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Techno - economic and energy-efficient LLDPE production via advanced sclairtech technology

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ABSTRACT

Linear Low-Density Polyethylene (LLDPE) is a widely used polymer in the plastics and packaging industries because of its flexibility and good mechanical properties. The increasing global demand for LLDPE encourages the development of more energy- and cost-efficient production technologies. This study aims to analyze the technical and economic feasibility of building an LLDPE plant using Advanced Sclairtech Technology (AST). The plant is designed with a production capacity of 287,000 tons/year and optimized using a Heat Exchanger Network (HEN). The design and evaluation of the HEN are carried out using Aspen Energy Analyzer software based on the Temperature Interval and Composite Curve methods. The analysis results show that implementing heat integration can reduce the high-pressure steam requirement from 204,541 kg/hour to 30,770 kg/hour and the cooling water requirement from 6,491,808 kg/hour to 1,527,774 kg/hour. The utility savings achieved exceed 80%, with a reduction in utility costs of USD 6,750 per hour. Economic analysis yields a Payback Period (PBP) of 3.03 years, a Net Present Value (NPV) of USD 84.15 million, an Internal Rate of Return (IRR) of 24.53%, and a Break-Even Point (BEP) of 24.46% of production capacity. Based on the technical and economic analysis results, the LLDPE plant using AST technology is considered feasible. It has the potential to be developed as a more efficient and sustainable LLDPE production technology.

Keywords: Advanced Sclairtech Technology, Heat Exchanger Network, Heat Integration, Linear Low-Density Polyethylene, Techno-economic Analysis

ABSTRAK

Linear Low-Density Polyethylene (LLDPE) merupakan salah satu polimer yang banyak digunakan dalam industri plastik dan kemasan karena memiliki fleksibilitas serta sifat mekanik yang baik. Peningkatan kebutuhan global terhadap LLDPE mendorong pengembangan teknologi produksi yang lebih efisien dari sisi energi dan ekonomi. Penelitian ini bertujuan untuk menganalisis kelayakan teknis dan ekonomi pembangunan pabrik LLDPE menggunakan Advanced Sclairtech Technology (AST). Pabrik dirancang dengan kapasitas produksi sebesar 287.000 ton/tahun dan dioptimalkan menggunakan Heat Exchanger Network (HEN). Perancangan dan evaluasi HEN dilakukan menggunakan perangkat lunak Aspen Energy Analyzer berdasarkan metode Temperature Interval dan Composite Curve. Hasil analisis menunjukkan bahwa penerapan integrasi panas mampu menurunkan kebutuhan uap bertekanan tinggi dari 204.541 kg/jam menjadi 30.770 kg/jam serta menurunkan kebutuhan air pendingin dari 6.491.808 kg/jam menjadi 1.527.774 kg/jam. Penghematan utilitas yang diperoleh mencapai lebih dari 80% dengan pengurangan biaya utilitas sebesar USD 6.750 per jam. Analisis ekonomi menghasilkan nilai Payback Period (PBP) sebesar 3,03 tahun, Net Present Value (NPV) sebesar USD 84,15 juta, Internal Rate of Return (IRR) sebesar 24,53%, dan Break-Even Point (BEP) sebesar 24,46% dari kapasitas produksi. Berdasarkan hasil analisis teknis dan ekonomi, pabrik LLDPE yang menggunakan teknologi AST dinilai layak dan berpotensi dikembangkan sebagai teknologi produksi LLDPE yang lebih efisien dan berkelanjutan.

Kata kunci: Analisis Tekno-ekonomi, Integrasi Panas, Jaringan Penukar Panas, Polietilena Linear Berdensitas Rendah, Teknologi Sclairtech Lanjutan.

1. INTRODUCTION

Polyethylene is a petrochemical product that plays an important role in the global plastics industry [1]. This material is widely used in various sectors, such as food packaging, bottles, plastic films, and industrial components [2]. One widely used type of polyethylene is Linear Low-Density Polyethylene (LLDPE), a short-branched linear polymer produced by copolymerizing ethylene with an α-olefin [1]. LLDPE offers advantages such as greater flexibility, higher tear resistance, clearer appearance, and better processability compared to other polyethylene types [3].

As the packaging and manufacturing industries develop, global demand for LLDPE continues to increase year by year [4]. Global market data from Bridge Market Research indicates that the LLDPE market value reached USD 47.33 billion in 2024 and is projected to reach USD 70.52 billion by 2032, with an annual growth rate of 5.11% during 2025–2032 [5]. This increase is driven by high demand for polymer materials in the flexible packaging industry, particularly for packaging films and other plastic-based products in the food and beverage sector [6].

Various polymerization technologies have been developed to produce LLDPE, including high-pressure, slurry, gas-phase, and solution processes [3]. Each technology has different operational characteristics. The high-pressure process offers a high production rate but requires significant energy consumption and specialized equipment capable of withstanding high operating pressures [7]. The slurry process operates under two-phase conditions at low temperatures, making it relatively stable and efficient, but its product flexibility is still limited. The gas-phase process is simpler and more economical because it does not use solvents, but it has challenges in controlling reaction heat. Meanwhile, the solution process offers product flexibility and better control of polymer properties, but requires more complex solvent separation and management systems [8].

Among the available technologies, Advanced Sclairtech Technology (AST) is one of the solution-process developments chosen because it offers advantages in process efficiency, operational stability, and flexibility in producing various grades of LLDPE products. However, studies on the techno-economic feasibility of building an LLDPE plant using AST technology remain limited. Therefore, this study aims to analyze the techno-economic feasibility of building an LLDPE plant using AST technology.

2. RESEARCH METHOD

2.1. Selection of Process Technology

Advanced Sclairtech Technology (AST) is a development of conventional Sclairtech technology, introduced in the late 1990s [9]. AST technology was chosen because it offers several advantages over other process technologies. This technology has a very short residence time, about 2–3 minutes, much lower than the Dowlex and Compact processes. This condition provides benefits, including increased operational stability and faster grade-to-grade transitions, thereby minimizing the amount of off-grade product [10]. In addition, compared to conventional Sclairtech processes, AST can operate at lower temperatures, reducing energy consumption and the potential for polymer resin degradation [3]. A comparison of process technologies in polyethylene production is presented in Table 1.

Table 1. Comparison of Polyethylene Production Processes [3]

Parameter	Dowlex	Sclairtech	AST	Compact
Residence time (min)	30	2–3	2–3	2–30
Pressure (bar)	23–27	100–200	Supercritical	100–200
Temperature (°C)	160–220	75–300	<200	130–200
Catalyst	Z-N	$VOCl_3$, $TiCl_4$, DEAO	Advanced Z-N, single-site	Z-N

In addition to having a very short residence time and relatively low operating temperature, the selection of AST is also influenced by the use of superior catalysts. This technology uses high-activity Advanced Ziegler–Natta single-site catalysts that provide more precise control over the polymer chain structure. Compared to conventional Ziegler–Natta catalysts, this catalyst can produce polyethylene with a narrower molecular weight distribution and a more uniform comonomer distribution. The use of this catalyst also enables high ethylene conversion of more than 95% [3].

2.2. Design Basis

Table 2. Plant Design Basis Data

Parameter	Value
Production capacity	287,000 tons/year
Operating days	330 days/year
Operating time	24 hours/day
Main product	LLDPE
Product purity	99%
Process technology	Advanced Sclairtech Technology (AST)
Main raw material	Ethylene
Comonomer	1-octene
Solvent	Cyclohexane
Catalyst type	Advanced Z–N single-site

The plant design is based on an LLDPE production capacity of 287,000 tons per year, with an operating time of 330 days per year and 24 hours per day. The main raw materials are ethylene, the primary monomer; 1-octene, a comonomer; and cyclohexane, the process solvent. The target product purity is 99%, in accordance with the specifications of the packaging and plastic film industry. The plant is located in a petrochemical industrial area with access to raw materials, utilities, and distribution infrastructure. The calculation is based on steady-state conditions with minimal material loss during the process [11].

2.3. Process Description

The production process for LLDPE using AST technology comprises 4 main stages, including raw material preparation, polymerization, product separation and purification, and final product formation [12]. The description of each stage is explained as follows:

- **Preparation of raw materials:** Raw materials in the form of ethylene, 1-octene, and cyclohexane are first treated until they reach the desired operating conditions. Next, the raw materials are mixed with a catalyst before being introduced into the polymerization reactor.
- **Polymerization:** The reaction takes place in a series of CSTR reactors arranged in series at an operating pressure of 202.65 bar and a temperature of around 165°C, which is above the melting point of LLDPE, ranging from 120–125°C [3]. These conditions ensure that the monomer, comonomer, and polymer remain dissolved in the solvent, maintaining a single phase. The reactor is operated adiabatically, so that the heat generated by the exothermic reaction is used to raise the temperature of the reaction mixture in the system.
- **Separation and purification of the product:** The reactor output product is then processed in a separation unit to separate unreacted monomer and solvent, so that both can be reused in the process. After this stage, the polymer is purified from catalyst residues and other impurities before proceeding to the next stage.
- **Final stage of product formation:** The polymer resulting from further purification is then converted into pellet or granule form to meet the product specifications required for industrial applications.

Figure 1 shows a flow diagram of the overall production process, which includes process stages, main equipment, and the direction of material flow.

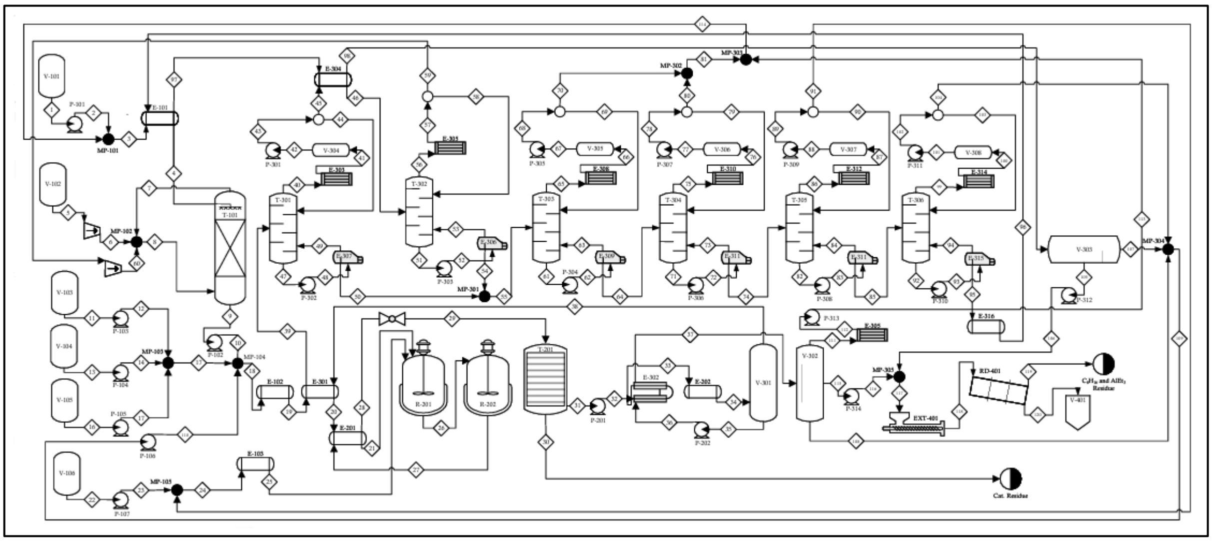

Figure 1. Flow diagram of the LLDPE production process using Advanced Sclairtech Technology (AST).

2.4. Mass and Energy Balance

The LLDPE plant with a capacity of 287,000 tons/year requires 278,827 tons/year of ethylene and about 1,212 tons/year of 1-octene as a comonomer. The production process uses cyclohexane as a solvent, with a requirement of up to 363,674 tons/year and a 15% recycle rate to improve solvent efficiency. The reactor is operated with a conversion of 95%, so most of the monomers can react and form the product. The remaining unreacted monomers are separated in the separation unit and then returned to the recycle system for reuse in the polymerization process. In addition, this AST-based LLDPE plant is equipped with nine heat exchanger units, comprising five heaters and four coolers, which help maintain stable operating temperatures at each stage of the production process.

Table 3. Main Hot Stream and Cold Stream Data

Stream	Tin (°C)	Tout (°C)	Duty (MW)
Hot stream 1	86.59	30	4.465
Hot stream 2	97.10	85	0.009
Hot stream 3	185.98	110	8.379
Hot stream 4	300	76.15	24.931
Hot stream 5	78.58	25	0.091
Cold stream 1	31.07	85	7.210
Cold stream 2	110	300	23.937
Cold stream 3	300	500	2.203
Cold stream 4	64.39	25	0.74

2.5. Heat Integration

Energy efficiency improvements are achieved by designing a Heat Exchanger Network (HEN) that integrates hot and cold streams in the process [13]. The design and evaluation of the HEN are performed using Aspen Energy Analyzer software. The HEN aims to optimally utilize heat from process streams to minimize the need for external energy [14]. The HEN design is analyzed using two methods, namely:

- **Temperature interval method**: Used to determine the minimum energy requirement (MER) of the system and to identify the pinch point as the basis for heat integration.
- **Composite curve method:** Used to visualize the relationship between hot and cold streams so that the process of heat integration and heat exchange matching can be carried out more effectively in HEN design.

By applying HEN, heat from high-temperature process streams can be reused to heat feed and recycle streams. This condition can significantly reduce the need for heating and cooling utilities, thereby lowering energy consumption, operating costs, and carbon emissions from the utility system [15].

2.6. Economic Analysis

The techno-economic analysis of the LLDPE plant using AST technology is carried out based on the operational and financial parameters that have been established as follows:

- **Project parameters:** The plant is designed with a production capacity of 287,000 tons/year and an operating period of 330 days/year with 24 hours of operation per day. The project life is set at 17 years, with a 2-year construction period.
- **Financial parameters:** The economic analysis uses a corporate tax rate of 22%, a minimum return on investment (ROI) of 16% for projects with medium risk levels, and a loan interest rate of 10.27%.
- **Methodology:** The economic evaluation is carried out using the study estimate method with a bare module cost approach to estimate investment costs and production costs in the early stages of plant design.

The economic feasibility of the project is further analyzed using several key indicators, namely Payback Period (PBP), Net Present Value (NPV), Internal Rate of Return (IRR), and Break-Even Point (BEP). In addition, a sensitivity analysis is conducted to determine the effects of changes in raw material prices and product selling prices on the project's economic feasibility.

3. RESULTS AND DISCUSSION

3.1. Heat Integration Analysis

The selection of the ΔTmin value plays an important role in balancing energy efficiency and investment cost. A lower ΔTmin value allows for greater internal heat recovery, but requires a larger heat exchanger area, thus increasing investment costs. Conversely, a higher ΔTmin can reduce the heat-transfer area, decrease the potential for heat recovery, and increase the need for external utilities. Therefore, a ΔTmin of 10°C is chosen because it is a commonly used value in HEN design and provides a good balance between energy efficiency and economic feasibility [16].

Under these conditions, the implementation of HEN successfully reduced the high-pressure steam requirement from 204,541 kg/hour to around 30,770 kg/hour, while the cooling water requirement decreased from 6,491,808 kg/hour to around 1,527,774 kg/hour. These results indicate that the applied heat integration maximized heat recovery between process streams and reduced dependence on external utilities. As a result, energy efficiency increased by more than 80%, and utility costs decreased from around USD 8,400 per hour to USD 1,650 per hour, resulting in savings of approximately USD 6,750 per hour.

Figure 2 shows the composite curve illustrating the relationship between hot and cold flow based on the enthalpy profile.

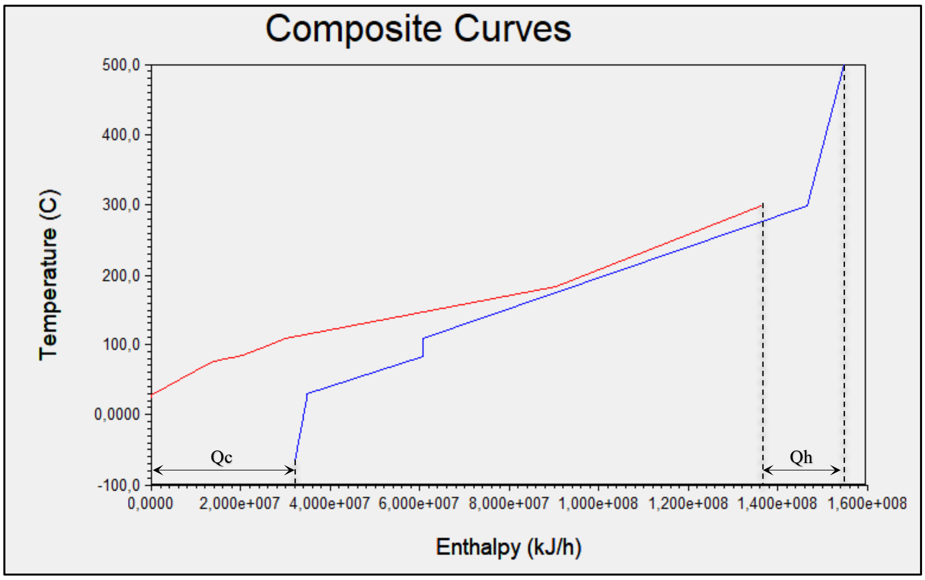

Figure 2. Composite curve.

The analysis of the composite curve shows the relationship between hot and cold streams in the system based on the change in enthalpy with respect to temperature. The red curve represents the hot composite curve, while the blue curve shows the cold composite curve. The horizontal distance between the two curves illustrates the need for external heating and cooling utilities. In this system, the minimum heating utility requirement (Qh) is 2.20 MW, and the minimum cooling utility requirement (Qc) is 5.27 MW. These results indicate that most of the process energy demand can be met by utilizing internal heat between process streams, thereby increasing the system's energy efficiency.

Figure 3 shows the grid diagram of heat integration illustrating the configuration of heat transfer between process streams in the HEN system.

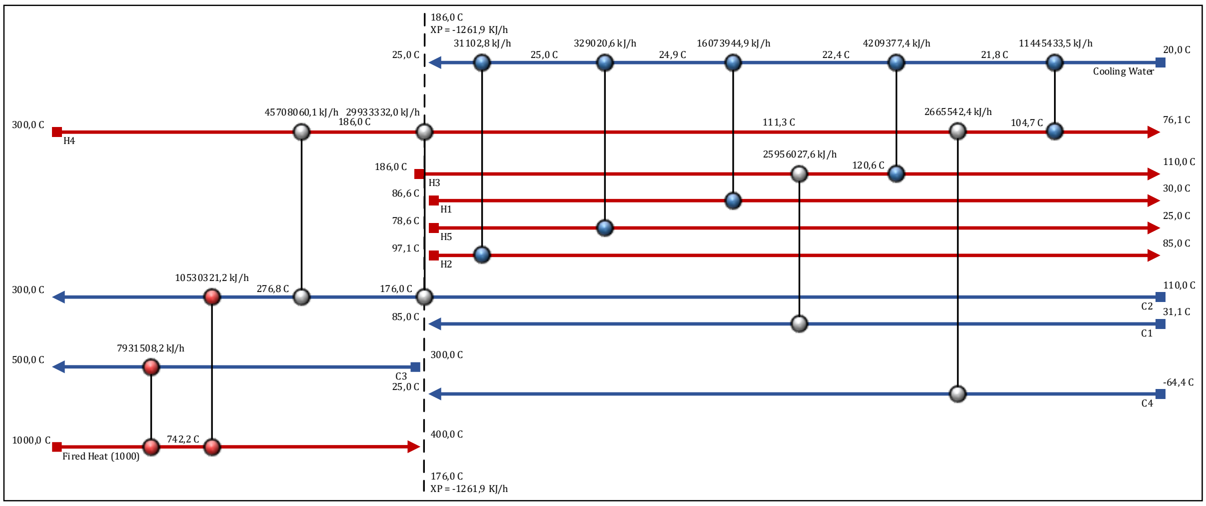

Figure 3. Grid diagram.

The analysis results for the grid diagram show the heat-transfer configuration between process streams in the HEN system. This diagram illustrates the relationship between the hot and cold streams, represented by red and blue lines, respectively. This heat integration system consists of four main hot streams and four main cold streams interconnected through a network of heat exchangers. The intersections of the streams, indicated by the vertical lines, represent heat transfer in the heat exchanger units.

The results indicate that heat from the high-temperature stream is reused to heat the cold stream, thereby reducing the need for external utilities. In addition, the diagram shows the use of heating utilities (fired heat) and cooling utilities (cooling water) at the end of the system to meet the minimum process energy requirements. With this configuration, heat integration within the system can improve energy efficiency and significantly reduce utility consumption.

3.2. Economic Analysis

Table 4. Estimated Capital and Operating Costs

Parameter	Value
Fixed Capital Investment (FCI)	USD 38.01 million
Working Capital Investment (WCI)	USD 4.22 million
Total Capital Investment (TCI)	USD 42.23 million
Total Product Cost (TPC)	USD 516.77 million/year
Product sales	USD 537.21 million/year

Economic analysis was conducted using the study estimate method, with a bare module cost approach based on several realistic assumptions. The estimation results indicate that the Total Capital Investment (TCI) is USD 42.23 million, including process equipment costs, utilities, installation, construction, and other indirect costs. Meanwhile, the annual Total Product Cost (TPC) reaches USD 516.77 million, covering raw material costs, utilities, labor, and maintenance. The selling price of LLDPE is set at USD 1,683 per ton, with a market fluctuation of ±7%.

The main economic indicators obtained from the analysis results include:

- **Payback Period (PBP):** 3.03 years
- **Net Present Value (NPV):** USD 84.15 million
- **Internal Rate of Return (IRR):** 24.53%
- **Break-Even Point (BEP):** 24.46% of the total capacity

The economic analysis indicates that constructing an LLDPE plant using AST technology is feasible. A PBP value of 3.03 years shows a relatively quick return on investment. A positive NPV and an IRR of 24.53% indicate that this project generates profit and meets the minimum feasibility limits for the petrochemical industry. In addition, a BEP value of 24.46% of production capacity indicates that the plant can still operate economically even though its capacity has not reached its maximum.

The evaluation of the economic resilience of the production system was conducted through a sensitivity analysis to changes in raw material and product selling prices. The analysis results indicate that the project remains feasible to execute under a 7% increase in raw material prices. This shows that the plant has fairly good economic resilience against changes in market conditions.

Figure 4 shows the trend in cumulative cash flow, indicating financial sustainability under the baseline conditions.

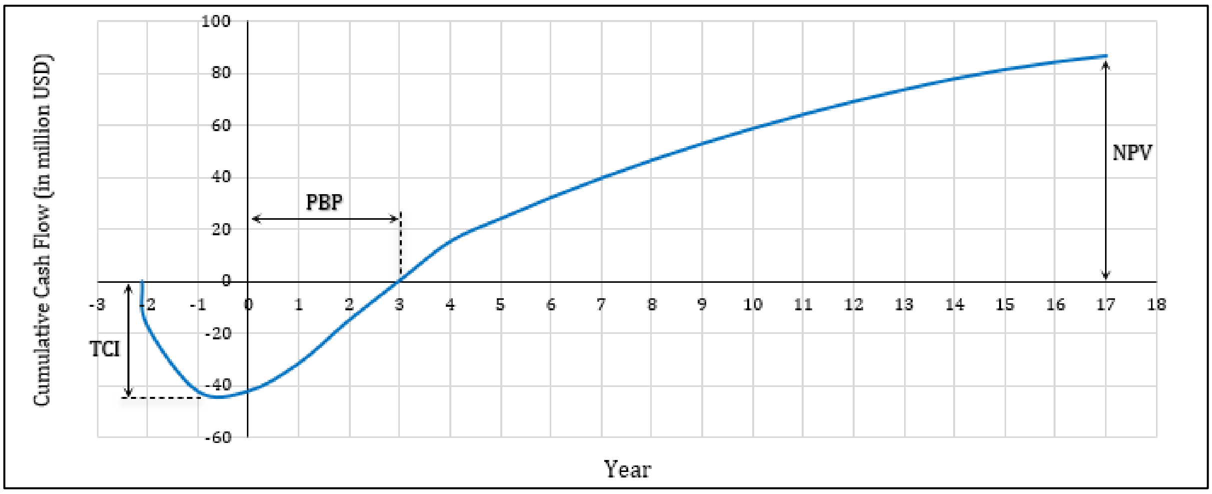

Figure 4. Cash flow diagram.

The cash flow diagram results show the relationship between cumulative cash flow and the project's operating time over 17 years. In the initial stage, the curve is negative due to initial investment expenditures, in the form of Total Capital Investment (TCI), for facility construction and equipment procurement. Once the project begins operating, the curve gradually increases as revenue from product sales is obtained. The curve crosses the zero line around the 3rd year of operation, indicating the Payback Period (PBP), the time required to recover the entire initial investment. After this point, the project starts generating net profit, as indicated by the positive cumulative cash flow. Throughout the project's life, cumulative cash flow continues to increase, reaching a Net Present Value (NPV) of 84.15 million USD. The positive NPV value indicates that the project provides economic benefits and is feasible to implement.

3.3. Comparison of AST Technology with Conventional Sclairtech

The comparison was conducted using AST technology data from this study and conventional Sclairtech process data obtained from previous research [10].

Table 5. Comparison of Estimated Investment and Operating Costs

Parameter	Sclairtech	AST
Operating temperature	300°C	±165°C
Operating pressure	138 bar	202.65 bar
Residence time	2–3 minutes	2–3 minutes
Catalyst	Z–N	Advanced Z–N single-site
Initial steam	219,004 kg/h	204,541 kg/h
Steam after HEN	85,758 kg/h	30,770 kg/h
Initial cooling water	2,901,315 kg/h	6,491,808 kg/h
Cooling water after HEN	23,821 kg/h	1,527,774 kg/h
Utility savings	±60%	>80%
Utility cost savings	USD 2,423/h	USD 6,750/h
PBP	3.21 years	3.03 years
NPV	USD 250.48 million	USD 84.15 million
IRR	16%	24.53%
BEP	31.04%	24.46%

Based on the comparison results, AST technology demonstrates better energy efficiency and improved profitability indicators, such as IRR, PBP, and BEP. However, the NPV remains lower than that of the conventional Sclairtech process. The implementation of HEN in AST technology yields greater utility savings, resulting in significant reductions in steam and cooling water consumption and lower operating costs. In addition, the lower operating temperature and the use of advanced single-site catalysts contribute to improved process stability and product quality. Overall, AST technology shows strong potential for more efficient and sustainable LLDPE production.

4. CONCLUSION

Based on the results of technical and economic analysis, an LLDPE plant using Advanced Sclairtech Technology (AST) is considered feasible for development. The implementation of the Heat Exchanger Network (HEN) successfully increased energy efficiency, resulting in utility savings of more than 80% and significantly reducing the demand for steam and cooling water. From an economic perspective, the project shows a Payback Period (PBP) of 3.03 years, a Net Present Value (NPV) of USD 84.15 million, an Internal Rate of Return (IRR) of 24.53%, and a Break-Even Point (BEP) of 24.46%.

The analysis results indicate that AST technology offers better energy and economic performance than conventional Sclairtech processes. Overall, integrating AST technology with an optimal thermal energy management system can yield a more efficient, economical, and sustainable LLDPE production process, with potential for further development in the petrochemical industry.

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