The Preliminary Design of Ethylene Glycol Plant Using Coal Gasification

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DOI: https://doi.org/10.51244/IJRSI.2026.1304000159

Received: 06 April 2026; Accepted: 12 April 2026; Published: 11 May 2026

ABSTRACT

Indonesia possesses abundant coal reserves that can be utilized as an alternative feedstock for ethylene glycol (EG) production. This study presents the preliminary design of an EG plant based on a coal gasification route, offering an alternative to the conventional ethylene oxide hydration process. In this process, coal is converted into synthesis gas (syngas) via gasification, followed by syngas conditioning and catalytic conversion into ethylene glycol. The proposed plant has a production capacity of 50,000 tons per year and operates for 330 days annually, 24 hours per day.The plant is planned to be located in Separi Village, Tenggarong Seberang District, Kutai Kartanegara Regency, East Kalimantan Province, covering an area of 16,000 m². The organizational structure adopts a line-and-staff system with a total workforce of 149 employees. Water for the process is supplied from the Mahakam River, while electricity is provided by the State Electricity Company (PLN) and supported by an on-site generator with a capacity of 10,420 kW. Economic evaluation indicates that the project is financially feasible, with a pay-out time (POT) of 3.57 years, a break-even point (BEP) of 25.71%, and an internal rate of return (IRR) of 24.01%.

Keywords: Coal, gasification, ethylene glycol preliminary plant design.

INTRODUCTION

Industry in Indonesia continues to grow along with the increasing demand for various chemical products. Currently, Indonesia still relies on imports of ethylene glycol from various countries, such as the United States, the Netherlands, the United Kingdom, Japan, and Canada, to meet domestic needs, especially in the polyester industry [1]. Ethylene glycol is one of the main raw materials in the textile and plastics industry, with approximately 27% of its production used for the manufacture of polyester fibers. This compound plays an important role in polyester synthesis, especially in the production of polyethylene terephthalate (PET), which is widely used in the packaging industry, such as plastic bottles, as well as in the manufacture of synthetic fibers for textiles. In addition, ethylene glycol (EG) is used as a raw material in the production of paints, brake fluids, solvents, alkyl resins, printing inks, cosmetics, and coolants [2].

Ethylene glycol, or 1,2-ethanediol, is an organic compound with the molecular formula $C_2H_6O_2$ containing two hydroxyl groups (-OH). This liquid is colorless, odorless, and has a sweet taste. Ethylene glycol is hygroscopic and can mix completely with polar solvents such as water, alcohol, glycol ethers, and acetone. At low temperatures, ethylene glycol tends to form a very viscous liquid and is difficult to crystallize [3]. Coal can be used as an alternative raw material in the EG production through gas synthesis (syngas), replacing the petroleum-based ethylene oxide hydration process. Utilizing coal as a carbon source for ethylene glycol production is a strategic solution in optimizing abundant coal reserves, especially in countries with large coal resources and reserves [4]. Coal is a fossil fuel derived from black or dark brown sedimentary rock that is flammable. Its formation takes place over millions of years through a geological process called coalification, in which organic materials such as leaves, twigs, and tree trunks undergo decomposition and compaction. The main elements that make up coal are carbon (C), hydrogen (H), and oxygen (O), with other elements such as sulfur (S) and nitrogen (N) in small amounts [5]. Based on the level of carbonization, coal is classified into

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IV April 2026

several types, ranging from those with the lowest to the highest carbon content, namely peat, lignite, sub-bituminous, bituminous, and anthracite. Coal with a high carbon content tends to have a higher calorific value, while high sulfur content can affect exhaust gas emissions during combustion [6].

From an economic perspective, coal-based ethylene glycol production has significant advantages compared to petroleum-based methods. The investment and operational costs of equipment in the coal-based process are lower, while the conversion efficiency remains high. Studies show that coal-based EG production costs can be saved up to 39.50% compared to petroleum-based methods, even though production yields remain comparable. These savings are mainly due to differences in raw material prices, where petroleum prices tend to be more volatile and more expensive than coal [7]. On an industrial scale, several methods can be used in the ethylene glycol production process, including ethylene carbonate hydration, ethylene oxide hydration, and gasification [10]. The ethylene carbonate hydration process involves a direct reaction between ethylene oxide and CO_2, forming an intermediate compound, ethylene carbonate, which is then hydrolyzed to ethylene glycol. In the initial stage, ethylene oxide is obtained through the oxidation of ethylene using a specific catalyst. The resulting oxidized gas is then directed to an absorption tower, where the ethylene oxide is absorbed by an absorbent solution before further processing. The ethylene oxide then reacts with CO_2 in the carbonation unit, producing ethylene carbonate as an intermediate product [11]. The production of ethylene glycol through the ethylene oxide hydration process consists of several main stages. The first stage is the preparation of raw materials, namely ethylene oxide and water, which must be conditioned to meet reactor specifications. Next, in the ethylene glycol synthesis stage, ethylene oxide reacts with water in a reactor at a certain temperature and pressure to produce ethylene glycol. This reaction takes place adiabatically and non-isothermally, which means the reactor must have good insulation to prevent heat loss to the environment [10].

Recent developments of the EG production have increasingly focused on alternative feedstocks and sustainable process routes. Conventional EG production via ethylene oxide hydration remains dominant; however, its dependence on petroleum-based resources raises concerns regarding long-term sustainability and economic volatility [12]. Recent studies have explored coal-based syngas conversion as a promising alternative, particularly for countries with abundant coal reserves [13]. For instance, several works have demonstrated that coal gasification followed by catalytic conversion of syngas into dimethyl oxalate and subsequent hydrogenation to EG offers competitive yields and improved carbon utilization efficiency [13, 14]. In addition, advancements in catalytic systems and reactor design have significantly improved the efficiency of syngas conversion pathways [15, 16]. Recent research highlights the role of copper-based catalysts in enhancing the hydrogenation of dimethyl oxalate to ethylene glycol, achieving high selectivity and conversion rates under optimized conditions [17, 18]. Techno-economic analyses conducted in recent studies also indicate that coal-based EG production can be economically competitive, particularly in regions with stable coal supply and high oil price volatility [13, 19].

Despite these advancements, there is still a lack of integrated studies that combine process design, mass and energy balance, and economic evaluation specifically tailored to Indonesian conditions. Most existing studies focus either on reaction mechanisms or standalone economic assessments without considering site-specific factors such as local resource availability, infrastructure, and market demand. Therefore, this study addresses this gap by developing a comprehensive preliminary design of an ethylene glycol plant based on coal gasification, incorporating technical, economic, and regional considerations relevant to Indonesia.

METHODS

Process Selection

Gasification is a coal conversion technology that converts solid fuel into synthetic gas (syngas), consisting of carbon monoxide (CO) and hydrogen (H_2). This syngas can be used as fuel or as a raw material in the chemical industry to produce compounds such as methanol, ammonia, and synthetic fuels [4]. The gasification process occurs in a gasifier, a reactor designed to convert coal through thermochemical reactions at high temperatures, ranging from 1000–1500°C, depending on the type of gasifier used [20]. A comparison of these processes can be seen in Table 1.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IV April 2026

Table 1. Comparison of Ethylene Glycol Production Processes

Types of Processes	Raw Materials	Economics	Sustainability
Ethylene Carbonate Hydration	Crude oil	Ethylene oxide dependence	Depends on the availability of CO_2
Ethylene Oxide Hydration	Crude oil	Crude oil prices fluctuate	Unsustainable (fossil-based)
Gasification	Coal	Non-petroleum alternative, suitable for countries with large coal reserves	Potentially sustainable through process optimization

Production capacity calculations for the next few years have been carefully conducted to ensure optimal production needs are met. Based on data published by the Central Statistics Agency (BPS), information on Indonesia's ethylene glycol imports can be found in Table 2.

Table 2. Ethylene Glycol Import Data [8]

Year	Production (Tons/Year)	i (%)
2017	400,025.98	0
2018	422,027.98	5.50
2019	432,047.76	2.37
2020	371,882.15	13.92
2021	438,225.94	17.84
2022	449,208.17	2.50
Average		2.38

Determining factory capacity can be calculated using the following Eq. (1) [9]:

$$F = P(1 + i)^n \tag{1}$$

Where,

F = Producted volume in the predicted year

P = Producted volume in the last year

i = Average annual growth rate

n = Difference in years

Therefore, the producted volume in the predicted year of 2029 is approximately 507,295.14 Tons. Based on production capacity calculations, the ethylene glycol plant has a capacity of 50,000 tons per year. This capacity is designed to meet 10% of the total domestic ethylene glycol import demand, utilizing coal as the primary raw material.

Plant location

To determine a plant location, several important factors must be considered, including raw material availability, marketing strategy, utility needs, geographic and social conditions, transportation systems, and labor availability [21]. Based on these considerations, the coal-based ethylene glycol plant will be located in Separi Village, Tenggarong Seberang District, Kutai Kartanegara Regency, East Kalimantan Province, near the Mahakam River.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IV April 2026

RESULTS AND DICUSSIONS

Process Description

The process used in this ethylene glycol manufacturing plant is the gasification process of coal, the primary raw material. Gasification offers an alternative to reducing petroleum use due to its high conversion rate. The following is a general overview of ethylene glycol production through the gasification process, as seen in Figure 1.

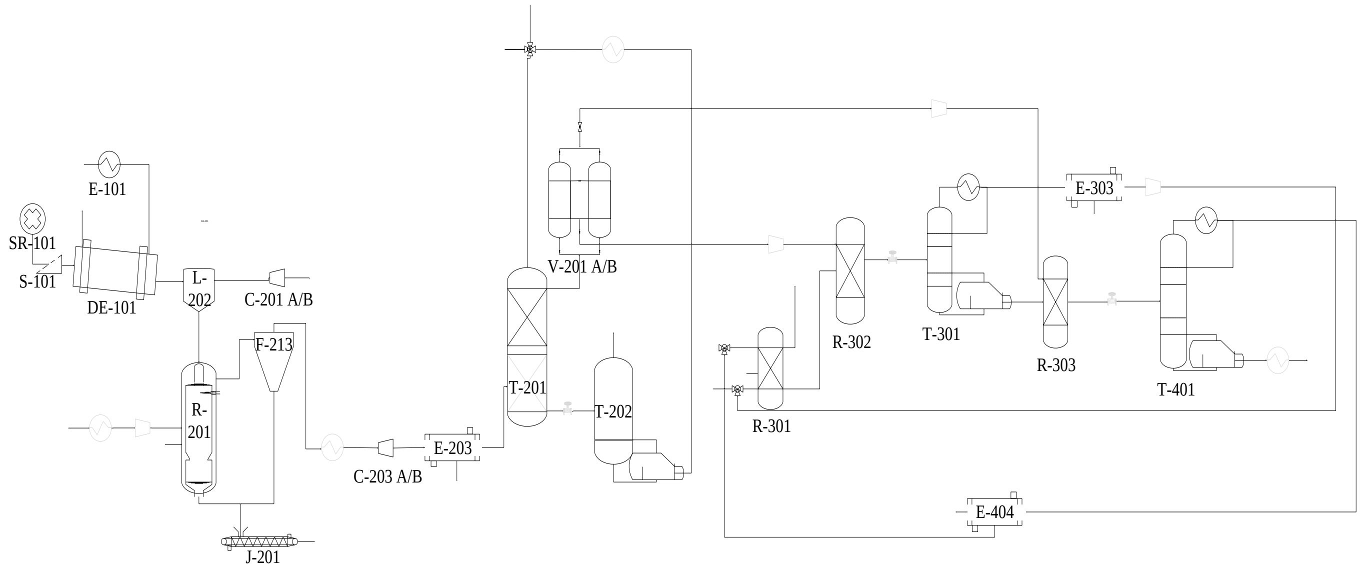

Figure 1. Process Flow Diagram (PFD) for Ethylene Glycol Production

Figure 1 shows that the gasification process begins with coal being taken from the stockpile, crushed in a hammer mill (SR-101) to a size of 0.2 mm, and then filtered using a screener (S-101) to achieve a uniform 30-mesh size. The drying process takes place in a rotary dryer (DE-101) using hot air from a heater (E-101) heated to 200°C. The dried coal is then sent to the lock hopper (L-202), where the material pressure is increased to 40 bar using high-pressure nitrogen from a compressor (C-201 A/B) before entering the gasification reactor (R-201). In this reactor, the coal undergoes a reaction at a temperature of 1500°C and a pressure of 40 bar, consisting of two zones:

Pyrolysis Zone

$$Coal \rightarrow CO + H_2 + CO_2 + H_2O + H_2S + N_2 + CH_4 + C + Ash \quad (2)$$

Gasification Zone

$$C + 0,35\ O_2 \rightarrow 0,97\ CO + 0,03\ CO_2 \quad (3)$$

$$C + H_2O \rightarrow CO + H_2 \quad (4)$$

$$C + CO_2 \rightarrow 2\ CO \quad (5)$$

$$C + 2\ H_2 \rightarrow CH_4 \quad (6)$$

$$H_2 + 0,5\ O_2 \rightarrow H_2O \quad (7)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (8)$$

The gasified ash is separated from the gas in the cyclone (F-201), then cooled in the screw cooling conveyor (J-201) to 48°C before being stored in the ash silo (L-203). Meanwhile, the hot gas is cooled in the cooler (E-

202) and its pressure is reduced in the expander (C-203 A/B) from 40 bar to 6 bar to facilitate the water condensation process. After that, the gas is cooled in the condenser (E-203) before entering the absorber (T-201), where a 15% MEA (monoethanolamine) solution is used to remove acid gases such as CO_2 and H_2S. The purified gas is then separated in the pressure swing adsorption (PSA) (V-201 A/B) to obtain pure hydrogen.

Hydrogen along with other gases is used in the methyl nitrite reactor (R-301) to react methanol, nitrogen monoxide (NO), and oxygen (O_2) to form methyl nitrite (CH_3ONO) with the reaction of Equation (9):

$$2\ CH_3OH + 2\ NO + \frac{1}{2}\ O_2 \rightarrow 2\ CH_3ONO + H_2O \qquad (9)$$

The methyl nitrite formed then reacts with carbon monoxide (CO) in a dimethyl oxalate reactor (R-302) to produce dimethyl oxalate ($(CH_3)_2C_2O_4$) through the reaction of Equations (10) and (11):

$$2\ CH_3ONO + 2\ CO \rightarrow (CH_3)_2C_2O_4 + 2\ NO \qquad (10)$$

$$2\ CH_3ONO + CO \rightarrow CO(OCH_3)_2 + 2\ NO \qquad (11)$$

Dimethyl oxalate is then purified in a distillation column (T-301) before being reacted with hydrogen (H_2) in an ethylene glycol reactor (R-303) at 235°C and 30 bar. This hydrogenation reaction takes place in two stages as shown in Equations (12) and (13):

$$(CH_3)_2C_2O_4 + 2\ H_2 \rightarrow 2\ CH_2OHCO_2CH_3 + CH_3OH \qquad (12)$$

$$CH_2OHCO_2CH_3 + 2\ H_2 \rightarrow 2\ (CH_2OH)_2 + CH_3OH \qquad (13)$$

The resulting ethylene glycol is then purified in a distillation column (T-401), where the main product, 99% pure ethylene glycol, is recovered from the bottom of the column. The methanol formed as a by-product is returned to the methyl nitrite reactor (R-301) after being separated in the condenser (E-404). The pure ethylene glycol product is then cooled in a cooler (E-401) to a safe temperature before being stored in a storage tank (TK-401) for distribution.

Mass Balance

Based on the mass balance calculation, this ethylene glycol plant requires 4,587 kg/hour of coal, 6.24 kg/hour of MEA, 296.88 kg/hour of N2, 2,012 kg/hour of O2, and 6,789 kg/hour of methanol, which will produce 6,318.89 kg/hour of ethylene glycol. This plant is planned to operate 330 days a year, 24 hours a day with a raw material capacity of 50,000 tons/year.

Energy Balance

Based on energy balance calculations, the gasification process in the entrained bed gasifier reactor requires 17,922,076 kJ/hour of energy. Meanwhile, the ethylene glycol purification stage by distillation requires 23,121,739 kJ/hour of energy.

Utility

The utility unit is a crucial component in supporting the success of the production process. Its function is to ensure the smooth operation of the factory and maintain production continuity [22]. To design an ethylene glycol plant, there are several main utility units, namely:

a. Water treatment unit: Responsible for processing and supplying water required for various production processes, including as raw material, coolant, and other needs in the factory [22, 23].

b. Steam supply unit: Generates and distributes steam required in various production stages, including as a source of energy to drive the turbines in the generators [22, 24].

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IV April 2026

c. Power generation unit: Provides electricity to all factory operational systems to ensure smooth production [22, 24].

d. Fuel supply unit: Responsible for providing and managing fuel used by factory machinery and equipment to maintain operational efficiency [22].

e. Waste treatment unit: Processes and disposes of production waste in accordance with applicable environmental quality standards to prevent pollution and maintain ecosystem balance [25, 26].

Based on the calculation results, the water requirements used in this ethylene glycol plant for steam, cooling water, and process water are 79,094 kg/hour, 2,583,648.39 kg/hour, and 276.89 kg/hour, respectively. The total water requirement is 294,877.73 kg/hour. And the total electricity requirement obtained from PLN is 10,419.66 kW, and a diesel-fueled generator as a backup.

Economic Analysis

The results of the economic analysis calculations are shown in Table 3.

Table 3. Results of economic analysis calculations

Economic Indicators	Value
BEP	3.57 Years
POT	25.71 %
IRR	24.01 %
MARR	18.00 %

The Break-Even Point (BEP) is the equilibrium point where total revenue equals total costs, both fixed and variable. In this situation, the company experiences neither profit nor loss. Payout Time (POT) is the time required to recoup the initial investment from the net profit generated. The Internal Rate of Return (IRR) is the rate of return on an investment, indicating the relative profit that can be obtained compared to the capital invested. The Minimum Attractive Rate of Return (MARR) is the minimum rate of return an investor expects before deciding to undertake a project [27].

Because the Internal Rate of Return (IRR) obtained exceeds the Minimum Acceptable Rate of Return (MARR) of 18% per year (Table 8-1 Peter, 2002) with a medium risk level, it can be concluded that establishing this ethylene glycol plant is economically feasible.

CONCLUSIONS

The Ethylene Glycol Plant Preliminary Design from Coal Gasification with a capacity of 50,000 tons/year is planned to operate 330 days per year with a gasification process using an entrained bed gasifier. This plant is located in Tenggarong Seberang District, Kutai Kartanegara, East Kalimantan, with a Limited Liability Company (PT) business entity and a line-staff organizational structure involving 149 workers. The need for coal raw materials is 4,587 kg/hour, with the use of steam, cooling water, and process water of 79,094 kg/hour, 2,583,648.39 kg/hour, and 276.89 kg/hour, respectively. Water is sourced from the Mahakam River with a total requirement of 294,877.73 kg/hour, while electricity is supplied from PLN at 10,419.66 kW with a diesel generator as a backup. Based on the economic analysis, the Pay Out Time (POT) was 3.57 years, Break Even Point (BEP) 25.71%, and Internal Rate of Return (IRR) 24.01%, indicating that this project is feasible to be established.

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