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Financial Evaluation of Alternatives for Industrial Methanol Production Using Renewable Energy with Heat Pump Technology

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Abstract: The purpose of this study was to evaluate the economic and financial alternatives for industrial methanol (MeOH) production in Colombia, taking advantage of renewable energy and heat pump technology. The main objective was to analyze the feasibility of converting an existing hydrogen production plant into a methanol synthesis plant at a refinery located in the Magdalena Medio region. The approach included the electrification of industrial processes using heat pumps, along with the incorporation of carbon capture technologies, using renewable photovoltaic energy. The study compared this proposal with a conventional fossil fuel-based process, using natural gas for the generation of thermal steam. To carry out the analysis, simulations of the methanol production process were performed using the ASPEN HYSYS V12.1 software, evaluating the mass and energy flows, as well as the investment (CAPEX) and operation (OPEX) costs. The determination and comparison of the levelized cost of methanol production (LCOM) for the different alternatives and market price scenarios reveal that the incorporation of a heat pump in the industrial process can significantly improve energy efficiency, reduce operating costs associated with energy, water/steam, and fuel gas, and allow for the financial viability of projects that use renewable energy and carbon capture and utilization (CCU) technologies. The results show that electrification through heat pumps and renewable energy improves energy performance by 15%, reduces operational costs by up to 25%, and lowers the levelized cost of methanol production (LCOM) to 456–492 USD/ton. These improvements demonstrate the financial viability and sustainability of methanol production in Colombia using this technology.

Keywords: electrification of chemical processes; heat pump; financial analysis; methanol

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1. Introduction

Projects or initiatives that cover the use of renewable energy are of great interest and importance today, given the implications and contributions they provide for the sustainability of society and contribution to global warming [1,2]. Among the main challenges that projects face beyond the technical challenge is obtaining adequate financial support to ensure the economic viability of businesses in the long term [3]. Aspects of performance and efficiency of the developed technologies affect the economic results of the projects [4] in the same way that the fluctuation and instability of renewable energy production for the photovoltaic case ultimately generates additional costs (depending on the type of user), which must be compensated for at a technical level, with electric energy storage systems such as Li-ion batteries or VRF thermal storage systems [5], among others. Currently, novel proposals called pumped thermal storage (PTES) are being studied.

These are systems similar to heat pumps (HPs), but in this case using water tanks as a means of thermal storage of solar energy, to then transfer this energy through a working fluid (R1233zdE) [6] to a low-temperature sink, which finally allows steam to be generated for the production of electricity [7]. The above are just some of the technological aspects that require a significant degree of maturity in order to generate confidence in the end user or investor. Currently, the financial sustainability of projects linked to renewable energies, bioprocesses or decarbonization show deficits and guarantees of economic resources over time, given that the timely and competitive returns that encourage investment are not always clear [8] at the government level, as well as uncertainties that arise in some regions in relation to policies associated with the prices of inputs, raw materials and products. In the end, it is not clear how society and markets can recognize decarbonization projects and the efficient use of renewable energies [9].

Methanol is a so-called primary fuel used for the production of a wide variety of chemical by-products, with an estimated production of 75 million tons by 2023 with an annual growth of 3.6%. The main demands today are grouped into the following: 35 million tons used for the production of olefins, with subsequent use in the petrochemical industry [10], 12 million as a mixture in gasoline and in combustion processes [11], and 10 million tons related to the production of MTBE, an important chemical additive of the ether family [12], which is an important improver of the properties of cetane in diesel [13] and is used for combustion engines in heavy machinery. The rest of the demand today is distributed between a variety of chemicals, biodiesel production, and fuel cells for electrical generation used in vehicles. Methanol production today is classified in a similar way to hydrogen production into three main categories [14]: gray methanol, which is the widely known and developed production from natural gas as a raw material, blue production, which uses the same mechanisms but adding carbon capture and storage (CCS) technologies to reduce emissions, and finally green production, which uses renewable energy (biomass, photovoltaic or wind) to induce water electrolysis to produce hydrogen (Figure 1), one of the fundamental raw materials for the catalytic process, which, together with the CO_2 produced by the SMR process or by CCU, which is one of the proposals in this work, allows the production of methanol according to the following chemical equations studied in the literature [15–17]:

$$CO + 2H_2 \leftrightarrow CH_3OH \tag{1}$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \tag{2}$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \tag{3}$$

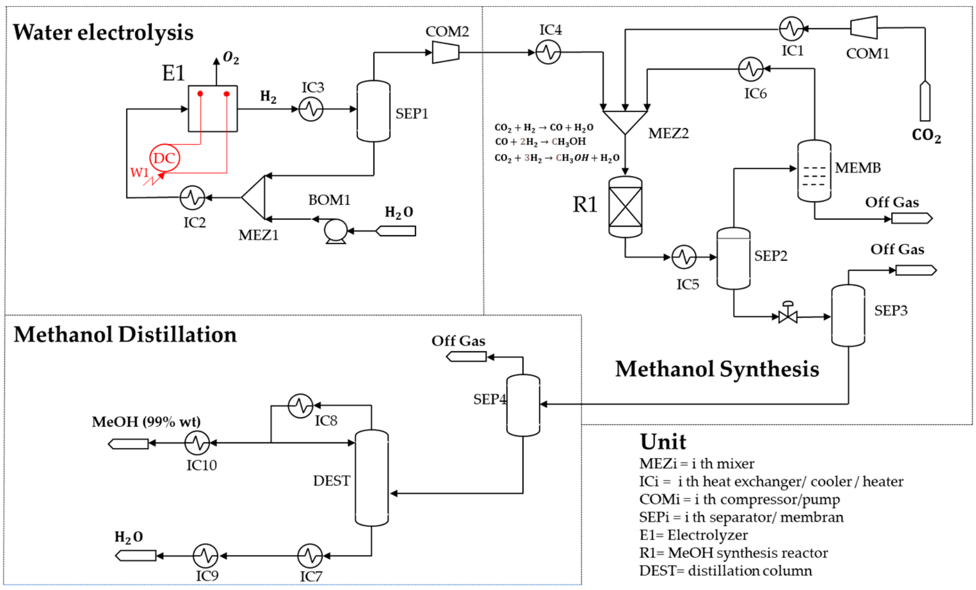

Figure 1. Process flow diagram of a "green" methanol production by electrolysis (ALT5).

In this study, the process flow diagrams, calculations, and estimates of a conventional plant for methanol production [18] were initially developed, presenting an improved technological variant compared to the commonly used SMR process in the industry. This variant, known as methane bi-reforming or combined reforming (CR) [19], offers improvements in terms of carbon emission reduction and energy efficiency. The study also examines the use of heat pumps to enhance energy efficiency in industrial distillation processes, specifically in methanol production. The integration of heat pumps allows for the recovery of low-temperature heat generated during the distillation process and its transfer to areas requiring higher thermal energy. Additionally, carbon capture and utilization (CCU) technology is incorporated to reduce CO_2 emissions by reusing the captured CO_2 in methanol synthesis, which not only contributes to emissions reduction but also improves the sustainability of the process in terms of energy and economics. This approach strengthens the potential for methanol production in Colombia by leveraging renewable energy sources such as photovoltaic solar power, which provides the energy necessary to operate both the heat pumps and the carbon capture system.

This process was simulated using ASPEN HYSYS V12.1 software with operational conditions found in the literature and experience of similar plants for hydrogen production. The results obtained from the process simulation, together with the mass and energy balances, were analyzed to evaluate the greenhouse gas emissions and volumetric production (methanol) of the process. A technological variant of the methanol production process is then proposed, consisting of modifying or adapting a plant originally arranged for the generation of hydrogen with SMR technology [20], located in the Magdalena Medio region, Colombia, to be a fuel methanol production plant. The plant incorporates, for the first time in Colombia, a heat pump (HP) system in its distillation column.

It is important to highlight that the two largest refineries in Colombia (Magdalena Medio and Cartagena) do not have this type of technology for their separation systems. The heat pump has been studied for some years as an application to easy hydrocarbon separation processes [21] due to the high energy efficiency provided in relation to a conventional separation system, where significant savings of up to 60% [22] in consumption can be obtained. Likewise, in the present study, a carbon capture technology (CCU) with DEA [23] is implemented, which is a widely known process at the industrial level (See Section 2.1) that in this case is used as an alternative to recover CO_2 emissions (generated in the flue gas of the reforming furnace) [24] to be reused later in the synthesis and production process of methanol. Finally, the proposed process is complemented by a renewable energy supply source (photovoltaic) from a plant located in the Magdalena Media region, which guarantees competitive rates for the electricity supplied.

The concept of heat pumps (HPs) is based on transferring heat from a low-temperature medium to a higher-temperature medium with the help of an external energy source or work applied to a fluid in the system [25,26]. The system is analogous to a reverse refrigeration cycle (Figure 2), which has enormous application potential, mainly in distillation columns.

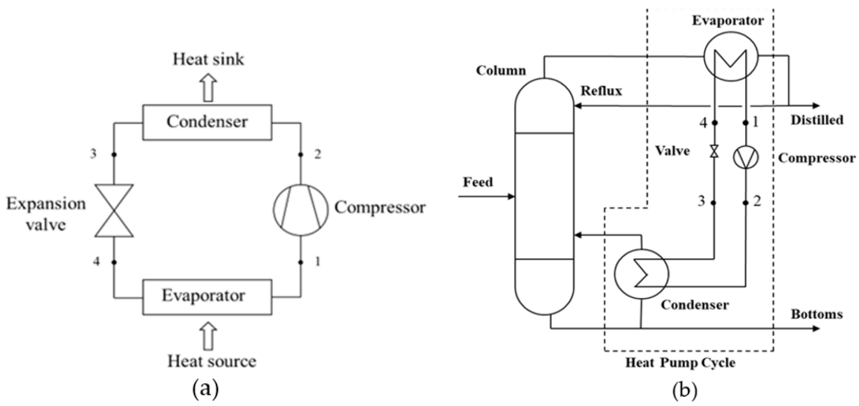

Figure 2. (**a**) Schematic diagram of the heat pump system and (**b**) application of the heat pump in the distillation column.

The CR process referred to as the base or reference case for the analysis is compared against different technological variants of the proposed process, ranging from green hydrogen production (electrolysis) for methanol synthesis to changes in methanol production technologies including natural gas price projections (raw material) until 2050 and electricity use, considering the origin and cost of the electricity supply (Colombian interconnection grid or photovoltaic generation). Using the simulated data (HYSYS V12) obtained, a techno-economic analysis of the processes and their variants is developed, including estimation of the capital cost (CAPEX) of the process equipment, the expected cash flow from methanol production with EBITDA, net present value (NPV), and the levelized cost of methanol production (LCOM). The CAPEX estimate additionally includes internal costs for carbon emissions into the atmosphere (USD 40/ton), which the Magdalena Medio refinery has established for all its technological investment projects, as a way to encourage cleaner processes with lower CO_2 emissions.

The resources obtained from CO_2 emission fees in the projects allow the refinery to have money for investment in carbon bonds or forestry projects in areas of influence. Colombia has also established a national tax for the use of natural gas [27], which is set at a value of USD 0.01/m^3 consumed. The NPV sensitivity analysis allows us to visualize the impact of the market price of methanol and the price of electric energy on the economic sustainability of a methanol plant with low carbon emissions. The proposal developed in this study allows us to demonstrate improvements in methanol production yields, savings in energy consumption through the use of heat pumps, and a reduction in carbon emissions. For scenarios in the years 2030–2050, this represents levelized costs of LCOM methanol production in ranges that can go from 456 to 492 USD/ton MeOH, which at expected average market prices of 500 USD/ton MeOH, represent positive NPV for investment projects of this type.

The results of this study allow us to provide a positive financial view on the viability of low-emission methanol production in the context of an oil-producing country, where the prices of raw materials (natural gas) and electricity generated from renewable sources, given the availability of the resource, are competitive in relation to other regions of the world [28].

2. Materials and Methods

The concept of electrification is evaluated at two levels: (1) electrification through the use of a heat pump applied to the plant's distillation system where the separation of a methanol–water mixture occurs and (2) electrification used for the production of green hydrogen (through electrolysis), which is one of the key components within the chemical reaction for the production of methanol, which corresponds to one of the cases evaluated and compared with the reference base case. Natural gas and electricity prices are key variables for determining the cost of methanol production and are based on price information that has been agreed upon through 20-year supply contracts for the facility that is the subject of this study (a fuel refinery located in the Magdalena Medio area of Colombia), which has shown interest in the development of the methanol economy, as an essential part of its decarbonization strategy and new business opportunities for its industrial plants.

Five scenarios were evaluated with the respective considerations in each case. The scenario called base case is identified as (Base) and corresponds to a methanol synthesis plant that uses a combined CR technology (Figure 3), which implements two processes: DR with injection of dry CO_2 as feed and SR with water, which is mixed with the gas and enters the oven [18]. In Figure 4, the scenarios ALT1–ALT4 are observed, where the ALT1 scenario corresponds to a gray hydrogen generation plant (SMR) with modified carbon capture for the production of methanol. The ALT2 scenario is similar to ALT1 but incorporates a heat pump system for its distillation column, using electrical energy from the Colombian power generation system (NIS) in which the hydroelectric source predominates. The ALT3 scenario is similar to ALT2 but includes a photovoltaic electrical supply in the facility for the heat pump in the distillation column. ALT4 implements 100% electrification of the plant proposed in ALT1 with the use of photovoltaic renewable supply for the reforming furnace

(R1; see Figure 4) using electric resistors [29] that replace natural gas as a source of thermal energy. The heat pump is also incorporated in the distillation column. The last scenario evaluated (ALT5) corresponds to the implementation of an electrolyzer (Figure 1) for the production of green hydrogen as a route for the hydrogenation of CO_2 and subsequent conversion to methanol [30,31].

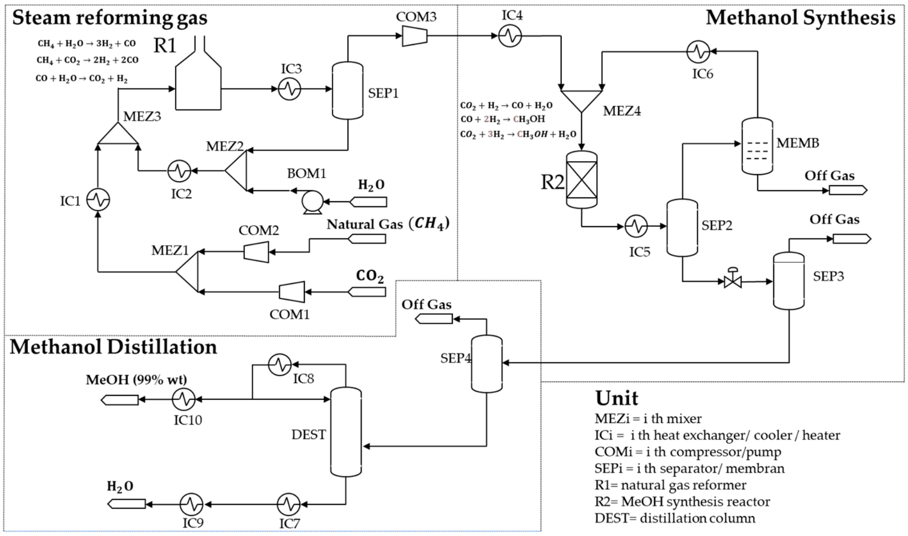

Figure 3. Process flow diagram of MeOH production plant simulated in HYSYS—base case.

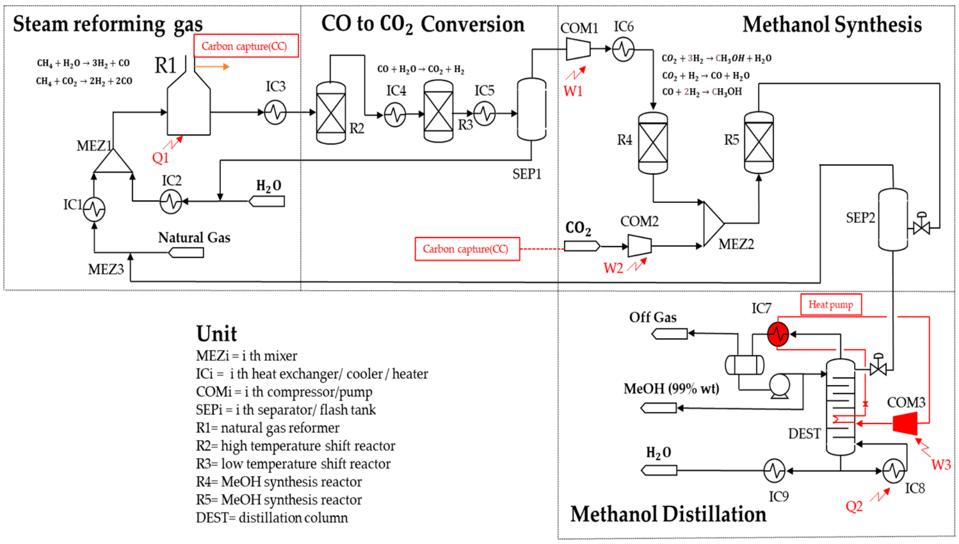

Figure 4. Process flow diagram of proposed MeOH production plant simulated in HYSYS (ALT 1-ALT4).

2.1. Estimation of the Performance of the Methanol Production Process

The determination of the mass and energy flows of the methanol production process (Figures 3 and 5) is carried out by simulation using the commercial software HYSYS V12.1, using the thermodynamic model of Peng Robinson for an annual production base of 70,000 tons and a methanol purity of 99.8% wt, where the CAPEX of the associated equipment is obtained using the Aspen Capital Cost tool and the OPEX of the facility, from real information collected from the refinery and supplemented with data from the literature [32]. The reforming furnace R1 (Figures 3 and 4) is simulated as a conversion reactor, the R1-R2 CO to CO_2 converters are simulated by equilibrium reactors, and the R4-R5 methanol synthesis reactors are of the conversion type. The distillation column is simulated with 25 theoretical plates and a reflux ratio of 0.96. The heat pump integrated between the top and bottom of the column uses propane as a working fluid and a centrifugal compressor of 850 KW power. The carbon capture unit (CCU; Figure 6) for use of CO_2 in the synthesis of methanol was simulated by a conventional T-2602 chemical absorption (20 theoretical stages) and a T-2601 stripping column (21 theoretical stages) using a DEA [33] amine solution which takes the combustion gas (flue gas) from the reforming furnace. The thermodynamic model used for the simulation of the amine is Acid Gas-Chemical Solvents and Peng Robinson for the transport of the gas and CO_2.

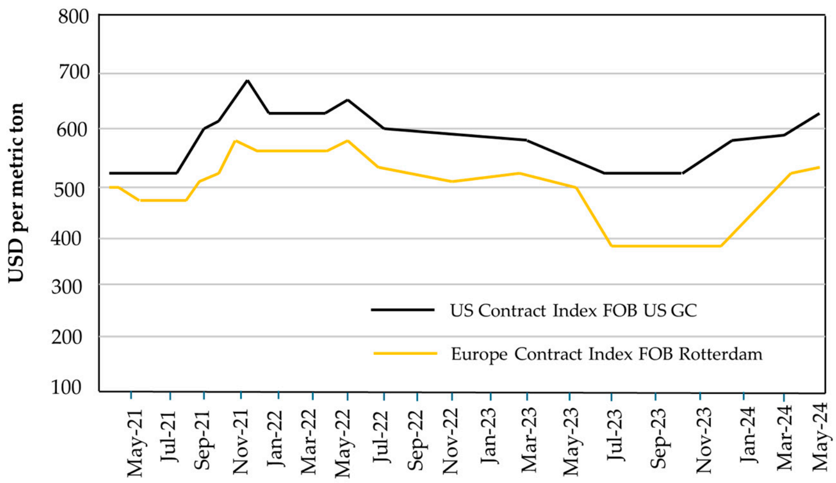

Figure 5. Behavior of international methanol prices from 2021 to 2024.

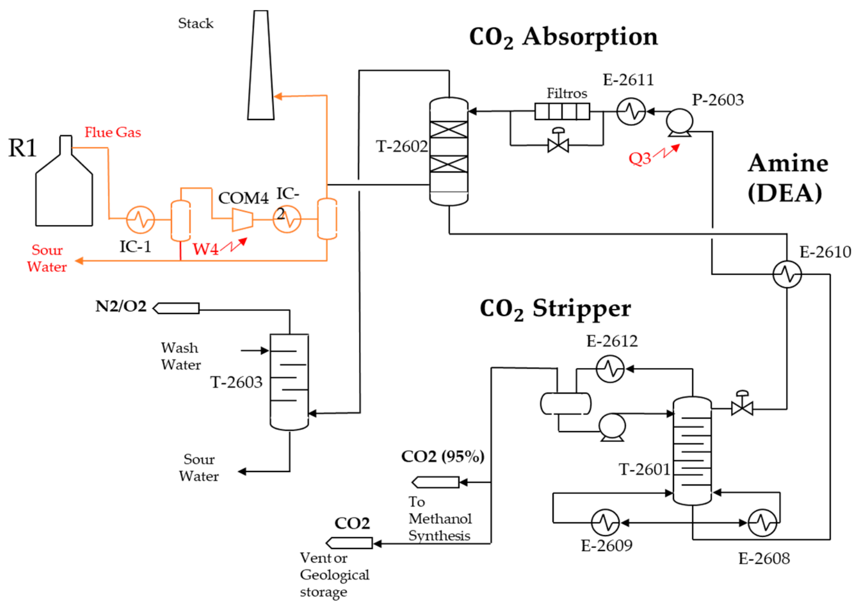

Figure 6. Process flow diagram of the existing carbon capture unit (CCU) based on DEA absorption (for Base, ALT 1 to ALT 3) (orange lines indicate changes required).

The plant defined as the base case for the analysis of alternatives is presented below (Figure 3), from which the capacity and energy consumption results for evaluation were obtained.

The base case (Figure 3) corresponds to a combined process (CR) scheme, where dry CO_2 enters as raw material at the unit inlet together with natural gas (CH_4), where the mixed gas is preheated to later join with the superheated steam in the reforming furnace, where the main endothermic reactions (R1) occur for the production of hydrogen under a catalytic medium of nickel oxide [34]. The product gas is compressed (COM3) towards a reactor (R2) to obtain methanol, where after some stages of separation and condensation of liquids, the water–methanol mixture obtained is sent to a distillation column of 20 theoretical plates to obtain a methanol steam at 99.8% wt. The production base of this plant for economic calculations is 181.4 ton/day.

The design and technical variants proposed in this study consider the adaptation or modification of a plant originally designed to produce gray hydrogen in the Magdalena Medio refinery with SMR technology, towards a new proposal for a methanol production plant (Figure 4), which means that some of the main equipment located mainly in the carbon capture section (CCU; Figure 6) can be used in the new proposed plant, generating significant savings in CAPEX compared to what would be the acquisition of a new methanol production plant with CCU for the refinery.

The production base of this new methanol plant is 190 tons/day, which represents an improvement in conversion levels in relation to the simulated unit of the base case (Base) for the same natural gas supply base as raw material.

The plant incorporates a heat pump system coupled with the distillation column, which allows us to recover part of the thermal energy from the top condenser to be transferred to the bottom heating system. This heat transfer procedure is carried out by a centrifugal compressor that uses a working fluid (propane) powered by energy supplied by a photovoltaic plant near the refinery with a capacity of 67 MW in an area of 45 hectares, which provides quite competitive rates in the cost of electric energy as presented in Table 1.

Table 1. Price of renewable energy source (RES).

Price Energy	COP/KWh	USD/KWh
Photovoltaic-Galilea	298	0.0745
Otra Gen Solar	243	0.0607
Electricity NIS	357	0.0892
Agricultural biomass	349	0.0872

NIS—National Electrical Interconnection System.

The concept analyzed for the base case plant and the proposed plant implements a carbon capture system (CCU) to mitigate emissions. It is not within the scope of this work to evaluate the impact or costs associated with the use and/or geological storage of the surplus capture steam. In the future, potential oil fields that could provide the capacity for storage and/or recovery of crude oil using the enhanced recovery (EOR) technique with CO_2 and water will be evaluated.

The environmental metrics used take into account the process and indirect CO_2 emissions caused by energy utilization (i.e., CO_2 generated due to heating or electricity consumption) and the CO_2 emissions with respect to different energy sources are in Table 2. It is assumed that the marginal CO_2 balance is calculated by

$$CO_{2\ \mathrm{net}} = CO_{2\ \mathrm{consumed}} - (CO_{2\ \mathrm{outlet}} + CO_{2\ \mathrm{indirect}}) \tag{4}$$

where $CO_{2\ \mathrm{net}}$ is the net abatement of CO_2 (kg), $CO_{2\ \mathrm{consumed}}$ is the mass (kg) of feedstock CO_2 that has been consumed in the process, and $CO_{2\ \mathrm{indirect}}$ is the emission resulting from energy consumption.

Table 2. Summary of key environmental indicators.

Balance (kg/kg MeOH)	Base Case	Improved Unit (ALT 3)
CO_2 consumed	0.3	0.30
CO_2 outlet	3.8	0.99
CO_2 net	−3.5	−0.79
CO_2 vent	1.64	0.62

2.2. Natural Gas and Electricity Price Forecast

The behavior of gas and electricity prices are key variables that allow us to determine the OPEX behavior over time, allowing us to identify the financial viability of the case studies. Figure 7 shows the expected natural gas price behavior curve according to estimates from the Magdalena Medio refinery, where expected maximum prices in 2050 are estimated to be around 9 USD/MMBTU.

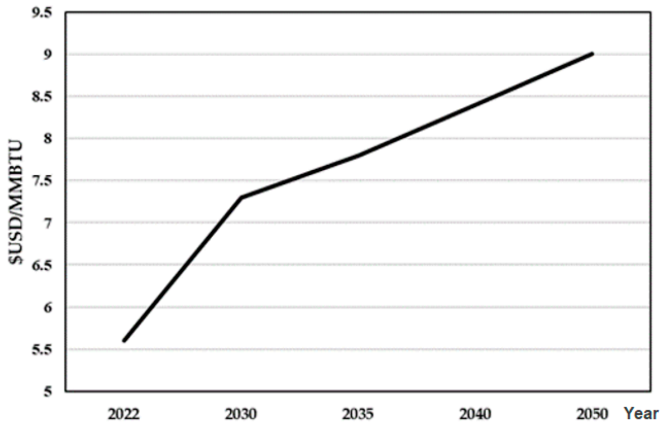

Figure 7. Expected gas price behavior for a gas-producing company in Colombia that would supply gas to the new methanol production facility.

Figure 8 shows the expected behavior of production prices taking the gas from the Cusiana field in Colombia as a reference, which estimates a downward trend considering the gas production prospects by the company that owns the Magdalena Medio refinery [35].

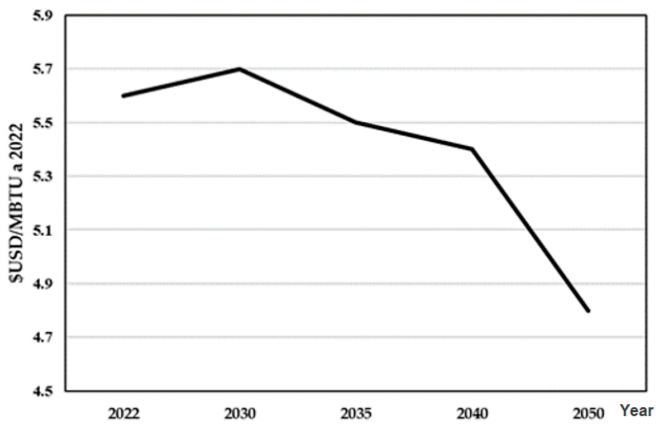

Figure 8. Expected behavior of the price of natural gas for the national government UPME at constant prices for the year 2022.

Table 1 shows an estimate of electricity prices in COP (Colombian currency) for the Magdalena Medio refinery through contracts with local supply companies that include renewable sources (photovoltaic–biomass).

Energy costs according to Table 1 are quite competitive when compared, for example, with a leading country in technology and renewable energy development, such as Spain, where the cost of renewable energy can be around 0.12 USD/KWh [36].

2.3. Price Trend and Demand for Methanol Worldwide

In Figure 5, the recent behavior of methanol prices in the European and American markets can be observed, where in the United States, in recent years, they have exceeded 500 USD/ton MeOH, making it a potential export market. The data presented in the figure are based on reference [11].

2.4. Financial Evaluation

The financial performance of the individual scenarios evaluated is based on the financial indicator of net present value NPV. The NPV is calculated using the following equation:

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \quad (5)$$

where C_t is the cash flow for year *t* and *r* is the estimated discount rate for this project of 8%. C_t is determined by the difference between the revenue per ton of methanol production and annualized operational expenses (OPEX). Depreciation of capital investment (CAPEX) is taken into account in OPEX where depreciation for 20 years is assumed, with a salvage value of 5% of the fixed capital costs. The financial evaluation period of the alternatives is *n* = 20 years.

In the final calculation, C_t is replaced by an incremental EBITDA that links the difference between the LCOM and the expected price of methanol, less the income tax which has been set at 35%. The above calculation of NPV allows us to identify the real benefit of each of the evaluated alternatives.

The LCOM (levelized cost of methanol) is defined as the unit value of methanol that allows the capital invested in CAPEX to be amortized, obtaining a return equal to the required discount rate covering the fixed and variable costs, including those associated with the emission of CO_2 [37].

$$LCOM = \frac{I_0 + \sum_{t=1}^{n} \frac{OM_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{M_{t,MeOH}}{(1+r)^t}} \quad (6)$$

where I_0 is the investment cost, OM is the operating and maintenance cost (O&M), F_t is the electricity and natural gas expenditure in year *t* provided by a purchasing agreement, and *n* and *r* have the same values as used for NPV. Most of the costs of the I_0 equipment are obtained from the simulation report by APEA V12.1 adjusted with information from ACCE V12.1 and the Chemical Plant Engineering Cost Index (CEPCI) of 2022. The calculations of OPEX consider the values of services (electricity, steam, and water), raw material costs, and fuel (natural gas), which are presented in Figures 2 and 8. The electricity prices were supplied by the Magdalena Medio refinery, according to internal purchase contracts until 2050. This OPEX estimate additionally includes the costs of operation and maintenance of the facility (O&M). Natural gas is mainly used as a raw material (reforming process) and fuel (furnaces and boilers) and is calculated per tonne of methanol produced.

2.5. Financial Estimation

Before the economic feasibility of each alternative, the cost of the main units is estimated and shown in Table 3. The details of the cost estimate for each item of equipment by service are shown in Appendix A.

Table 3. Main equipment cost estimation.

Unit	Quantity	USD	Source
Reformer	1	6,231,097	ACCE
MeOH Reactor	2	432,900	ACCE
Distillation Column	1	712,700	ACCE
Drums	4	395,900	ACCE
Heat Exchangers	7	1,060,800	ACCE
Compressors	4	14,811,200	ACCE

The information in Table 3 allows us to estimate the CAPEX required for the main equipment of the new plant, adjusted with a scale factor. CAPEX is one of the main variables for determining the LCOM, which, when compared with the methanol price forecast, allows us to determine the real financial viability of the project.

Table 4 shows the prices of raw materials used for methanol production, where the values for natural gas and water are based on prices obtained from the Magdalena Medio refinery. For the analysis of alternative 5 (ALT5), Table 5 presents the estimated values for a PEM-type electrolyzer, along with its commercial efficiencies [38], specified for the production of 14 MMSCFD (1391 kg/h) of hydrogen, which is the amount required for methanol production in the base case. The expected equivalent energy consumption for the electrolysis process ranges from 50.4 to 54.7 kWh/kg H_2.

Table 4. Raw material price.

Material	Price	Unit	Source
MeOH	510	USD/ton	MMSA
Natural Gas	0.023	USD/KWh	Refinery
Process Water	0.0012	USD/kg	Refinery

Table 5. Electrolyzer price.

Hydrogen Production	Unit	Year 2030	Year 2040	Year 2050
Installed Capacity	MW	76.2	71.2	70.2
Electrolyzer Efficiency	%	70	75	76
Equipment Cost	KUSD/kW	0.69	0.35	0.32
Investment	M USD	52.6	25.09	22.3
Required Hydrogen	kg H_2/día	--	38,122	--

2.6. Sensitivity Analysis

An important part of the study is to evaluate how the NPV of each alternative varies in relation to the price of electricity and to identify what the value should be that makes a certain alternative viable, considering 3 possible scenarios of the price of methanol according to Figure 9, 480–500–600 USD/ton MeOH, where it is identified that the trends in the American and European markets (FOB) on average have obtained values higher than 500 USD/ton.

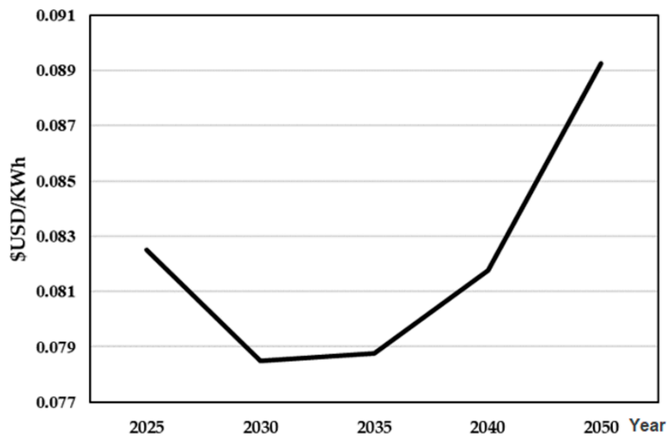

Figure 9. Expected electricity price behavior for the Magdalena Medio Refinery according to purchase contracts with the national grid with which the new methanol production facility is being evaluated.

In Figures 10–12, the NPV is presented with a variation in the cost of electricity from 0.025 to 0.09 USD/KWh. The cost of electricity is in a range of 31% to 34% of the levelized cost of methanol for the Base unit and the alternatives (ALT1 to ALT 4). In the case of green methanol production (ALT 5) from the PEM type electrolyzer [39], the value of the cost of electric energy ranges between 90 and 92% of the total production cost. Although for the estimation of the cost of green hydrogen production, the effect of the cost of electric energy can be between 69 and 72% of the total cost, the specific considerations of the methanol production process, which additionally include the operation of a distillation column for the separation of water and methanol, represent a greater impact on the financial viability of the process, where the LCOM ranges between 659 and 737 USD/ton MeOH. The estimates obtained in Figures 10–12 considered a maximum natural gas price value of USD 9/MMBTU; the price of natural gas is represented with the LCOM values that range between 43 and 62%.

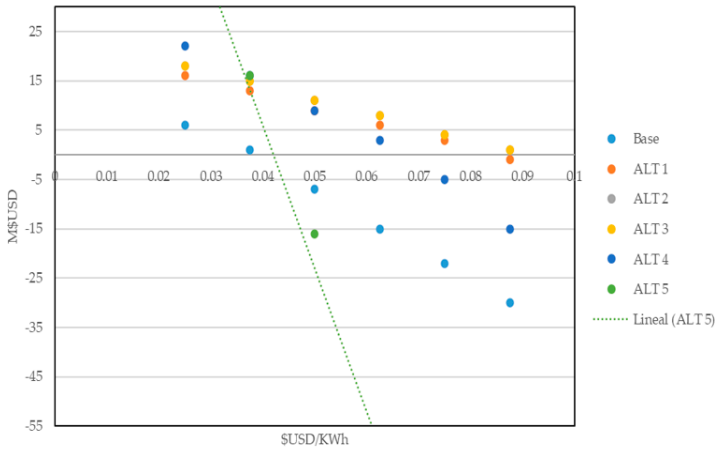

Figure 10. NPVs of each scenario with varying electricity prices (methanol price of USD 480/ton).

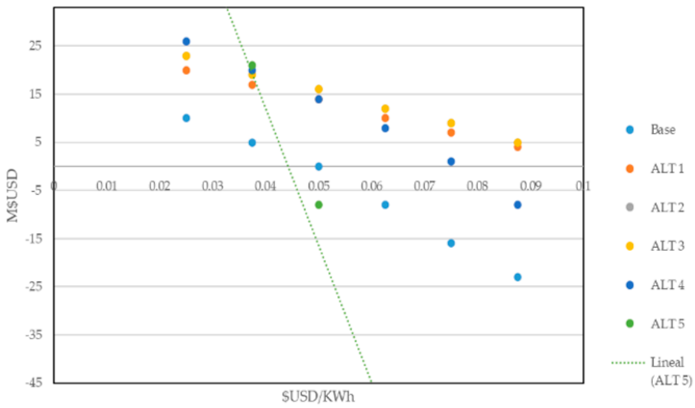

Figure 11. NPVs of each scenario with varying electricity prices (methanol price of USD 500/ton).

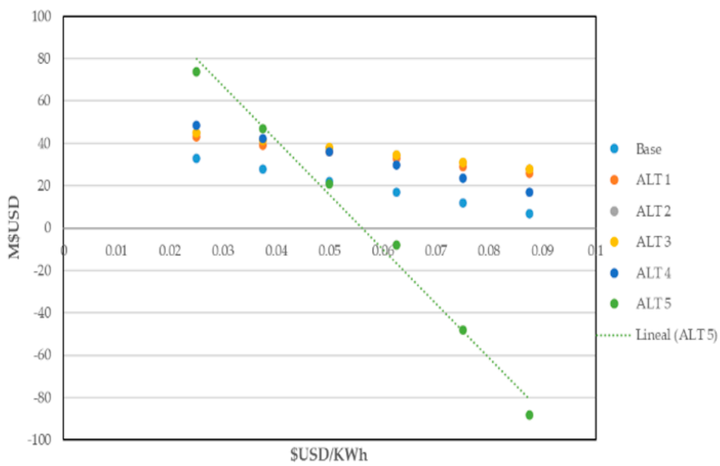

Figure 12. NPVs of each scenario with varying electricity prices (methanol price of USD 600/ton).

3. Results

The final feasibility estimate is based on an economic analysis that includes the estimation of the levelized cost of production of methanol (LCOM) for the period of 2030–2050 brought to net present value, which is compared with the expected market prices of methanol and the expected projections of natural gas and electricity prices for the unit in a time horizon of 20 years.

The results of the five alternatives proposed and compared with the combined technology base case unit (Base) allow us to determine that the carbon capture units (CCUs) have a significant impact on the financial viability of the units due to the high energy consumption linked to the process of compressing CO_2 from low-pressure conditions to the levels required for absorption with DEA. The combined technology for the base case presents a higher energy demand in its reforming system due to the effects of the injection of CO_2 as feed for the R1 furnace. This makes the project viable at low electricity price levels, such as USD 0.025, for example, for methanol prices in the market of USD 480/ton. Electricity price values below USD 0.03/kWh are not expected to be viable in the Colombian context in the medium term.

Methanol market prices are uncertain, although some local linear trends with cycle (LLTC) prediction models [40] allow us to identify expected ranges between 480 and 520 USD/ton by 2050. In this analysis, values obtained for the year 2024 have been taken as a reference. In this case, for average values of USD 500/ton, it can be observed that ALT 3 (Figure 11), which implements a heat pump system coupled to the distillation column and uses photovoltaic sources, generates positive NPVs that make this alternative viable, making this an adequate implementation proposal even at electricity costs close to 0.08 USD/KWh (Appendix A).

ALT 4, which electrifies the reforming system using technologies already studied [29] and where the furnace represents about 78% of the energy demand of the unit established for this case at 23 MWh, allows us to establish the viability of the alternative, at electricity prices of 0.06 USD/KWh and lower. Finally, ALT 5, which covers the production of green methanol through the use of electrolysis technology, shows greater financial complexity considering the high energy demand established for this process, which is close to 82 MWh.

Figure 12 presents a scenario of greater financial viability for the studied alternatives for methanol production, considering a market price of USD 600/ton, highlighting, as in the previous cases, the advantage of ALT3 due to the overall energy efficiency of the process, and considering that this proposal represents a saving of close to 29% compared to the consumption of the base case (Base).

According to the results, ALT3 in any of the cases allows us to demonstrate financial advantages for its implementation. Table 6 summarizes the inputs and outputs of the financial analysis between the case and base and ALT3 for an average methanol price of USD 500. Tables 7–9 summarize the simulated data in HYSYS between the base case and the improved unit (ALT 3) as well as the operational information of both processes (Appendix A). The above information supports the comparative estimates of improved unit (ALT 3) performance and the flows and costs for financial analysis. The benefits of the improved process in terms of production yields, cost, and effects on decarbonization are summarized in Tables 7–9, where increases in methanol production (5%) and reductions in vented CO_2 (62%) are observed.

Table 6. Inputs and outputs of financial analysis—LCOM-ALT 3.

Financial Inputs	Units	2030		2040		2050	
		Base	**ALT 3**	**Base**	**ALT 3**	**Base**	**ALT 3**
Raw material (natural gas)							
Gas price	USD/MMBTU	7.3	7.3	8.4	8.4	9.1	9.1
Natural gas use-methanol unit	MMSCFD	3.48	3.48	3.48	3.48	3.48	3.48
Fuel gas-methanol unit	MMSCFD	3.40	3.30	3.40	3.30	3.40	3.30
Natural gas cost	USD/Ton MeOH	264	261	304	300	330	324.9
Unit capacity	Ton MeOH/day	182	190	182	190	182	190
Energy							
Energy price	COP/kWh	357	243	357	243	357	243
Energy price	USD/MWh	89.25	60.75	89.25	60.75	89.25	60.75
Electricity use MeOH unit +C.C	kWh/Ton MeOH	2239.2	1521.0	2239.2	1521.0	2239.2	1521
Capture CO_2	kWh/Ton CO_2	972	972	972	972	972	972
Methanol cost +Carbon capture	USD/Ton MeOH	199.8	92.4	199.8	92.4	199.8	92.4
CAPEX							
Investment	M USD	31.2	30.4	38.4	37.7	48.5	46.6
Performance	hs/year	8760	8760	8760	8760	8760	8760
Utilization	%	1	1	1	1	1	1
WACC	%	8%	8%	8%	8%	8%	8%
Life	years	20	20	20	20	20	20
Annual cost	M USD/year	3.2	3.1	3.9	3.8	4.9	4.7
Methanol cost	USD/Ton MeOH	48	45	29	28	25	23
OPEX							
Cost O&M	% Capex	4%	4%	4%	4%	4%	4%
Total OPEX	USD/Ton MeOH	99.8	59	92.6	52	90.7	50
Raw material (Natural gas)	USD/Ton MeOH	264	261	304	300	330	325
Energy	USD/Ton MeOH	200	92	200	92	200	92
CAPEX	USD/Ton MeOH	48	45	29	28	25	23
OPEX	USD/Ton MeOH	100	59	93	52	91	50
Total LCOM (levelized cost of methanol)	USD/Ton MeOH	612	456	626	472	645	490

Table 7. Comparative simulated methanol yields.

Variable	Base Case	Improved Unit (ALT 3)
MeOH Production (kg MeOH/kg Gas)	2.42	2.54

Table 8. Utility consumption per kilogram of MeOH produced.

Variable	Base Case	Improved Unit (ALT 3)
Fuel gas (KW/kg MeOH)	12	5.6
Steam (kg steam/kg MeOH)	7	3.5
Electricity (KW/kg MeOH)	2.3	1.6

Table 9. Utility cost per kilogram of MeOH produced.

Variable	Base Case	Improved Unit (ALT 3)
Fuel gas (USD/kg MeOH)	0.27	0.13
Steam HP (USD/kg MeOH)	0.002	0.001
Steam LP (USD/kg MeOH)	0.077	0.039
Electricity (USD/kg MeOH)	0.16	0.11

4. Conclusions

The analysis in this paper considers the financial evaluation of the technological variants of a proposed process for the production of methanol using a heat pump and renewable photovoltaic energy, which is compared with the technical and energy performance of a conventional CR (Base) production process, where a typical amine-based carbon capture unit (CCU) (DEA) is incorporated in both processes, which contributes to the overall reduction in CO_2 emissions from the units.

In the analysis carried out and the results obtained, the main drivers for calculating the financial viability of alternatives are related to the cost of natural gas used as raw material and fuel for the generation of thermal energy in the process, as well as the consumption of electrical energy used as a substitute for thermal energy or as a source of mechanical work generation in pumps and compressors specified for the unit.

In the global performance analysis, the process proposed in this work (ALT3), with the implementation of a heat pump system and renewable energy supply, offers greater energy efficiency represented by a reduction in electricity and fuel gas consumption, as well as in steam and water utilities (OPEX) required for the operation of the equipment, which allows for industrial installation and a levelized production cost (LCOM) of 25% less, compared to the costs of a conventional CR unit with electricity from the national grid. At this point, it is emphasized that the prices of photovoltaic generation in the region under the contracts signed between the supplier and the Magdalena Medio refinery are quite competitive, which contributes to the financial viability of this project in the region.

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Abbreviations

ACCE	Aspen Capital Cost Estimator	MMBTU	millions british thermal units
ALTi	Alternatives or scenarios to evaluate	MMSCFD	million standard cubic feet per day
APEA	Aspen Process Economic Analyser	MTBE	methyl terbutyl ether
CAPEX	Capital expenditures (USD)	NIS	Colombian national interconnection system
CCS	carbon capture storage	NPV	net present value (USD)
CCU	carbon capture utilization	LCOM	Levelized Cost of Methanol (USD/kg MeOH)
CR	combined reforming	Li	lithium
CEPCI	chemical engineering plant cost index	OPEX	Operational expenditures (USD)
DEA	Di ethanolamine	PEM	Proton Exchange Membrane Electrolyser
DME	dimethyl eter	PTES	Pumped Thermal Electricity Storage
DR	dry reforming	VRF	variable refrigerant flow
FOB	free on board	SMR	steam methane reforming
EBITDA	earnings before interest, taxes, depreciation and amortization	SR	steam reforming
HP	heat pump	r	discount rate
MeOH	methanol	RES	renewable energy source

Appendix A

Table A1. Rotating equipment.

Rotating Machinery	Fluid	$USD	Source
Compressor COM1	Gas Syn	2,324,600	ACCE v12
Compressor COM2	CO_2	1,568,000	ACCE v12
Compressor COM3	Propane	1,214,900	ACCE v12
Compressor COM4	Flue Gas	9,703,700	ACCE v12

Table A2. Heat exchangers.

Heat Exchangers	Fluid	$USD	Source
IC6	Gas Syn	213,300	ACCE v12
IC7	MeOH	227,300	ACCE v12
IC8	Sour Water	81,000	ACCE v12
IC9	Flue Gas LP	106,200	ACCE v12
IC10	Flue Gas HP	181,100	ACCE v12
Cooler Distill-Heat Pump	Propane	103,500	ACCE v12
Heater Distill-Heat Pump	Propane	148,400	ACCE v12

Table A3. Separators.

Separators Drums	Fluid	M USD	Source
SEP-2	MeOH	108,300	ACCE v12
SEP-3	Flue Gas LP	175,900	ACCE v12
SEP-4	Flue Gas HP	111,700	ACCE v12

Table A4. Summary of the utility use in the base case MeOH Plant.

No	Unit Name	Inlet		Outlet		Duty (kW)	Service
		P (bar)	T (°C)	P (bar)	T (°C)		
R1	Reforming Reactor	18.00	398.8	18.00	950	36,980	Gas Heater
R2	MeOH Reactor	68.86	255.0	68.86	255	−4820	Cooling Water
IC1	Heater	21.00	49.8	20.00	398.9	1088	Gas Heater
IC2	Heater	18.00	30.2	18.00	398.9	84,930	Gas Heater
IC3	Cooler	18.00	950.0	17.00	30	−120,600	Cooling Water
IC4	Heater	72.00	215.00	71.00	255	740.90	Steam HP
IC5	Cooler	68.86	255.00	68.72	40	−6067	Cooling Water
IC6	Heater	68.72	40.00	68.58	255	355	HP vapor
IC7	Cooler	1.36	62.33	1.29	40	−108	Cooling Water
IC8	Cooler	2.39	125.80	2.33	40	−339.0	Cooling Water
Condenser	Cooler	1.36	62.30	1.36	62.3	−5036	Cooling Water
Reboiler	Heater	2.39	125.80	2.39	125.8	5616	Steam LP
COMP1	Compressor	12.04	37.80	25.14	108.3	38	Electricity
COMP2	Compressor	24.46	30.00	71.30	906.6	1057	Electricity
BOMB1	Pump	11.36	37.70	25.14	37.91	4	Electricity
BOMBA2	Pump	24.46	30.00	25.14	30.01	2	Electricity

Table A5. Summary of the utility use in the carbon capture unit—base case MeOH Plant.

No	Unit Name	Inlet		Outlet		Duty (kW)	Service
		P (bar)	T (°C)	P (bar)	T (°C)		
IC9	Cooler	1.15	242.0	1.01	37	−12,620	Cooling Water
IC10	Cooler	18.25	512.2	18.11	37	−18,760	Cooling Water
E2611	Cooler	2.11	125.1	1.97	37.7	−12,350	Cooling Water

Table A5. *Cont.*

No	Unit Name	Inlet		Outlet		Duty (kW)	Service
		P (bar)	T (°C)	P (bar)	T (°C)		
E2612	Cooler	1.42	82.0	1.28	35	−2601	Cooling Water
Condenser	Cooler	1.42	98.0	1.42	82.2	−7729	Cooling Water
Reboiler	Heater	2.25	133.0	2.25	133	30,820	Steam LP
COMP3	Compressor	1.01	37	18.25	512.8	15,820	Electricity
P2603	Pump	1.97	37.7	18.11	38	97.49	Electricity

Table A6. Summary of the utility use in the improved unit (ALT 3) MeOH Plant.

No	Unit Name	Inlet		Outlet		Duty (kW)	Service
		P (bar)	T (°C)	P (bar)	T (°C)		
R1	Reforming Reactor	24.80	422.0	24.80	830.6	18,030	Gas Heater
R2	MeOH Reactor	71.62	255.0	71.62	255	−4490	Cooling Water
IC1	Heater	25.14	221.2	24.80	426.7	23,690	Heater
IC2	Heater	25.14	39.2	24.80	398.9	5123	Heater
IC3	Cooler	24.46	830.6	23.08	357.2	−20,678	Cooling Water
IC4	Heater	23.08	376.20	22.34	203.3	−7284	Cooling Water
IC5	Cooler	22.39	203.30	21.70	60	−24,918	Cooling Water
IC6	Heater	71.96	230	71.62	255	413	Steam HP
IC7	Cooler	71.62	255	71.27	43.33	−9758	Cooling Water
IC8	Cooler	2.39	125.80	2.33	30	−558.8	Cooling Water
Condenser	Cooler	1.36	75	1.36	75	−5679	Cooling Water
Reboiler	Heater	2.39	125.80	2.39	125.8	6282	Steam LP
COMP1	Compressor	21.70	60.00	71.96	230.3	3553	Electricity
COMP2	Compressor	12.04	76.70	71.62	276.8	119	Electricity

Table A7. Summary of the utility use in the carbon capture unit and improved unit (ALT 3) MeOH Plant.

No	Unit Name	Inlet		Outlet		Duty (kW)	Service
		P (bar)	T (°C)	P (bar)	T (°C)		
IC9	Cooler	1.15	242.0	1.01	37	−6152	Cooling Water
IC10	Cooler	18.25	512.2	18.11	37	−9143	Cooling Water
E2611	Cooler	2.11	125.1	1.97	37.7	−12,350	Cooling Water
E2612	Cooler	1.42	82.0	1.28	35	−1179	Cooling Water
Condenser	Cooler	1.42	98.0	1.42	82.2	−3701	Cooling Water
Reboiler	Heater	2.25	133.0	2.25	133	19,540	Steam LP
COMP4	Compressor	1.01	37	18.25	512.8	7713	Electricity
P2603	Pump	1.97	37.7	18.11	38	88	Electricity

Table A8. Summary of the utility use in the improved unit (ALT 3) MeOH Plant with heat pump (HP).

No	Unit Name	Inlet		Outlet		Duty (kW)	Service
		P (bar)	T (°C)	P (bar)	T (°C)		
R1	Reforming Reactor	24.80	422.0	24.80	830.6	18,030	Heater
R2	MeOH Reactor	71.62	255.0	71.62	255	−4490	Cooling Water
IC1	Heater	25.14	221.2	24.80	426.7	23,690	Heater
IC2	Heater	25.14	39.2	24.80	398.9	5123	Heater
IC3	Cooler	24.46	830.6	23.08	357.2	−20,678	Cooling Water
IC4	Heater	23.08	376.20	22.34	203.3	−7284	Cooling Water
IC5	Cooler	22.39	203.30	21.70	60	−24,918	Cooling Water
IC6	Heater	71.96	230	71.62	255	413	Steam HP
IC7	Cooler	71.62	255	71.27	43.33	−9758	Cooling Water
IC8	Cooler	2.39	125.80	2.33	30	−558.8	Cooling Water

Table A8. *Cont.*

No	Unit Name	Inlet		Outlet		Duty (kW)	Service
		P (bar)	T (°C)	P (bar)	T (°C)		
COMP1	Compressor	21.70	60.00	71.96	230.3	3553	Electricity
COMP2	Compressor	12.04	76.70	71.62	276.8	119	Electricity
COMP3	Heat Pump	14.85	53	25.51	84.28	848	Electricity

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