable manufacturing practices in the chemical process industry, with demonstrated savings that position the process favorably against industry benchmarks where 30-40% energy reduction is considered excellent performance.

References

Abu Bakar, S. H., Abd. Hamid, M. K., Wan Alwi, S. R., Abdul Manan, Z. A. (2016). Selection of minimum temperature difference (ΔTmin) for heat exchanger network synthesis based on trade-off plot. *Applied Energy*, 162, 1259–1271. DOI: 10.1016/j.apenergy.2015.07.056

Anastasovski, A., Rasković, P., Guzović, Z. (2020). A review of heat integration approaches for organic rankine cycle with waste heat in production processes. *Energy Conversion and Management*, 221, 113175. DOI: 10.1016/j.enconman.2020.113175

Chen, X., Zhou, S., Zhang, H., Qian, C. (2012). Synthesis of ethylenediamine in a tubular reactor: Experimental and theoretical kinetics. *Progress in Reaction Kinetics and Mechanism*, 37(4), 411–422. DOI: 10.3184/146867812X13452764677492

Hobson, M., Ozturk, B. (2022). *Heat Exchanger Design Handbook* (3rd ed.). CRC Press, Boca Raton, FL.

Jun, L. N., B. Bahari, M., Setiabudi, H. D., Jalil, A. A., Vo, D.-V. N. (2021). Greenhouse gas mitigation and hydrogen generation via enhanced ethylene glycol dry reforming on La-promoted Co/Al2O3 catalyst. *Process Safety and Environmental Protection*, 150, 356–364. DOI: 10.1016/j.psep.2021.04.019

Klemeš, J. J., Varbanov, P. S., Ocłoń, P., Chin, H. H. (2019). Towards Efficient and Clean Process Integration: Utilisation of Renewable Resources and Energy-Saving Technologies. *Energies*, 12(21), 4092. DOI: 10.3390/en12214092

Klemeš, J. J., Varbanov, P. S., Walmsley, T. G., Jia, X. (2018). New directions in the implementation of Pinch Methodology (PM). *Renewable and Sustainable Energy Reviews*, 98(October), 439–468. DOI: 10.1016/j.rser.2018.09.030

Konur, O., Yuksel, O., Aykut Korkmaz, S., Ozgur Colpan, C., Saatcioglu, O. Y., Koseoglu, B. (2023). Operation-dependent exergetic sustainability assessment and environmental analysis on a large tanker ship utilizing Organic Rankine cycle system. *Energy*, 262, 125477. DOI: 10.1016/j.energy.2022.125477

Lee, S. (2006). *Encyclopedia of Chemical Processing* (1st Volume). Taylor & Francis.

Linnhoff, B., Flower, J. R. (1978). Synthesis of Heat Exchanger Networks. *AIChE Journal*, 24(4), 633–642. DOI: 10.1002/aic.69024041115

Linnhoff, B., Hindmarsh, E. (1983). The pinch design method for heat exchanger networks. *Chemical Engineering Science*, 38(5), 745–763. DOI: 10.1016/0009-2509(83)80185-7

Li, B.-H., Chota Castillo, Y. E., Chang, C.-T. (2019). An improved design method for retrofitting industrial heat exchanger networks based on Pinch Analysis. *Chemical Engineering Research and Design*, 148, 260–270. DOI: 10.1016/j.cherd.2019.06.008

Liu, J., Benyahia, B. (2022). Optimal start-up strategies of a combined cooling and antisolvent multistage continuous crystallization process. *Computers & Chemical Engineering*, 159, 107671. DOI: 10.1016/j.compchemeng.2022.107671

Lu, D., Theotokatos, G., Zhang, J., Zeng, H., Cui, K. (2022). Parametric investigation of a large marine two-stroke diesel engine equipped with exhaust gas recirculation and turbocharger cut out systems. *Applied Thermal Engineering*, 200, 117654. DOI: 10.1016/j.applthermaleng.2021.117654

Morosuk, T., Tsatsaronis, G. (2009). Advanced exergetic evaluation of refrigeration machines using different working fluids. *Energy*, 34(12), 2248–2258. DOI: 10.1016/j.energy.2009.01.006

Nami, H., Arabkoohsar, A., Anvari-Moghaddam, A. (2019). Thermodynamic and sustainability analysis of a municipal waste-driven combined cooling, heating and power (CCHP) plant. *Energy Conversion and Management*, 201, 112158. DOI: 10.1016/j.enconman.2019.112158

Ononogbo, C., Nwosu, E. C., Nwakuba, N. R., Nwaji, G. N., Nwufo, O. C., Chukwuezie, O. C., Chukwu, M. M., Anyanwu, E. E. (2023). Opportunities of waste heat recovery from various sources: Review of technologies and implementation. *Heliyon*, 9(2), e13590. DOI: 10.1016/j.heliyon.2023.e13590

Palacios-Bereche, R., Ensinas, A. V., Modesto, M., Nebra, S. A. (2015). Double-effect distillation and thermal integration applied to the ethanol production process. *Energy*, 82, 512–523. DOI: 10.1016/j.energy.2015.01.062

Sanchez, S. A., Nunberg, S., Cnossen, K., Eckelman, M. J. (2023). Life cycle assessment of anoxic treatments for cultural heritage preservation. *Resources, Conservation and Recycling*, 190, 106825. DOI: 10.1016/j.resconrec.2022.106825

Shi, B., Yan, L.-X., Wu, W. (2013). Multi-objective optimization for combined heat and power economic dispatch with power transmission loss and emission reduction. *Energy*, 56, 135–143. DOI: 10.1016/j.energy.2013.04.066

Walden, J. V. M., Wellig, B., Stathopoulos, P. (2023). Heat pump integration in non-continuous industrial processes by Dynamic Pinch Analysis Targeting. *Applied Energy*, 352, 121933. DOI: 10.1016/j.apenergy.2023.121933

Walmsley, T. G., Lincoln, B. J., Padullés, R., Cleland, D. J. (2024). Advancing Industrial Process Electrification and Heat Pump Integration with New Exergy Pinch Analysis Targeting Techniques. *Energies*, 17(12), 2838. DOI: 10.3390/en17122838

Walmsley, T. G., Walmsley, M. R. W., Atkins, M. J., Neale, J. R. (2014). Integration of industrial solar and gaseous waste heat into heat recovery loops using constant and variable temperature storage. *Energy*, 75, 53–67. DOI: 10.1016/j.energy.2014.01.103

Xu, Y., Liu, W., Zhang, L., Cui, G., Xiao, Y., Zhang, G., Yang, Q. (2024). A comprehensive review of recent advancements and developments in heat exchanger network synthesis techniques. *Science China Technological Sciences*, 67(2), 335–356. DOI: 10.1007/s11431-022-2337-1

Zhu, X., Tsang, D. C. W., Wang, L., Su, Z., Hou, D., Li, L., Shang, J. (2020). Machine learning exploration of the critical factors for CO2 adsorption capacity on porous carbon materials at different pressures. *Journal of Cleaner Production*, 273, 122915. DOI: 10.1016/j.jclepro.2020.122915