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Research Article

Improving Energy Efficiency with Energy Recovery for Propylene Production

Andi Nadhif Athallah Hurairah, Danu Pasa Arkajaya, Tenisyah Ramadhani*, Virgi Achmad Fahrezi

Department of Chemical Engineering, Faculty of Engineering, Universitas Diponegoro Jl. Prof. Soedarto SH, Tembalang Campus, 50275, Semarang, Central Java, Indonesia.

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Abstract

Propylene production through the metathesis of 2-butene is a well-established method. However, energy efficiency in this process remains an area of improvement. This study focuses on optimizing energy consumption by integrating heat recovery and reducing the reliance on external energy sources. Simulations were conducted using Aspen HYSYS V11 to compare the basic and modified processes. Modifications included utilizing heat from condensers and coolers to power compressors and heaters, eliminating redundant heating units. Thermodynamic analyses confirmed the endothermic nature of the reactions. Results indicated a significant reduction in total heat flow, from 2.983×10^8 kJ/h to 1.564×10^8 kJ/h, leading to improved specific energy consumption. With a production capacity of 15,400 tons/year, the optimized process demonstrated enhanced energy efficiency and sustainability. This study highlights the potential of process modifications to achieve energy savings, lower production costs, and minimize environmental impact in the chemical industry.

Keywords: Propylene production; 2-butene metathesis; energy efficiency; heat recovery; Aspen HYSYS; process optimization; specific energy consumption; sustainable chemical processes

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1. Introduction

Propylene, CH_2=$CHCH_3$, also referred to as propene, methylethene, 1-propylene, 1-propene, or methylethylene, is an unsaturated aliphatic hydrocarbon characterized by a double bond between its first and second carbon atoms [12]. Propylene is a vital petrochemical product that plays a key role as a primary raw material in the production of numerous materials organic chemicals, such as resins, plastics, synthetic rubber, and gasoline [11]. Currently, propylene is produced mainly from naphtha steam cracking and fluid catalytic cracking (FCC) units, and a small part of propylene is produced from dehydrogenation of propane and metathesis of ethylene and 2-butene units [9]. The fluid catalytic cracking unit (FCCU) is a versatile and complex unit. After the cracking process is performed, the products are separated in a train of distillation columns according to their boiling points. The C4

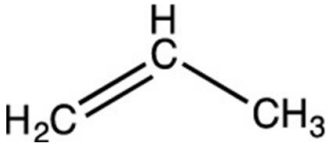

Figure 1. Propylene molecular structure

* Corresponding Author.
Email: tenisyahramadhani@gmail.com (T. Ramadhani)

fraction is separated into a light fraction (denoted as iBB), comprising of isobutene and isobutane, and a heavy fraction (denoted as nBB), which contains mainly 2-butene (about 70%) and n-butane (30%). The latter is a low-value by-product, typically routed to the LPG pool for blending with other components. However, 2-butene can be processed as a reactant in isomerization–metathesis reactions, leading to more cost-attractive olefins, such as ethylene, propylene, and higher olefins [3].

In recent years, there has been significant growth in the demand for propylene. These include propylene production from methanol (MTP), the methanol to olefin (MTO) process, butene cracking, metathesis of 2-butene with ethylene, metathesis of 2-butene and 1-butene, and dehydrogenation of propane. Metathesis is a catalytic process involving the rearrangement of double bonds. n the metathesis of 2-butene, by products such as 1-butene, ethylene, 2-pentene, and 3-hexene are also generated. Therefore, controlling the production of byproducts and ensuring the purification of propylene are of paramount importance. The production of propylene via olefin metathesis reaction is an established method, having been in used in production for tens of years, with a WO_3/SiO_2 catalyst used most frequently [7]. In the olefin metathesis process, typically, metal oxides such as tungsten, molybdenum, and rhenium on a meso porous support like SiO_2 are commonly used [7].

The Figure 2 is the basic flow chart of the propylene production from 2-butene. As presented in Table 1, the first step in the metathesis of 2-butene is isomerization to 1-butene, which is a reversible reaction. Therefore, either 2-butenes, 1-butene, or a combination of both can be employed as the Input feed to the reactor. This metathesis process involves isomerization, self-metathesis of 1-butene, and cross-metathesis between 1-butene and 2-butene. Additionally, at high temperatures, 2-butene can break into ethylene and propylene. It is important to highlight that these are the primary reactions [7].

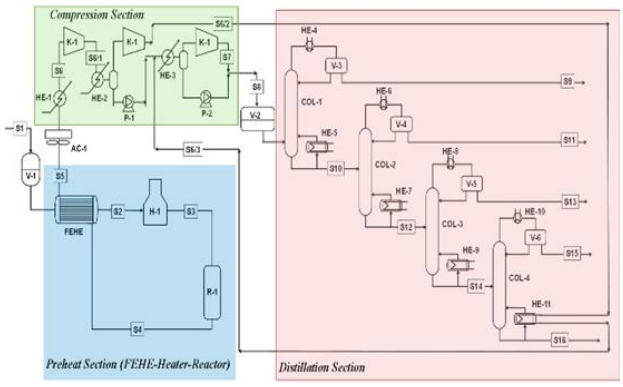

Figure 2. Basic process flow diagram of propylene production [3].

Many previous studies regarding propylene production have discussed increasing mass production or efficiency. However, research on energy efficiency in propylene production is still limited. This efficiency process takes the form of energy savings which aims to maximize economic potential and minimize the impact on the environment [13]. In propylene production, the hydrogenation process is a unit that requires a large amount of energy. As a result of this gap, this research aims to increase energy efficiency by means of energy recovery and heater integration. Simulation process of propylene production from 2-butene using Aspen HYSYS software. Aspen HYSYS allows users to describe processes quickly and effectively because the thermodynamics and unit operations provided are quite accurate and comprehensive [2].

2. Methods

2.1 Property Package

Aspen HYSYS has various thermodynamic equations. The selection of appropriate equations is aimed at analyzing phase equilibrium and the enthalpy of mixed compounds. In the simulation process of propylene production by metathesis of 2-butene, the Peng-Robinson property package is used [8].

2.2 Strategy Modification of Energy Recovery

Energy recovery is a fundamental approach to enhancing the energy efficiency of industrial processes [14], particularly in high-energy-demand systems such as propylene production. This strategy focuses on utilizing waste energy generated during production through devices such as energy recovery systems, coolers, and heaters. These systems are designed to optimize energy use by facilitating heat transfer between process streams without direct contact, reducing external energy consumption, and supporting overall process sustainability. The application of heat integration technology in propane-propylene

Table 1. The main reaction in butene metathesis

Reactions	Process
1-Butene↔2-Butene	Isomerization
1-Butene + 2-Butene ↔ Propylene + 2-Pentene	Cross-Metathesis
1-Butene + 1-Butene ↔ Ethylene + 3-Hexene	Self-Metathesis
2-Butene ↔ Propylene + Ethylene	Cracking

separation has been shown to reduce energy consumption by up to 70% while improving product recovery and operational safety [15].

In the context of propylene production, energy recovery plays a pivotal role in optimizing the system's energy requirements. Waste heat generated during operations, such as multistage compression, can be captured and reused to preheat raw materials or support other energy-intensive stages in the process. [19] highlighted that optimizing low-temperature heat recovery technologies significantly enhances system efficiency, while [9] emphasized the role of integrating power-to-heat systems in reducing greenhouse gas emissions and energy costs.

A key challenge in energy recovery lies in the effective management of temperature increases resulting from compression stages. These temperature increases necessitate cooling to maintain compressor efficiency. Energy recovery systems address this challenge by capturing heat during compression and repurposing it to heat incoming feed streams, thereby minimizing external heating requirements. [5] further noted that sustainable energy recovery technologies not only lower operational costs but also extend equipment lifespan.

To achieve maximum energy recovery, [1] proposed a novel methodology integrating the energy-to-area ratio (Q/A parameter) into the design of heat exchanger networks. This method enables the identification of optimal energy transfer pathways that minimize exchanger areas while meeting energy targets. By implementing this strategy, industrial processes can achieve significant reductions in energy consumption, operational costs, and environmental impacts.

In the propylene production system, specific energy consumption (Sec) [16] can be calculated using the following equation:

$$\text{Sec}\ \left(\frac{\text{kJ}}{\text{ton}}\right) = \frac{\text{Energy consumption}\ \left(\frac{\text{kJ}}{\text{year}}\right)}{\text{production quantity}\ \left(\frac{\text{ton}}{\text{year}}\right)} \quad (1)$$

Through systematic application of energy recovery strategies, propylene production processes can be modified to enhance energy efficiency, reduce dependency on external utilities, and align with sustainable industrial practices.

3. Result and Discussion

3.1 Thermodynamic Studies

Standard reaction enthalpy data at 298 K can be seen in the Table 2 [20]. The ΔG°f for each component at 298 K can be seen in the Table 3.

$\Delta H°f = \Sigma\Delta H°f\ \text{product} - \Sigma\Delta H°f\ \text{reactant}$ [10]

$\Delta H°f = (\Delta H°f\ \text{Propylene} + 2\ \text{Pentene}) - (\Delta H°f\ 1\ Butene + 2\ Butene)$

$= (19.7 - 26.3)\ \text{kJ/mole} - (-0.5 - 7.4)\ \text{kJ/mole}$

$= 1.3\ \text{kJ/mole}$

From the calculation of the heat of reaction, a positif ΔH value is obtained. A positive ΔH indicates that the reaction is endothermic (produces heat). Endothermic enthalpy refers to the amount of energy required for a chemical reaction that absorbs heat from its surroundings. In endothermic reactions, the enthalpy change (ΔH) is positive, indicating that energy must be supplied to break chemical bonds in the reactants [4,18].

$\Delta G°f = \Sigma\Delta G°f\ \text{product} - \Sigma\Delta G°f\ \text{reactant}$

$\Delta G°f = (\Delta G°f\ \text{Propylene} + 2\ \text{Pentene}) - (\Delta G°f\ 1\ Butene + 2\ Butene$

$= (62.2 + 73.5)\ \text{kJ/mole} - (70.4 + 65.5)\ \text{kJ/mole}$

$= -0.2\ \text{kJ/mole}$

$\Delta G° = -\text{R T}\ ln\ K_{298}$

$ln\ K_{298} = \frac{-\Delta G°}{R\ T}$

$= \frac{-(-200\frac{\text{J}}{\text{mole}})}{8.314\frac{\text{J}}{\text{mole K}}\ 298K}$

$= 0.0807$

$K_{298} = exp^{(0.0807)}$

$= 1.0909$

$ln\ \frac{K_{298}}{K} = \frac{\Delta H°_R}{R}\left(\frac{1}{298} - \frac{1}{T}\right)$

$= \frac{6200\frac{\text{J}}{\text{mole K}}}{8.314\frac{\text{J}}{\text{mole K}}}\left(\frac{1}{298} - \frac{1}{784.7K}\right)$

$= 1.5521$

$\text{K} = \frac{1.0909}{exp^{(1.5521)}}$

$= 0.2311$

Table 2. Standard heat of reaction data at 298 K

Component	ΔH°f (kJ/mol)
1-Butene	-0.5
2-Butene	-7.4
Propylene	19.7
2-Pentene	-26.3
Ethylene	52.5
3-Hexene	-47.3

Table 3. ΔG°f each component at 298 K

Component	ΔG°f (kJ/mol)
1-Butene	70.4
2-Butene	65.5
Propylene	62.2
2-Pentene	73.5
Ethylene	68.5
3-Hexene	84.4

When the rate constant *K* approaches zero, the reaction is considered irreversible [6]. This reaction is irreversible because it approaches zero, with a *K* value of 0.2311.

3.2 Difference Between Basic and Modified Process

The simulation of the propylene production for basic and modified process using Aspen HYSYS V11 is as follows. Figure 3 and Figure 5 show the HYSYS simulation and the process flow diagram of basic process, respectively. Whereas for the modified process, the simulation using HYSYS V11 is shown by Figure 4 and the process flow diagram is shown by Figure 6. In the basic process, there is only one recycle process, from the top of the distillation column (Column3) which is recycled to be re-mixed with n-butane and 2-butane feed in tank 1 (Tank1) and the absence of a heat that can be used as a energy recovery. Due to the absence of a heat that can be used as a energy recovery, in the modified process flow diagram have 2 recycle of energy is was use the heat recovery from condensor 3 at distilation column 3 (QCon3) and cooler (Q6) is chosen to be used in energy for operation of compresor (K-1) and heater 2 (HE-2). In addition, heater 1 (HE-1) is also removed because it is considered unnecessary, which improves energy efficiency and reduces production costs.

3.3 Energy Recovery for Compressor and Heater

The n-butene and 2-butene separation process in distillation column 3 and the cooling system in HE-3 require a series of thermal procedures to heat and cool the compounds. In propylene production, the main reaction is classified as an endothermic reaction, which requires a continuous supply of heat to drive the process. As a result, the thermal energy required for this endothermic reaction can be optimized through energy recovery systems [17]. For instance, the heat generated by condenser 3 in distillation column 3 (QCon3) and the cooling system in HE-3 (Q6) can be utilized for other processes, preventing energy waste. The heat from condenser 3 (QCon3) can be repurposed as an energy source for compressor (K-1), while the heat from the cooling system of HE-3 (Q6) can be redirected to supply energy to heater 2 (HE-2). In

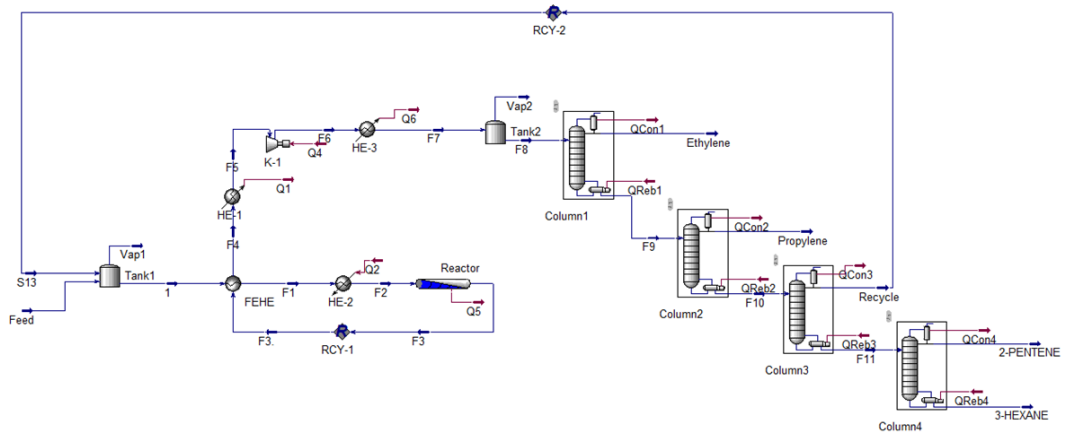

Figure 3. Process flow diagram without modification

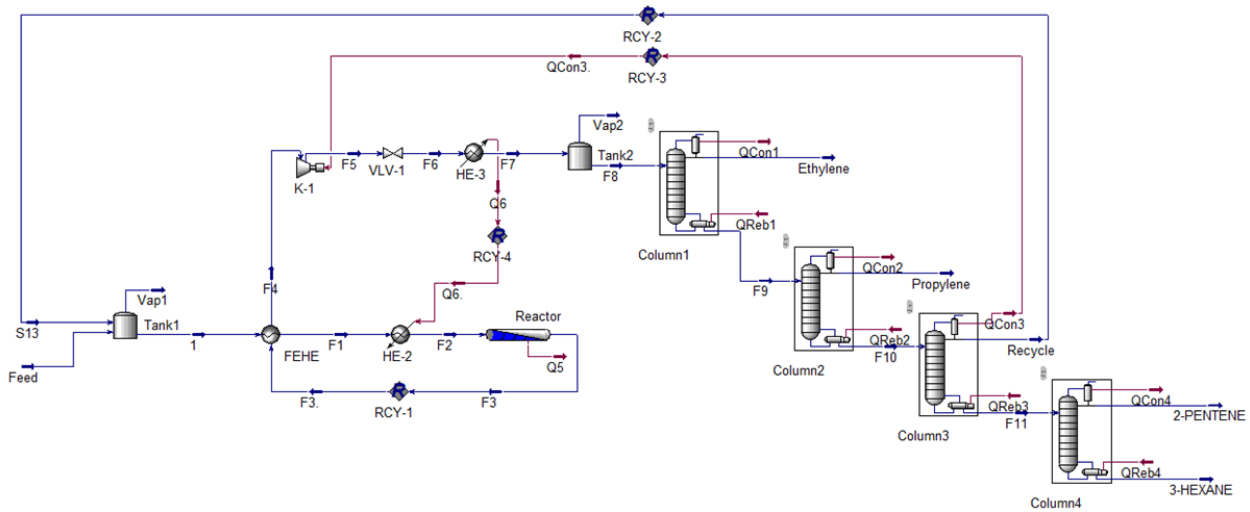

Figure 4. Process flow diagram with modification

the basic process, the compressor (K-1) operates using external energy (Q4), and heater 2 (HE-2) uses another external energy source (Q2).

In the modified process, however, the compressor (K-1) utilizes energy from the condenser in distillation column 3 (QCon3), and heater 2 (HE-2) operates using energy recovered from the cooler HE-3 (Q6). This modification significantly improves energy recovery efficiency, reduces dependency on external energy sources, and enhances process sustainability.

With this series of modification processes, the heat generated from the condenser 3 (QCon3) at distillation column 3 and cooler HE-3 (Q6) will not be wasted. In addition, the use of an energy recovery by using the heat from condenser 3 (QCon3) from distillation column 3 and cooler HE-3 (Q6) as a energy for operation in compressor (K-1) and heater 2 (HE-2) will be more efficient in energy than using a Q4 and Q2 that requires additional energy during the process.

3.4 Comparison of Energy Efficiency after Optimization

According to the research we have done, there is an effect of increasing energy efficiency during the simulation process before and after modification. Here in Figure 3 and Figure 4, there is a comparison of process simulation and modification of propylene production with 2-butene using ASPEN HYSYS V11. The following table compares energy before and after modification.

Based on the data in Table 4, it is known that the amount of heat flow in the simulation before and after modification has decreased, which shows considerable energy efficiency. In addition to less energy used, this also indirectly reduces the number of tools used such heater (HE-1). For comparison, the specific energy consumption (Sec) value can be used as a reference to calculate energy efficiency. In the production of propylene

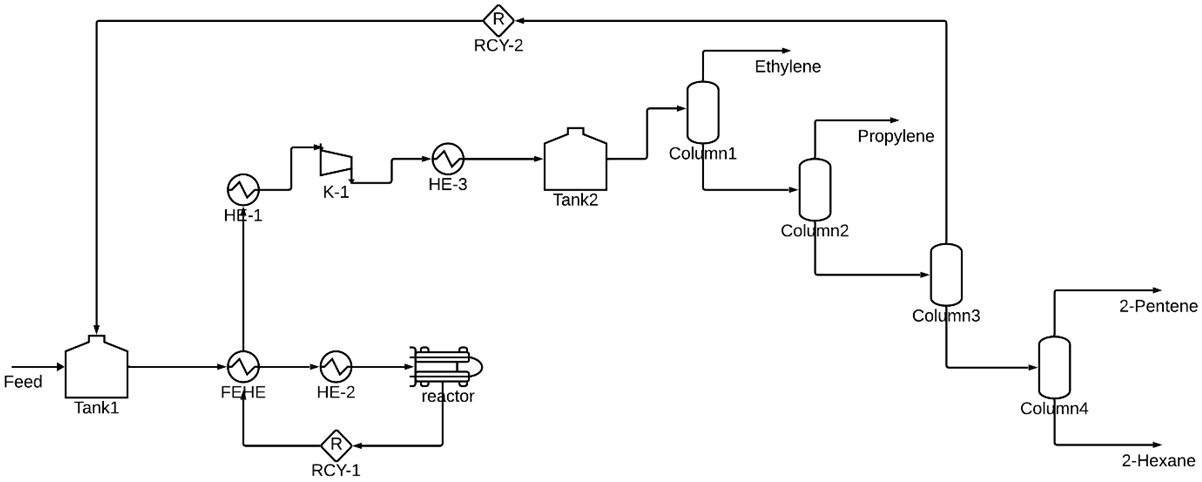

Figure 5. Process flow diagram basic

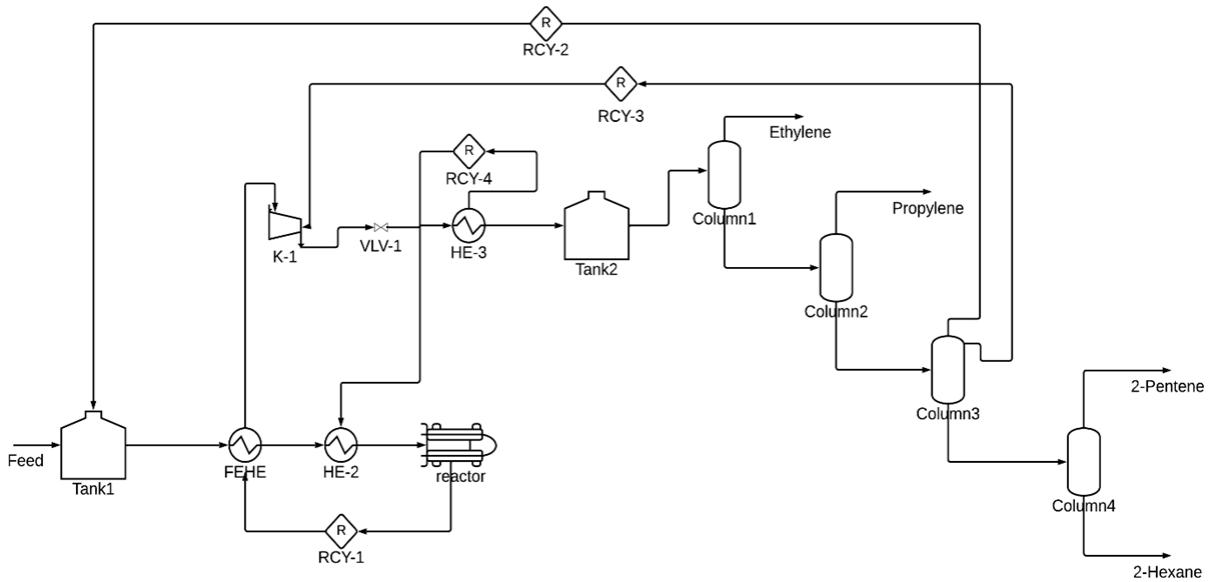

Figure 6. Process flow diagram with modification

with a capacity of 15,400 tons/year, the specific energy consumption is summarized in Figure 7.

4. Conclusion

This study highlights the significant potential of energy recovery and heater integration to enhance energy efficiency in propylene production via 2-butene metathesis. Using Aspen HYSYS V11 simulations, the process was optimized, reducing total heat flow from 2.983 kJ/h to 1.564 kJ/h, eliminating redundant heating units, and utilizing waste heat from condensers and coolers to power compressors and heaters. These improvements reduce external energy reliance, lower costs, and support sustainable chemical manufacturing. The findings advance knowledge on minimizing energy waste and environmental impact, with future research suggested on scaling this method and integrating renewable energy sources.

Credit Author Statement

Author Contributions: A. N. A. Hurairah: Resources, Writing – Review & Editing, Supervision; D. P. Arkajaya: Methodology, Formal Analysis, Writing – Original Draft Preparation, Visualization; T. Ramadhani: Methodology, Validation, Writing – Review & Editing, Data Curation; V. A. Fahrezi: Conceptualization, Software, Project Administration, Investigation, Resources, Writing – Review & Editing, Validation. All authors have read and agreed to the published version of the manuscript.

Table 4. Comparison of energy used

Unit	Basic (kJ/h)	Modification (kJ/h)
Q2	1.400×10^8	-
Q4	3.287×10^7	-
QReb1	3.917×10^7	4.995×10^7
QReb2	8.682×10^6	7.550×10^6
QReb3	7.737×10^7	9.877×10^7
QReb4	1.275×10^5	1.294×10^5
Total	2.983×10^8	1.564×10^8

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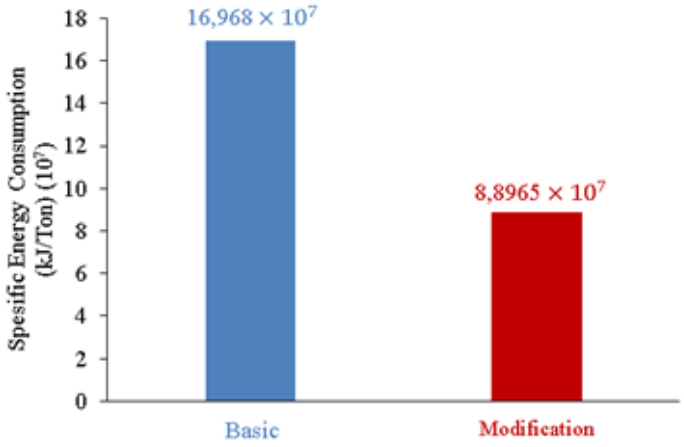

Figure 7. Specific energy consumption of 15,400 tons/year production capacity

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