Supplementary Material

Renewable natural gas value chain based on cryogenic CCUS and power-to-gas for a net-zero CO2 economy

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# S1. System description

S1.1. Case 1: Power-to-gas

RNG production: Power-to-gas (SOEC co-electrolysis, methanation)

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Fig. S1.1. Block diagram of RNG value chain: Case 1.

Table S1.1. Design parameters of the PtG process [1].

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Parameter | Value | Unit |
| H2O | Feed temperature | 25 | °C |
| Feed pressure | 1 | bar |
| Feed mass flow rate | 64.32 | kg/s |
| CO2 | Feed temperature | 25 | °C |
| Feed pressure | 1 | bar |
| Feed mass flow rate | 39.28 | kg/s |
| SOEC inlet temperature | | 600 | °C |
| SOEC operating pressure | | 1 | bar |
| SOEC stack power size | | 749.85 | MW |
| HTM inlet temperature | | 450 | °C |
| HTM operating pressure | | 1 | bar |
| HTM reactor type | | Isothermal | - |
| LTM 1 inlet temperature | | 200 | °C |
| LTM 1 operating pressure | | 8 | bar |
| LTM 1, 2, 3 reactor type | | Adiabatic | - |
| Drum inlet temperature | | 30 | °C |
| Isentropic efficiency of the compressor | | 80 | % |

RNG transportation: RNG liquefaction, RNG/CO2 shipment

Table S1.2. Design parameters of the SMR process [2], [3].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Component | Parameter | | Value | Unit |
| RNG | Feed temperature | | 25.00 | °C |
| Feed pressure | | 8.00 | bar |
| Feed mass flow rate | | 14.74 | kg/s |
| L-RNG | Product temperature | | −162.03 | °C |
| Product pressure | | 6.00 | bar |
| Product mass flow rate | | 14.74 | kg/s |
| Mixed refrigerant | Suction pressure | | 150 | kPa |
| Discharge pressure | | 4,500 | kPa |
| Outlet temperature of the cold mixed refrigerant | | 29.00 | °C |
| Composition  (mol%) | N2 | 19.90 | - |
| CH4 | 40.10 | - |
| C2H6 | 0.04 | - |
| C3H8 | 0.03 | - |
| i-C4H10 | 25.19 | - |
| n-C4H10 | 14.74 | - |
| Minimum temperature approach in the heat exchangers | | | 3.00 | °C |
| Logarithmic mean temperature difference | | | 10.72 | °C |
| Cooler discharge temperature | | | 30.00 | °C |
| Pressure drop in the multi-stream heat exchanger | | | 100 | kPa |
| Pressure drop in the cooler | | | 0 | kPa |
| Isentropic efficiency of the pump and compressors | | | 75 | % |
| Compression ratio of compressor 1 | | | 3.33 | - |
| Compression ratio of compressor 2 | | | 3.00 | - |
| Compression ratio of compressor 3 | | | 3.00 | - |
| Compression ratio of compressor 4 | | | 3.00 | - |
| Liquefaction rate | | | 100 | % |

RNG utilization: Power generation, Absorption-based CCS

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Fig S1.2. Schematic of the renewable natural gas (RNG) power plant based on the natural gas combined cycle (NGCC) (Reprinted from Ref. [2])

Table S1.3. Composition of the RNG and air [4].

|  |  |  |  |
| --- | --- | --- | --- |
| Parameters | | Air | RNG (from PtG) |
| Flow rate (kg/s) | | 635.0 | 14.74 |
| Pressure (bar) | | 1.013 | 30.0 |
| Temperature (°C) | | 15.0 | 30.0 |
| Composition (mol%) | N2 | 77.30 | – |
| O2 | 20.74 | – |
| H2 | – | 0.04 |
| H2O | 1.01 | 0.40 |
| CO2 | 0.03 | 3.01 |
| Ar | 0.92 | – |
| CH4 | – | 96.03 |
| C2H6 | – | 0.00 |
| C3H8 | – | 0.00 |

Table S1.4. Design parameters of the NGCC power plant process [4].

|  |  |  |
| --- | --- | --- |
| Component | Parameter | Value |
| Gas turbine unit | | |
| Air compressor | Pressure ratio | 15.4 |
| Isentropic efficiency (%) | 88.0 |
| Mechanical efficiency (%) | 99.0 |
| Combustor | Efficiency (%) | 99.5 |
| Pressure loss (%) | 3.5 |
| Exit temperature (°C) | 1,405.0 |
| Gas turbine | Inlet temperature (°C) | 1,328.0 |
| Exhaust temperature (°C) | 615.0 |
| Steam turbine unit | | |
| Heat recovery steam generator | HP/IP/LP steam temperature (°C) | 565.0/297.0/295.0 |
| HP/IP/LP pinch point temperature (°C) | 10.0/10.0/10.0 |
| HP/IP/LP approach point temperature (°C) | 8.0/10.0/16.4 |
| HP SPHT 1 steam outlet temperature (°C) | 510.0 |
| RHT 1/2 steam outlet temperature (°C) | 520.0/565.0 |
| HP ECON 1/2 water outlet temperature (°C) | 208.0/280.0 |
| Pressure losses on gas/water/steam sides (%) | 1.5/5.0/3.0 |
| Steam turbines | HP/IP/LP steam turbine inlet pressure (bar) | 98.8/24.0/4.0 |
| HP/IP/LP steam turbine isentropic efficiency (%) | 87.0/91.0/89.0 |
| Condenser | Pressure (bar) | 0.074 |
| Cooling water inlet temperature (°C) | 25.0 |
| Cooling water temperature rise (°C) | 10.0 |
| Generator | Efficiency | 98.5 |

Table S1.5. Design parameters of the MEA-based CO2 absorption process [2], [5], [6].

|  |  |  |
| --- | --- | --- |
| Parameters | | Value |
| Inlet gas temperature (°C)/pressure (bar(a)) | | 40/1.1 |
| Inlet gas flow rate (kmol/h) | | 85,000 |
| Inlet gas compositions (mol%) | N2 | 74.34 |
| O2 | 12.59 |
| H2 | 0.02 |
| Ar | 0.88 |
| H2O | 8.34 |
| CO2 | 3.82 |
| Lean solvent temperature/pressure (°C/bar) | | 40/1.1 |
| Lean solvent flow rate (kmol/h) | | 120,000 |
| Lean solvent compositions (mass%) | H2O | 65.50 |
| CO2 | 5.50 |
| Amine (MEA) | 29.00 |
| Number of stages/pressure in absorber (bar) | | 10/1.1 |
| Number of stages/pressure in stripper (bar) | | 6/2.0 |

S1.2. Case 2: Cryogenic CCS

RNG utilization: Cryogenic CCS

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Fig. S1.2. Block diagram of RNG value chain: Case 2.

Table S1.6. Design parameters of the cryogenic CCS process [2], [4].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Component | Parameter | | Value | Unit |
| Flue gas | Feed temperature | | 127.5 | °C |
| Feed pressure | | 59.4 | kPa |
| Feed mass flow rate | | 649.7 | kg/s |
| Composition (mol%) | N2 | 74.34 | % |
| CO2 | 3.82 | % |
| O2 | 12.59 | % |
| H2O | 8.34 | % |
| H2 | 0.02 | % |
| L-RNG | Feed temperature | | −162.00 | °C |
| Feed pressure | | 6.00 | bar |
| Feed mass flow rate | | 14.74 | kg/s |
| Composition (mol%) | N2 | – | % |
| O2 | – | % |
| H2 | 0.04 | % |
| H2O | 0.40 | % |
| CO2 | 3.01 | % |
| Ar | – | % |
| CH4 | 96.03 | % |
| Solid CO2 | Product temperature | | –50.0 | °C |
| Product pressure | | 8.00 | bar |
| Discharge temperature of coolers 1 and 2 | | | 30.00 | °C |
| Minimum temperature approach in the heat exchangers | | | 3.00 | °C |
| Discharge pressure of the compressor 1, 2, and 3 | | | 100.0/300.0/800.0 | kPa |
| Discharge pressure of the turbine | | | 55.0 | kPa |
| Isentropic efficiency of the compressor | | | 80 | % |
| Isentropic efficiency of the turbine | | | 80 | % |

S1.3. Case 3: Cryogenic CCUS

RNG transportation: RNG liquefaction using cryogenic-CCUS

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Fig. S1.3. Block diagram of RNG value chain: Case 3.

Table S1.7. Design parameters of the RNG liquefaction process using cryogenic CCUS [2].

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Parameter | | | | Value | Unit |
| Solid CO2 | | Feed temperature / pressure | | −50.0 | °C |
| Feed pressure | | 8.0 | bar |
| Feed mass flow rate | | 38.91 | kg/s |
| RNG | | Feed temperature | | 25.0 | °C |
| Feed pressure | | 8.0 | bar |
| Feed mass flow rate | | 14.74 | kg/s |
| L-RNG | | Product temperature | | −162.0 | °C |
| Product pressure | | 6.0 | bar |
| Product mass flow rate | | 14.74 | kg/s |
| Discharge pressure of the valve 1 | | | | 1.00 | bar |
| Cold stream outlet vapor fraction of heat exchanger 1 | | | | 0.55 | - |
| Cold stream outlet temperature of heat exchanger 1 | | | | −73.9 | °C |
| Minimum temperature approach in the heat exchangers | | | | 1.0 | °C |
| Pressure drop in the heat exchangers | | | | 0.0 | kPa |
| ORC 1 | Cond 1/2 | | Minimum temperature approach | 3.0 | °C |
| Heat 1/2 | | Outlet temperature | 27.0/30.0 | °C |
| Turb 1/2 | | Discharge pressure | 8.0/2.0 | bar |
| Pump 2 | | Discharge pressure | 33.0 | bar |
| ORC 2 | Cond 3 | | Minimum temperature approach | 3.0 | °C |
| Heat 3/4/5 | | Outlet temperature | 30.0/30.0/30.0 | °C |
| Turb 3/4/5 | | Discharge pressure | 25.0/15.0/8.0 | bar |
| Pump 3 | | Discharge pressure | 33.0 | bar |

S1.4. Case 4: Heat integration

RNG production: Heat integration between SOEC co-electrolysis and methanation

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Fig. S1.4. Block diagram of RNG value chain: Case 4.

Table S1.8. Design parameters of the PtG process after heat integration.

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Parameter | Value | Unit |
| H2O | Feed temperature | 25 | °C |
| Feed pressure | 1 | bar |
| Feed mass flow rate | 64.32 | kg/s |
| CO2 | Feed temperature | 25 | °C |
| Feed pressure | 1 | bar |
| Feed mass flow rate | 39.28 | kg/s |
| SOEC inlet temperature | | 600 | °C |
| SOEC operating pressure | | 1 | bar |
| SOEC stack power size | | 749.85 | MW |
| HTM inlet temperature | | 450 | °C |
| HTM operating pressure | | 1 | bar |
| HTM reactor type | | Isothermal | - |
| LTM 1 inlet temperature | | 200 | °C |
| LTM 1 operating pressure | | 8 | bar |
| LTM 1, 2, 3 reactor type | | Adiabatic | - |
| HX 1 / 2 / 3 / 4 / 5 exchanger duty | | 36.4 / 18.2 / 102.8 / 80.9 / 23.8 | MWth |
| Drum inlet temperature | | 30 | °C |
| Isentropic efficiency of the compressor | | 80 | % |

# S2. Techno-economic analysis

To determine if the proposed RNG value chain is economically feasible, we compared the levelized cost of electricity (LCOE) generated by an RNG power plant with that of the FNG value chain. The LCOE is the production cost per kWh of electricity. We calculated the LCOE for 2020 and 2050 while taking into account that the cost of renewable energy sources and the investment expenditure of the PtG process will decrease due to the carbon-neutral strategy. This will help us determine if the RNG value chain can replace FNG effectively in 2020 and how much the economic feasibility of RNG will increase in 2050. LCOE is expressed as follows Eq. (1) [7,8]:

|  |  |
| --- | --- |
|  | (1) |

where is investment expenditures, is operations and maintenance expenditures, is fuel expenditures, and is electrical energy generated in the year . denotes the discount rate, and is the expected lifetime of the system or power station. was assumed to be 10%, and was assumed to be 10 years [9].

For this work, a techno-economic analysis was carried out using the Aspen Process Economic Analyzer (APEA). However, calculating the investment costs of SOEC electrolyzers, methanation reactors, and combustors using APEA was challenging. Hence, values from previous studies [10,11] were used to estimate the costs. Investment expenditures in LCOE are expressed as follows Eq. (2):

|  |  |
| --- | --- |
|  | (2) |

where , , , and are investment expenditures of overall, RNG production, transportation, and utilization, respectively. Investment expenditures of RNG production are expressed as follows Eqs. (3)–­(6):

|  |  |
| --- | --- |
|  | (3) |
|  | (4) |
|  | (5) |
|  | (6) |

The investment cost of the PtG process () is calculated by adding up the investment costs of various components. These components include the SOEC electrolyzer (), high- and low-temperature methanation reactors (), heat exchangers (), which include the heater, cooler, and heat exchanger (), compressors (), and drum ().

The investment cost of the SOEC electrolyzer is calculated with a cost-capacity factor of 0.6, considering the chemical plant cost indexes (CEPCI) [10]. denotes the investment cost of the referenced SOEC electrolyzer and is equal to $ 3,656,805 [11]. and denote the power consumed by the proposed and referenced SOEC electrolyzers, respectively. The referenced SOEC electrolyzer has a power consumption of 10 MWe [11]. The investment costs of the methanation reactors are also calculated with a cost-capacity factor of 0.6, considering the chemical plant cost indexes (CEPCI) [10]. denotes the investment cost of the referenced methanation reactor and is equal to $ 248,857 [11]. and denote the flow rate of RNG in the proposed and referenced methantation reactor of the final stage, respectively [11]. The referenced methanation reactor has a flow rate of 0.179 kg/s\_RNG [11]. Investment expenditures of RNG transportation are expressed as follows Eqs. (7)–­(8):

|  |  |
| --- | --- |
|  | (7) |
|  | (8) |

The investment cost of the RNG transportation process () is calculated by adding up the investment costs of various components in the liquefaction process. These components include the heat exchangers (), compressors (), drums (), pumps (), turbines (), valves (), and multi-stream heat exchanger (). Investment expenditures of RNG utilization are expressed as follows Eqs. (9)–­(13):

|  |  |
| --- | --- |
|  | (9) |
|  | (10) |
|  | (11) |
|  | (12) |
|  | (13) |

The cost of investing in the RNG utilization process () is calculated by adding up the investment costs of the NGCC power plant (() and the CCS process (). The investment cost of the NGCC power plant consists of the combustor (), compressor (), turbines (), heat exchangers (), and pumps (). The investment cost of the combustor () is calculated using a cost-capacity factor of 0.6, taking into account the chemical plant cost indexes (CEPCI) [10]. represents the investment cost of the referenced combustor, which is equal to 0.7 $ [12]. The flow rate of RNG in the proposed combustor is represented by , while represents the flow rate of RNG in the referenced combustor, which is 9 kg/s\_RNG [12].

The investment cost of a conventional CCS process, denoted as , can be calculated by combining the costs of absorption and compression. This includes the investment costs of absorbers (), strippers (), pumps (), heat exchangers (), compressors (), and drums ().

On the other hand, the investment cost for a cryogenic CCS process, denoted as , can be calculated by adding up the investment costs of heat exchangers (), drums (), compressors (), turbines (), and multi-stream heat exchangers (). The multi-stream heat exchanger is a cryogenic CO2 capture unit made up of aluminum tubes, and its investment cost has been validated from a previous study [13]. Operations and maintenance expenditures are expressed as follows Eqs. (14):

|  |  |
| --- | --- |
|  | (14) |

where and are the power consumption in the RNG production and transportation, respectively. and denote the cost of renewable electricity and catalyst in the methanation reactor, respectively. The cost of the catalysis in the methanation reactor is equal to 1.9 $/h [11]. and denote the flow rate of RNG in the proposed and referenced methanation reactor of the final stage, respectively [11]. The referenced methanation reactor has a flow rate of 0.179 kg/s\_RNG [11]. A case study of renewable energy sources is conducted. Table S2.1 lists the data on the levelized cost of renewable electricity.

Table S2.1. Data on the levelized cost of renewable electricity [14].

|  |  |  |  |
| --- | --- | --- | --- |
| Year reference | Renewable energy source | LCOE ($/kWh) | |
| Lower bound | Upper bound |
| 2020 | Solar | 0.0488 | 0.0732 |
| 2050 | Solar | 0.0185 | 0.0336 |
| 2020 | Onshore wind | 0.0610 | 0.0815 |
| 2050 | Onshore wind | 0.0307 | 0.0670 |
| 2020 | Offshore wind | 0.0687 | 0.0687 |
| 2050 | Offshore wind | 0.0364 | 0.0364 |

Fuel expenditures for FNG are expressed as follows Eq. (15):

|  |  |
| --- | --- |
|  | (15) |

Fuel expenditures for FNG were estimated at 16.70 $/GJ, based on the non-household cost of South Korea (a major FNG import region with limited renewable energy sources), excluding maritime transportation [15].

# S3. Simulation results



Fig. S3.1. Model of the power-to-gas (PtG) process.

Table S3.1. Simulation results of the streams of the power-to-gas (PtG) process.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stream | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 |
| Temperature (oC) | 25.00 | 600.00 | 25.00 | 600.00 | 599.98 | 599.97 | 600.00 | 600.00 |
| Pressure (bar) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mass flow (kg/s) | 64.32 | 64.32 | 39.28 | 39.28 | 103.60 | 103.91 | 103.91 | 103.91 |
| Mole flow (kmol/s) | 3.57 | 3.57 | 0.89 | 0.89 | 4.46 | 4.62 | 4.62 | 6.40 |
| Components mole fractions (%) | | | | | | | | |
| H2O | 100.00 | 100.00 | 0.00 | 0.00 | 80.00 | 77.28 | 77.57 | 11.19 |
| CO2 | 0.00 | 0.00 | 100.00 | 100.00 | 20.00 | 19.32 | 19.04 | 2.75 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.39 | 3.11 | 47.00 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 27.87 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.28 | 11.19 |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Stream | 109 | 110 | 111 | 112 | 113 | 114 | 115 | 116 |
| Temperature (oC) | 600.00 | 600.00 | 600.00 | 600.00 | 600.00 | 600.00 | 600.00 | 25.00 |
| Pressure (bar) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mass flow (kg/s) | 103.91 | 46.79 | 6.32 | 40.47 | 6.00 | 0.32 | 0.32 | 0.12 |
| Mole flow (kmol/s) | 6.40 | 4.62 | 3.14 | 1.48 | 2.98 | 0.16 | 0.16 | 0.00 |
| Components mole fractions (%) | | | | | | | | |
| H2O | 9.23 | 12.80 | 0.00 | 39.85 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 | 4.70 | 6.52 | 0.00 | 20.30 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 48.96 | 67.88 | 100.00 | 0.00 | 100.00 | 100.00 | 100.00 | 0.00 |
| O2 | 27.87 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 21.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 9.23 | 12.80 | 0.00 | 39.85 | 0.00 | 0.00 | 0.00 | 0.00 |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 79.00 |
| Stream | 117 | 118 | 119 | 201 | 202 | 301 | 302 | 303 |
| Temperature (oC) | 600.00 | 600.00 | 600.00 | 599.96 | 450.00 | 450.00 | 725.00 | 971.90 |
| Pressure (bar) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 3.30 | 8.00 |
| Mass flow (kg/s) | 0.12 | 57.12 | 57.24 | 46.48 | 46.48 | 46.48 | 46.48 | 46.48 |
| Mole flow (kmol/s) | 0.00 | 1.79 | 1.79 | 4.46 | 4.46 | 3.30 | 3.30 | 3.30 |
| Components mole fractions (%) | | | | | | | | |
| H2O | 0.00 | 0.00 | 0.00 | 13.25 | 13.25 | 41.64 | 41.64 | 41.64 |
| CO2 | 0.00 | 0.00 | 0.00 | 6.75 | 6.75 | 3.16 | 3.16 | 3.16 |
| H2 | 0.00 | 0.00 | 0.00 | 66.75 | 66.75 | 31.27 | 31.27 | 31.27 |
| O2 | 21.00 | 100.00 | 99.82 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 17.72 | 17.72 | 17.72 |
| CO | 0.00 | 0.00 | 0.00 | 13.25 | 13.25 | 6.21 | 6.21 | 6.21 |
| N2 | 79.00 | 0.00 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Stream | 304 | 305 | 306 | 307 | 308 | 309 | 310 | 311 |
| Temperature (oC) | 200.00 | 504.07 | 200.00 | 363.26 | 200.00 | 251.96 | 25.00 | 25.00 |
| Pressure (bar) | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Mass flow (kg/s) | 46.48 | 46.48 | 46.48 | 46.48 | 46.48 | 46.48 | 46.48 | 14.74 |
| Mole flow (kmol/s) | 3.30 | 2.97 | 2.97 | 2.76 | 2.76 | 2.70 | 2.70 | 0.94 |
| Components mole fractions (%) | | | | | | | | |
| H2O | 41.64 | 50.82 | 50.82 | 61.63 | 61.63 | 65.43 | 65.43 | 0.35 |
| CO2 | 3.16 | 4.52 | 4.52 | 1.50 | 1.50 | 0.37 | 0.37 | 1.07 |
| H2 | 31.27 | 19.08 | 19.08 | 6.04 | 6.04 | 1.49 | 1.49 | 4.29 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 17.72 | 25.24 | 25.24 | 30.81 | 30.81 | 32.71 | 32.71 | 94.28 |
| CO | 6.21 | 0.34 | 0.34 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Stream | 312 | X1 | X2 | X3 | X4 | X5 | X6 | X7 |
| Temperature (oC) | 25.00 | - | - | - | - | - | - | - |
| Pressure (bar) | 8.00 | - | - | - | - | - | - | - |
| Mass flow (kg/s) | 31.74 | - | - | - | - | - | - | - |
| Mole flow (kmol/s) | 1.76 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Components mole fractions (%) | | | | | | | | |
| H2O | 100.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |



Fig. S3.2. Model of the single mixed refrigerant (SMR) process.

Table S3.2. Simulation results of the streams of the single mixed refrigerant (SMR) process.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Stream | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 |
| Temperature (oC) | 29.00 | 98.53 | 30.00 | 95.04 | 30.00 | 30.00 | 107.47 | 30.00 |
| Pressure (bar) | 1.50 | 5.00 | 5.00 | 14.99 | 14.99 | 14.99 | 44.96 | 14.99 |
| Mass flow (kg/s) | 64.18 | 64.18 | 64.18 | 64.18 | 64.18 | 45.82 | 45.82 | 18.36 |
| Mole flow (kmol/hr) | 6,555.77 | 6,555.77 | 6,555.77 | 6,555.77 | 6,555.77 | 5,377.01 | 5,377.01 | 1,178.76 |
| Components mole fractions (%) | | | | | | | | |
| N2 | 19.90 | 19.90 | 19.90 | 19.90 | 19.90 | 24.09 | 24.09 | 0.77 |
| CH4 | 40.10 | 40.10 | 40.10 | 40.10 | 40.10 | 47.95 | 47.95 | 4.30 |
| C2H6 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.02 |
| C3H8 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 |
| i-C4H10 | 25.19 | 25.19 | 25.19 | 25.19 | 25.19 | 18.43 | 18.43 | 56.02 |
| n-C4H10 | 14.74 | 14.74 | 14.74 | 14.74 | 14.74 | 9.45 | 9.45 | 38.85 |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Stream | 109 | 110 | 111 | 112 | 113 | 114 | LNG1 | NG |
| Temperature (oC) | 32.58 | 71.31 | 30.00 | -165.00 | -172.67 | 29.00 | -162.03 | 25.00 |
| Pressure (bar) | 44.96 | 44.96 | 44.96 | 44.96 | 2.50 | 1.50 | 6.00 | 8.00 |
| Mass flow (kg/s) | 18.36 | 64.18 | 64.18 | 64.18 | 64.18 | 64.18 | 14.74 | 14.74 |
| Mole flow (kmol/hr) | 1,178.76 | 6,555.77 | 6,555.77 | 6,555.77 | 6,555.77 | 6,555.77 | 3,156.04 | 3,156.04 |
| Components mole fractions (%) | | | | | | | | |
| N2 | 0.77 | 19.90 | 19.90 | 19.90 | 19.90 | 19.90 | 0.00 | 0.00 |
| CH4 | 4.30 | 40.10 | 40.10 | 40.10 | 40.10 | 40.10 | 96.03 | 96.03 |
| C2H6 | 0.02 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.00 | 0.00 |
| C3H8 | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.00 | 0.00 |
| i-C4H10 | 56.02 | 25.19 | 25.19 | 25.19 | 25.19 | 25.19 | 0.00 | 0.00 |
| n-C4H10 | 38.85 | 14.74 | 14.74 | 14.74 | 14.74 | 14.74 | 0.00 | 0.00 |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.40 | 0.40 |
| CO2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.01 | 3.01 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.55 | 0.55 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table S3.3. Single mixed refrigerant (SMR) process model validation with literature [3].

|  |  |  |  |
| --- | --- | --- | --- |
| **Performance** | **Simulation** | **Literature [3]** | **Error (%)** |
| COMP1 (kW) | 16,887 | 17,513.29 | 3.58 |
| COMP2 (kW) | 14,856 | 15,337.60 | 3.14 |
| COMP3 (kW) | 11,823 | 13,024.71 | 9.23 |
| PUMP (kW) | 290 | 114.24 | 153.85 |
| Total power consumption (kW) | 43,856 | 49,989.84 | 12.27 |

텍스트, 도표, 평면도, 기술 도면이(가) 표시된 사진

자동 생성된 설명

Fig. S3.3. Model of the renewable natural gas (RNG) power plant based on the natural gas combined cycle (NGCC).

Table S3.4. Natural gas combined cycle power plant model validation with literature [1],[33].

|  |  |  |  |
| --- | --- | --- | --- |
| **Performance** | **Simulation** | **Literature [1],[33]** | **Error (%)** |
| **Gas turbine unit (MW)** | **254.65** | **253.65** | **0.39** |
| Air compressor (MW) | 249.24 | 249.58 | 0.14 |
| Gas turbine (MW) | 507.77 | 507.09 | 0.13 |
| **Steam turbine unit (MW)** | **136.98** | **139.87** | **2.04** |
| HP turbine (MW) | 27.38 | 28.49 | 3.90 |
| IP turbine (MW) | 45.50 | 47.94 | 5.09 |
| LP turbine (MW) | 65.46 | 66.26 | 1.21 |
| Circulating pumps (MW) | 1.36 | 1.33 | 2.52 |
| **Plant net power (MW)** | **391.62** | **393.47** | **0.47** |
| **Plant efficiency (%)** | **55.88** | **56.21** | **0.47** |

텍스트, 도표, 평면도, 기술 도면이(가) 표시된 사진

자동 생성된 설명

Fig. S3.4. Model of the renewable natural gas (RNG) power plant based on the natural gas combined cycle (NGCC).

Table S3.5. MEA-based CO2 absorption process model validation with literature [5].

|  |  |  |  |
| --- | --- | --- | --- |
| **Performance** | **Simulation** | **Literature [5]** | **Error (%)** |
| CO2 capture rate (%) | 89.7 | 90.00 | 0.39 |
| Heat consumption (MWthermal) | 144.2 | 138.00 | 2.52 |
| Specific power consumption (MJe/kgCO2) | 4.15 | 4.11 | 0.99 |



Fig. S3.5. Model of the cryogenic CO2 capture and storage (CCS) process.

Table S3.6. Simulation results of the streams of the cryogenic CO2 capture and storage (CCS) process.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Stream** | **101** | **102** | **103** | **104** | **105** | **106** | **107** |
| Temperature (oC) | 127.46 | 30.00 | 29.96 | 29.96 | 89.89 | 30.00 | -147.30 |
| Pressure (bar) | 0.59 | 0.59 | 0.59 | 0.59 | 1.00 | 1.00 | 1.00 |
| Mass flow (kg/s) | 649.74 | 649.74 | 638.84 | 614.90 | 614.90 | 614.90 | 614.90 |
| Mole flow (kmol/s) | 22.97 | 22.97 | 22.36 | 21.03 | 21.03 | 21.03 | 21.03 |
| Components mole fractions (%) | | | | | | | |
| N2 | 75.00 | 75.00 | 77.03 | 81.90 | 81.90 | 81.90 | 81.90 |
| CO2 (g) | 3.86 | 3.86 | 3.96 | 4.21 | 4.21 | 4.21 | 0.00 |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.21 |
| O2 | 12.70 | 12.70 | 13.04 | 13.87 | 13.87 | 13.87 | 13.87 |
| H2O | 8.42 | 8.42 | 5.94 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C2H6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C3H8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| n-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| i-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | **108** | **109** | **110** | **201** | **202** | **301** | **302** |
| Temperature (oC) | -147.30 | -187.16 | 16.45 | 29.96 | 29.96 | -162.00 | 16.45 |
| Pressure (bar) | 1.00 | 0.55 | 0.55 | 0.59 | 0.59 | 6.00 | 6.00 |
| Mass flow (kg/s) | 575.93 | 575.93 | 575.93 | 10.90 | 23.94 | 14.74 | 14.74 |
| Mole flow (kmol/s) | 20.15 | 20.15 | 20.15 | 0.61 | 1.33 | 0.88 | 0.88 |
| Components mole fractions (%) | | | | | | | |
| N2 | 85.50 | 85.50 | 85.50 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (g) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.01 |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.01 | 0.00 |
| O2 | 14.48 | 14.48 | 14.48 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2O | 0.00 | 0.00 | 0.00 | 100.00 | 100.00 | 0.40 | 0.40 |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 96.03 | 96.03 |
| C2H6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C3H8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| n-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| i-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 0.02 | 0.02 | 0.02 | 0.00 | 0.00 | 0.55 | 0.55 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | **401** | **402** | **403** | **404** | **405** | **406** |  |
| Temperature (oC) | -147.30 | -67.00 | 24.96 | -53.00 | 29.56 | -48.90 |  |
| Pressure (bar) | 1.00 | 1.00 | 3.00 | 3.00 | 8.00 | 8.00 |  |
| Mass flow (kg/s) | 38.97 | 38.97 | 38.97 | 38.97 | 38.97 | 38.97 |  |
| Mole flow (kmol/s) | 0.89 | 0.89 | 0.89 | 0.89 | 0.89 | 0.89 |  |
| Components mole fractions (%) | | | | | | | |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CO2 (g) | 0.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |  |
| CO2 (s) | 100.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| C2H6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| C3H8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| n-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| i-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |



Fig. S3.6. Model of the RNG liquefaction process using cryogenic CO2 capture, utilization, and storage (CCUS).

Table S3.7. Simulation results of the streams of the RNG liquefaction process using cryogenic CO2 capture, utilization, and storage (CCUS).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Stream** | NG-1 | NG-2 | NG-3 | LNG-1 | LCO2-1 | SCO2-1 | GCO2-1 |
| Temperature (oC) | 25.00 | -70.90 | -70.90 | -162.00 | -48.90 | -73.89 | -73.89 |
| Pressure (bar) | 8.00 | 8.00 | 8.00 | 6.00 | 8.00 | 1.00 | 1.00 |
| Mass flow (kg/s) | 14.74 | 14.74 | 14.74 | 14.74 | 38.91 | 38.91 | 38.91 |
| Mole flow (kmol/s) | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 | 0.88 |
| Components mole fractions (%) | | | | | | | |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2O | 0.40 | 0.40 | 0.40 | 0.40 | 0.00 | 0.00 | 0.00 |
| CO2 (g) | 3.01 | 3.01 | 3.01 | 0.00 | 100.00 | 40.72 | 55.30 |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 3.01 | 0.00 | 59.28 | 44.70 |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 96.03 | 96.03 | 96.03 | 96.03 | 0.00 | 0.00 | 0.00 |
| C2H6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C3H8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| n-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| i-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH3F | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 0.55 | 0.55 | 0.55 | 0.55 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | GCO2-2 | GCO2-3 | R1 | R2 | R3 | R4 | R5 |
| Temperature (oC) | -37.30 | 27.00 | 25.00 | 94.24 | 30.00 | 95.05 | 30.00 |
| Pressure (bar) | 1.00 | 1.00 | 1.50 | 5.00 | 5.00 | 14.99 | 14.99 |
| Mass flow (kg/s) | 38.91 | 38.91 | 52.57 | 52.57 | 52.57 | 52.57 | 52.57 |
| Mole flow (kmol/s) | 0.88 | 0.88 | 1.49 | 1.49 | 1.49 | 1.49 | 1.49 |
| Components mole fractions (%) | | | | | | | |
| N2 | 0.00 | 0.00 | 19.90 | 19.90 | 19.90 | 19.90 | 19.90 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (g) | 100.00 | 100.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 40.10 | 40.10 | 40.10 | 40.10 | 40.10 |
| C2H6 | 0.00 | 0.00 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| C3H8 | 0.00 | 0.00 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| n-C4H10 | 0.00 | 0.00 | 14.74 | 14.74 | 14.74 | 14.74 | 14.74 |
| i-C4H10 | 0.00 | 0.00 | 25.19 | 25.19 | 25.19 | 25.19 | 25.19 |
| CH3F | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | R6 | R7 | R8 | R9 | R10 | R11 | R12 |
| Temperature (oC) | 30.00 | 107.51 | 30.00 | 32.58 | 71.31 | 30.00 | -162.00 |
| Pressure (bar) | 14.99 | 44.96 | 14.99 | 44.96 | 44.96 | 44.96 | 44.96 |
| Mass flow (kg/s) | 37.53 | 37.53 | 15.04 | 15.04 | 52.57 | 52.57 | 52.57 |
| Mole flow (kmol/s) | 1.22 | 1.22 | 0.27 | 0.27 | 1.49 | 1.49 | 1.49 |
| Components mole fractions (%) | | | | | | | |
| N2 | 24.09 | 24.09 | 0.77 | 0.77 | 19.90 | 19.90 | 19.90 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (g) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 47.95 | 47.95 | 4.30 | 4.30 | 40.10 | 40.10 | 40.10 |
| C2H6 | 0.04 | 0.04 | 0.02 | 0.02 | 0.04 | 0.04 | 0.04 |
| C3H8 | 0.03 | 0.03 | 0.04 | 0.04 | 0.03 | 0.03 | 0.03 |
| n-C4H10 | 9.45 | 9.45 | 38.85 | 38.85 | 14.74 | 14.74 | 14.74 |
| i-C4H10 | 18.43 | 18.43 | 56.02 | 56.02 | 25.19 | 25.19 | 25.19 |
| CH3F | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | R13 | R14 | 1-1 | 1-2 | 1-3 | 1-4 | 1-5 |
| Temperature (oC) | -170.25 | 25.00 | -34.26 | -66.04 | -64.50 | 30.00 | 91.00 |
| Pressure (bar) | 2.50 | 1.50 | 2.00 | 2.00 | 33.00 | 33.00 | 33.00 |
| Mass flow (kg/s) | 52.57 | 52.57 | 21.24 | 21.24 | 21.24 | 21.24 | 21.24 |
| Mole flow (kmol/s) | 1.49 | 1.49 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 |
| Components mole fractions (%) | | | | | | | |
| N2 | 19.90 | 19.90 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (g) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 40.10 | 40.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C2H6 | 0.04 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C3H8 | 0.03 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| n-C4H10 | 14.74 | 14.74 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| i-C4H10 | 25.19 | 25.19 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH3F | 0.00 | 0.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | 1-6 | 1-7 | 1-8 | 2-1 | 2-2 | 2-3 | 2-4 |
| Temperature (oC) | 6.06 | 30.00 | -34.26 | 30.00 | -31.52 | -29.00 | 30.00 |
| Pressure (bar) | 8.00 | 8.00 | 2.00 | 8.00 | 8.00 | 33.00 | 33.00 |
| Mass flow (kg/s) | 21.24 | 21.24 | 21.24 | 4.27 | 4.27 | 4.27 | 4.27 |
| Mole flow (kmol/s) | 0.62 | 0.62 | 0.62 | 0.13 | 0.13 | 0.13 | 0.13 |
| Components mole fractions (%) | | | | | | | |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (g) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C2H6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C3H8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| n-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| i-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH3F | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | 2-5 | 2-6 | 2-7 | 2-8 | 2-9 | 2-10 |  |
| Temperature (oC) | 9.98 | 30.00 | -2.43 | 30.00 | -4.78 | 30.00 |  |
| Pressure (bar) | 25.00 | 25.00 | 15.00 | 15.00 | 8.00 | 8.00 |  |
| Mass flow (kg/s) | 4.27 | 4.27 | 4.27 | 4.27 | 4.27 | 4.27 |  |
| Mole flow (kmol/s) | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |  |
| Components mole fractions (%) | | | | | | | |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CO2 (g) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CO2 (s) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| Ar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| C2H6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| C3H8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| n-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| i-C4H10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CH3F | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |  |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |  |

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Fig. S3.7. Model of the power-to-gas (PtG) processes after heat integrations.

Table S3.8. Simulation results of the power-to-gas (PtG) processes after heat integrations.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Stream** | **101** | **102** | **103** | **104** | **105** | **106** | **107** |
| Temperature (oC) | 25.00 | 600.00 | 25.00 | 600.00 | 599.98 | 599.97 | 600.00 |
| Pressure (bar) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mass flow (kg/s) | 64.32 | 64.32 | 39.28 | 39.28 | 103.60 | 103.91 | 103.91 |
| Mole flow (kmol/s) | 3.57 | 3.57 | 0.89 | 0.89 | 4.46 | 4.62 | 4.62 |
| Components mole fractions (%) | | | | | | | |
| H2O | 100.00 | 100.00 | 0.00 | 0.00 | 80.00 | 77.28 | 77.28 |
| CO2 | 0.00 | 0.00 | 100.00 | 100.00 | 20.00 | 19.32 | 19.32 |
| H2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.39 | 3.39 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | **108** | **109** | **110** | **111** | **112** | **113** | **114** |
| Temperature (oC) | 600.00 | 600.00 | 600.00 | 600.00 | 600.00 | 600.00 | 600.00 |
| Pressure (bar) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mass flow (kg/s) | 103.91 | 103.91 | 46.79 | 6.32 | 40.47 | 6.00 | 0.32 |
| Mole flow (kmol/s) | 6.40 | 6.40 | 4.62 | 3.14 | 1.48 | 2.98 | 0.16 |
| Components mole fractions (%) | | | | | | | |
| H2O | 11.15 | 9.23 | 12.80 | 0.00 | 39.85 | 0.00 | 0.00 |
| CO2 | 2.79 | 4.70 | 6.52 | 0.00 | 20.30 | 0.00 | 0.00 |
| H2 | 47.04 | 48.96 | 67.88 | 100.00 | 0.00 | 100.00 | 100.00 |
| O2 | 27.87 | 27.87 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CO | 11.15 | 9.23 | 12.80 | 0.00 | 39.85 | 0.00 | 0.00 |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | **115** | **116** | **117** | **118** | **119** | **201** | **301** |
| Temperature (oC) | 600.00 | 25.00 | 600.00 | 600.00 | 600.00 | 599.96 | 450.00 |
| Pressure (bar) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Mass flow (kg/s) | 0.32 | 0.12 | 0.12 | 57.12 | 57.24 | 46.48 | 46.48 |
| Mole flow (kmol/s) | 0.16 | 0.00 | 0.00 | 1.79 | 1.79 | 4.46 | 3.30 |
| Components mole fractions (%) | | | | | | | |
| H2O | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 13.25 | 41.64 |
| CO2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 6.75 | 3.16 |
| H2 | 100.00 | 0.00 | 0.00 | 0.00 | 0.00 | 66.75 | 31.27 |
| O2 | 0.00 | 21.00 | 21.00 | 100.00 | 99.82 | 0.00 | 0.00 |
| CH4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 17.72 |
| CO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 13.25 | 6.21 |
| N2 | 0.00 | 79.00 | 79.00 | 0.00 | 0.18 | 0.00 | 0.00 |
| **Stream** | **302** | **303** | **304** | **305** | **306** | **307** | **308** |
| Temperature (oC) | 725.00 | 971.90 | 200.00 | 504.17 | 200.12 | 363.41 | 200.16 |
| Pressure (bar) | 3.30 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Mass flow (kg/s) | 46.48 | 46.48 | 46.48 | 46.48 | 46.48 | 46.48 | 46.48 |
| Mole flow (kmol/s) | 3.30 | 3.30 | 3.30 | 2.97 | 2.97 | 2.76 | 2.76 |
| Components mole fractions (%) | | | | | | | |
| H2O | 41.64 | 41.64 | 41.64 | 50.81 | 50.81 | 61.62 | 61.62 |
| CO2 | 3.16 | 3.16 | 3.16 | 4.52 | 4.52 | 1.51 | 1.51 |
| H2 | 31.27 | 31.27 | 31.27 | 19.09 | 19.09 | 6.05 | 6.05 |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| CH4 | 17.72 | 17.72 | 17.72 | 25.24 | 25.24 | 30.81 | 30.81 |
| CO | 6.21 | 6.21 | 6.21 | 0.34 | 0.34 | 0.01 | 0.01 |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Stream** | **309** | **310** | **311** | **312** |  |  |  |
| Temperature (oC) | 252.18 | 25.00 | 25.00 | 25.00 |  |  |  |
| Pressure (bar) | 8.00 | 8.00 | 8.00 | 8.00 |  |  |  |
| Mass flow (kg/s) | 46.48 | 46.48 | 14.74 | 31.74 |  |  |  |
| Mole flow (kmol/s) | 2.70 | 2.70 | 0.94 | 1.76 |  |  |  |
| Components mole fractions (%) | | | | | | | |
| H2O | 65.42 | 65.42 | 0.35 | 100.00 |  |  |  |
| CO2 | 0.37 | 0.37 | 1.08 | 0.00 |  |  |  |
| H2 | 1.49 | 1.49 | 4.31 | 0.00 |  |  |  |
| O2 | 0.00 | 0.00 | 0.00 | 0.00 |  |  |  |
| CH4 | 32.71 | 32.71 | 94.26 | 0.00 |  |  |  |
| CO | 0.00 | 0.00 | 0.00 | 0.00 |  |  |  |
| N2 | 0.00 | 0.00 | 0.00 | 0.00 |  |  |  |

Table S3.9. Energy consumption of the PtG process before and after heat integration

|  |  |  |  |
| --- | --- | --- | --- |
| Equipments | Value | | Units |
| Before HI\* | After HI |
| SOEC co-electrolyzer | 749.85 | 749.89 | MWe |
| Compressor | 73.92 | 73.92 | MWe |
| Heaters | 262.23 | 0.07 | MWth |
| Coolers | −405.50 | −143.37 | MWth |

\*HI: Heat integration

Table S3.10. Simulation results of the streams of the PtG process before and after heat integration

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Components | | Specification | Value | | Units |
| Before HI | After HI |
| Input | H2O | Mass flow | 64.32 | 64.32 | kg/s |
| CO2 | Mass flow | 39.28 | 39.28 | kg/s |
| Output | H2\* | Mass flow | 6.00 | 6.00 | kg/s |
| RNG | Mass flow | 14.74 | 14.74 | kg/s |
| Temperature | 25 | 25 | °C |
| Pressure | 8 | 8 | bar |
| Composition (mol%) | 100.00 | 100.00 | % |
| H2O | 0.35 | 0.40 | % |
| CO2 | 1.07 | 3.01 | % |
| H2 | 4.29 | 0.55 | % |
| O2 | 0.00 | 0.00 | % |
| CH4 | 94.28 | 96.03 | % |
| CO | 0.00 | 0.00 | % |
| N2 | 0.00 | 0.00 | % |
| HHV | 36,206 | 36,139 | kJ/Sm3 |
| WI | 47,707 | 47,609 | kJ/Sm3 |
| SG | 0.57597 | 0.57621 | - |

\*H2 is in the syngas from SOEC.

Table S3.11. Energy consumption of the NGCC power plant

|  |  |  |
| --- | --- | --- |
| Equipments | Value | Units |
| Air compressor | 246.75 | MWe |
| Water pumps | 1.37 | MWe |
| Gas turbines | −507.71 | MWe |
| Steam turbines | −138.34 | MWe |
| Total power consumption | −397.93 | MWe |

Table S3.12. Energy consumption of the cryogenic CCS process

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Equipments | | Value | | Units | |
| Capture | Compressors | 42.21 | | MWe | |
| Turbines | −23.38 | | MWe | |
| Storage | Compressors | 5.58 | | MWe | |
| Heaters | 25.44 | | MWth | |
| Coolers | −18.61 | | WMth | |
| Total power consumption | | | 24.41 | | MWe |

Table S3.13. Energy consumption of the liquefactiaon process without and with cryogenic CCUS

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Equipments | | Value | | Units |
| w/o CCUS | w/ CCUS |
| Refrigeration cycle | Compressors | 20.25 | 16.51 | MWe |
| Pump | 0.13 | 0.25 | MWe |
| Turbines | 0.00 | −2.94 | MWe |
| Heat exchange | HEX1 | 0.00 | −3.28 | MWth |
| MSHE1 | −12.87 | −10.18 | MWth |
| Total power consumption | | 20.39 | 20.39 | MWe |
| Heat exchange to liquefy NG | | −12.87 | −13.47 | MWth |

# S4. Detailed techno-economic analysis results

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Fig. S4.1. Levelized cost of electricity (LCOE) breakdown of each value chain in 2020

Fig. S4. 1 shows the breakdown of the LCOE for each value chain in 2020. Breaking down only the LCOE for 2020 helps identify the variables that significantly impact costs. It also helps analyze why the LCOE will decrease in 2050.

In the FNG value chain, investment costs account for 33.6% and O&M costs account for 66.4%. Because the FNG value chain does not include the investment cost of the PtG process, the ratio of investment cost in the LCOE is lower than in other cases. However, the O&M cost ratio is high because the fuel (FNG) must be purchased externally. It was confirmed that the FNG and grid electricity costs significantly affected the LCOE in Case 1.

In Case 1 of the RNG value chain, investment costs accounted for 39.6% and O&M costs accounted for 60.4%. Because the RNG value chain requires a PtG process, the investment cost of the PtG process is additional. Renewable energy is also required to operate the PtG process, resulting in renewable energy costs accounting for 99.8% of the O&M costs. Therefore, the LCOE of Case 1 was significantly affected by the investment cost of the PtG process and renewable energy costs.

In Case 2, the amine-based CCS process was replaced with a cryogenic CCS process, thereby reducing energy consumption and the O&M cost ratio. However, because the cryogenic CCS process is composed of expensive aluminum tubes [13], the proportion of investment costs has increased. Therefore, the LCOE of Case 2 was significantly affected by the investment and renewable energy costs of the PtG and cryogenic CCS processes.

In Case 3, cryogenic CCUS was added to the SMR-based liquefaction process, thereby reducing the power consumption of the refrigeration cycle and decreasing O&M costs. Additionally, as the refrigeration cycle load decreases, the investment cost decreases, reducing the overall investment cost of the liquefaction process despite the additional ORC units. Therefore, the LCOE in Case 3 was also the most influenced by the investment and renewable energy costs of the PtG and cryogenic CCS processes.

Finally, in Case 4, heat integration was performed during the PtG process, and the investment cost increased because of the installation of additional heat exchangers. On the other hand, heat integration reduces the renewable energy required for the PtG process, thus reducing O&M costs. Case 4 was confirmed to have the greatest impact on the investment and renewable energy costs of the PtG and cryogenic CCS processes.

Table S4.1. Techno-economic analysis results of the proposed RNG value chains and FNG one

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Specification | Case 1 | Case 2 | Case 3 | Case 4 | FNG |
| CAPEX ($) | 462,881,514 | 493,094,513 | 481,634,859 | 470,905,615 | 337,709,397 |
| OPEX ($) | 704,989,923 | 704,989,923 | 700,811,314 | 534,270,713 | 668,861,128 |
| Power generation (MWh) | 4,444,392 | 4,863,144 | 4,863,144 | 4,863,144 | 4,444,392 |
| LCOE\* ($/MWh) | 262.77 | 246.36 | 243.14 | 206.69 | 226.48 |

\*LCOE: Levelized cost of electricity

Table S4.2. Breakdown of CAPEX results of Case 1

|  |  |  |  |
| --- | --- | --- | --- |
| CAPEX | | Value ($) | Percentage |
| PtG (before HI\*) | Heater | 10,863,000 | 2.3% |
| Electrolyzer | 50,211,170 | 10.8% |
| Cooler | 1,510,236 | 0.3% |
| Methanation reactor | 3,614,702 | 0.8% |
| Compressor | 58,919,509 | 12.7% |
| Drum | 53,500 | 0.0% |
| Total | 125,172,117 | 27.0% |
| Liquefaction (SMR) | Cooler | 1,394,700 | 0.3% |
| Compressor | 21,661,500 | 4.7% |
| MSHE | 18,176,200 | 3.9% |
| Pump | 126,600 | 0.0% |
| Drum | 69,000 | 0.0% |
| Total | 41,428,000 | 9.0% |
| Power plant | Air compressor | 196,605,530 | 42.5% |
| Gas turbine | 50,571,295 | 10.9% |
| Combustor | 1,277,861 | 0.3% |
| Heat exchanger | 763,902 | 0.2% |
| Cooler | 1,228,746 | 0.3% |
| Pump | 716,300 | 0.2% |
| Turbine | 24,242,989 | 5.2% |
| Drum | 935,100 | 0.2% |
| Total | 276,341,725 | 59.7% |
| CCS (MEA-absorption) | Absorber | 4,766,500 | 1.0% |
| Stripper | 686,200 | 0.1% |
| Pump | 187,400 | 0.0% |
| Lean cooler | 555,300 | 0.1% |
| Reboiler | 970,500 | 0.2% |
| Condenser | 67,300 | 0.0% |
| Preheater | 12,899 | 0.0% |
| Drum | 46,800 | 0.0% |
| Compressor | 12,047,173 | 2.6% |
| Cooler | 436,700 | 0.1% |
| Drum | 162,900 | 0.0% |
| Total | 19,939,672 | 4.3% |
| Total | | 462,881,514 | 100.0% |

\*HI: Heat integration

Table S4.3. Breakdown of CAPEX results of Case 2

|  |  |  |  |
| --- | --- | --- | --- |
| CAPEX | | Value ($) | Percentage |
| PtG (before HI\*) | Heater | 10,863,000 | 2.2% |
| Electrolyzer | 50,211,170 | 10.2% |
| Cooler | 1,510,236 | 0.3% |
| Methanation reactor | 3,614,702 | 0.7% |
| Compressor | 58,919,509 | 11.9% |
| Drum | 53,500 | 0.0% |
| Total | 125,172,117 | 25.4% |
| Liquefaction (SMR) | Cooler | 1,394,700 | 0.3% |
| Compressor | 21,661,500 | 4.4% |
| MSHE | 18,176,200 | 3.7% |
| Pump | 126,600 | 0.0% |
| Drum | 69,000 | 0.0% |
| Total | 41,428,000 | 8.4% |
| Power plant | Air compressor | 196,605,530 | 39.9% |
| Gas turbine | 50,571,295 | 10.3% |
| Combustor | 1,277,861 | 0.3% |
| Heat exchanger | 763,902 | 0.2% |
| Cooler | 1,228,746 | 0.2% |
| Pump | 716,300 | 0.1% |
| Turbine | 24,242,989 | 4.9% |
| Drum | 935,100 | 0.2% |
| Total | 276,341,725 | 56.0% |
| CCS (Cryogenic) | Cooler | 8,821,200 | 1.8% |
| Compressor | 15,018,132 | 3.0% |
| MSHE 1 (CCC) | 12,301,700 | 2.5% |
| MSHE 2 | 489,700 | 0.1% |
| Drum | 8,646,800 | 1.8% |
| Turbine | 4,875,139 | 1.0% |
| Total | 50,152,671 | 10.2% |
| Total | | 493,094,513 | 100.0% |

\*HI: Heat integration

Table S4.4. Breakdown of CAPEX results of Case 3

|  |  |  |  |
| --- | --- | --- | --- |
| CAPEX | | Value ($) | Percentage |
| PtG (before HI\*) | Heater | 10,863,000 | 2.3% |
| Electrolyzer | 50,211,170 | 10.4% |
| Cooler | 1,510,236 | 0.3% |
| Methanation reactor | 3,614,702 | 0.8% |
| Compressor | 58,919,509 | 12.2% |
| Drum | 53,500 | 0.0% |
| Total | 125,172,117 | 26.0% |
| Liquefaction  (Cryogenic) | Cooler | 1,484,200 | 0.3% |
| Heater | 134,400 | 0.0% |
| Heat exchanger | 20,846 | 0.0% |
| Compressor | 18,676,300 | 3.9% |
| Turbine | 1,890,100 | 0.4% |
| Pump | 307,300 | 0.1% |
| MSHE | 7,391,400 | 1.5% |
| Drum | 63,800 | 0.0% |
| Total | 29,968,346 | 6.2% |
| Power plant | Air compressor | 196,605,530 | 40.8% |
| Gas turbine | 50,571,295 | 10.5% |
| Combustor | 1,277,861 | 0.3% |
| Heat exchanger | 763,902 | 0.2% |
| Cooler | 1,228,746 | 0.3% |
| Pump | 716,300 | 0.1% |
| Turbine | 24,242,989 | 5.0% |
| Drum | 935,100 | 0.2% |
| Total | 276,341,725 | 57.4% |
| CCS (Cryogenic) | Cooler | 8,821,200 | 1.8% |
| Compressor | 15,018,132 | 3.1% |
| MSHE 1 (CCC) | 12,301,700 | 2.6% |
| MSHE 2 | 489,700 | 0.1% |
| Drum | 8,646,800 | 1.8% |
| Turbine | 4,875,139 | 1.0% |
| Total | 50,152,671 | 10.4% |
| Total | | 481,634,859 | 100.0% |

\*HI: Heat integration

Table S4.5. Breakdown of CAPEX results of Case 4

|  |  |  |  |
| --- | --- | --- | --- |
| CAPEX | | Value ($) | Percentage |
| PtG (after HI\*) | Heat exchanger | 457,093 | 0.1% |
| Heater | 18,900 | 0.0% |
| Electrolyzer | 50,211,170 | 10.7% |
| Cooler | 1,168,000 | 0.2% |
| Methanation reactor | 3,614,702 | 0.8% |
| Compressor | 58,919,509 | 12.5% |
| Drum | 53,500 | 0.0% |
| Total | 114,442,873 | 24.3% |
| Liquefaction  (Cryogenic) | Cooler | 1,484,200 | 0.3% |
| Heater | 134,400 | 0.0% |
| Heat exchanger | 20,846 | 0.0% |
| Compressor | 18,676,300 | 4.0% |
| Turbine | 1,890,100 | 0.4% |
| Pump | 307,300 | 0.1% |
| MSHE | 7,391,400 | 1.6% |
| Drum | 63,800 | 0.0% |
| Total | 29,968,346 | 6.4% |
| Power plant | Air compressor | 196,605,530 | 41.8% |
| Gas turbine | 50,571,295 | 10.7% |
| Combustor | 1,277,861 | 0.3% |
| Heat exchanger | 763,902 | 0.2% |
| Cooler | 1,228,746 | 0.3% |
| Pump | 716,300 | 0.2% |
| Turbine | 24,242,989 | 5.1% |
| Drum | 935,100 | 0.2% |
| Total | 276,341,725 | 58.7% |
| CCS (Cryogenic) | Cooler | 8,821,200 | 1.9% |
| Compressor | 15,018,132 | 3.2% |
| MSHE 1 (CCC) | 12,301,700 | 2.6% |
| MSHE 2 | 489,700 | 0.1% |
| Drum | 8,646,800 | 1.8% |
| Turbine | 4,875,139 | 1.0% |
| Total | 50,152,671 | 10.7% |
| Total | | 470,905,615 | 100.0% |

\*HI: Heat integration

Table S4.6. Breakdown of CAPEX results of the FNG value chain

|  |  |  |  |
| --- | --- | --- | --- |
| CAPEX | | Value ($) | Percentage |
| Liquefaction (SMR) | Cooler | 1,394,700 | 0.4% |
| Compressor | 21,661,500 | 6.4% |
| MSHE | 18,176,200 | 5.4% |
| Pump | 126,600 | 0.0% |
| Drum | 69,000 | 0.0% |
| Total | 41,428,000 | 12.3% |
| Power plant | Air compressor | 196,605,530 | 58.2% |
| Gas turbine | 50,571,295 | 15.0% |
| Combustor | 1,277,861 | 0.4% |
| Heat exchanger | 763,902 | 0.2% |
| Cooler | 1,228,746 | 0.4% |
| Pump | 716,300 | 0.2% |
| Turbine | 24,242,989 | 7.2% |
| Drum | 935,100 | 0.3% |
| Total | 276,341,725 | 81.8% |
| CCS (MEA-absorption) | Absorber | 4,766,500 | 1.4% |
| Stripper | 686,200 | 0.2% |
| Pump | 187,400 | 0.1% |
| Lean cooler | 555,300 | 0.2% |
| Reboiler | 970,500 | 0.3% |
| Condenser | 67,300 | 0.0% |
| Preheater | 12,899 | 0.0% |
| Drum | 46,800 | 0.0% |
| Compressor | 12,047,173 | 3.6% |
| Cooler | 436,700 | 0.1% |
| Drum | 162,900 | 0.0% |
| Total | 19,939,672 | 5.9% |
| Total | | 337,709,397 | 100.0% |

Table S4.7. Breakdown of CAPEX results of of the proposed RNG value chains and FNG one

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Components | Case 1 | Case 2 | Case 3 | Case 4 | FNG |
| Renewable energy ($) | 4,319,340,195 | 4,319,340,195 | 4,293,664,450 | 3,270,344,552 | – |
| Catalyst ($) | 12,517,699 | 12,517,699 | 12,517,699 | 12,517,699 | – |
| Grid electricity ($) | – | – | – | – | 380,442,178 |
| Fuel (FNG) ($) | – | – | – | – | 3,729,419,905 |
| Total | 4,331,857,893 | 4,331,857,893 | 4,306,182,148 | 3,282,862,251 | 4,109,862,083 |

# S5. Detailed life cycle GHG emissions results

Table S5.1. LCGHG emissions of the proposed RNG value chains

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| LCGHG emissions (kgCO2eq/MWhNG) | | Case 1 | Case 2 | Case 3 | Case 4 |
| Solar PV | Transportation | 2.23 | 2.23 | 1.51 | 1.51 |
| Utilization | 0.03 | 0.01 | 0.01 | 0.01 |
| Production | 118.99 | 118.99 | 118.99 | 90.26 |
| Total | 121.26 | 121.24 | 120.51 | 91.78 |
| Offshore wind | Transportation | 0.68 | 0.68 | 0.46 | 0.46 |
| Utilization | 0.01 | 0.00 | 0.00 | 0.00 |
| Production | 36.36 | 36.36 | 36.36 | 27.57 |
| Total | 37.06 | 37.05 | 36.83 | 28.04 |
| Hydropower | Transportation | 0.63 | 0.63 | 0.43 | 0.43 |
| Utilization | 0.01 | 0.00 | 0.00 | 0.00 |
| Production | 33.56 | 33.56 | 33.56 | 25.45 |
| Total | 34.20 | 34.19 | 33.99 | 25.88 |
| Geothermal | Transportation | 1.00 | 1.00 | 0.68 | 0.68 |
| Utilization | 0.02 | 0.00 | 0.00 | 0.00 |
| Production | 53.17 | 53.17 | 53.17 | 40.32 |
| Total | 54.18 | 54.17 | 53.85 | 41.00 |

Table S5.2. Indirect GHG emissions of the proposed RNG value chains

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Indirect GHG emissions (kgCO2eq/MWhNG) | | Case 1 | Case 2 | Case 3 | Case 4 |
| Solar PV | Transportation | 2.23 | 2.23 | 1.51 | 1.51 |
| Utilization | 0.03 | 0.01 | 0.01 | 0.01 |
| Production | 119.04 | 119.04 | 119.04 | 90.31 |
| Total | 121.30 | 121.29 | 120.56 | 91.83 |
| Offshore wind | Transportation | 0.68 | 0.68 | 0.46 | 0.46 |
| Utilization | 0.01 | 0.00 | 0.00 | 0.00 |
| Production | 36.41 | 36.41 | 36.41 | 27.62 |
| Total | 37.10 | 37.10 | 36.88 | 28.09 |
| Hydropower | Transportation | 0.63 | 0.63 | 0.43 | 0.43 |
| Utilization | 0.01 | 0.00 | 0.00 | 0.00 |
| Production | 33.61 | 33.61 | 33.61 | 25.50 |
| Total | 34.25 | 34.25 | 34.04 | 25.93 |
| Geothermal | Transportation | 1.00 | 1.00 | 0.68 | 0.68 |
| Utilization | 0.01 | 0.00 | 0.00 | 0.00 |
| Production | 53.22 | 53.22 | 53.22 | 40.37 |
| Total | 54.23 | 54.22 | 53.90 | 41.05 |

Table S5.3. Direct GHG emissions of the proposed RNG value chains

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Direct GHG emissions (kgCO2eq/MWhNG) | Case 1 | Case 2 | Case 3 | Case 4 |
| Transportation | 0.00 | 0.00 | 0.00 | 0.00 |
| Utilization | 0.01 | 0.00 | 0.00 | 0.00 |
| Production | -0.05 | -0.05 | -0.05 | -0.05 |
| Total | -0.05 | -0.05 | -0.05 | -0.05 |

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