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Waste CO_2 to CO for Energy Storage

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Abstract

In this report, we present a process design for the storage of electricity using solid oxide fuel cell (SOFC) technology to convert electrical energy to chemical fuel via the reduction of carbon dioxide. The goal of this project was to design a system that could alleviate the issues around the intermittent nature of renewable energy production, which must phase out the use of fossil fuels in the future. The overall process was developed for two storage strategies, and the economics feasibility of the design is considered and reported. The key aspect of this process is its reversible nature. Both the production and consumption of the chemical fuel are achieved in the same plant, both with the SOFC technology.

Two cases are presented. In both, carbon monoxide is produced via electrolysis during high-production hours for solar and wind power. Carbon dioxide is renewably sourced from fermentation plants. In the first case, the carbon monoxide is pressurized for storage at 2,000 psig. In the second case, the carbon monoxide is minimally compressed to 5 psig and stored at near atmospheric conditions. It was found that for the high-pressure storage case, the efficiency of the process was 53.5%, and in the low-pressure storage case, the efficiency was 54.6%.

Two pricing strategies were considered. The first assigned an opportunity cost of electricity storage to the off-peak electricity price. In this scenario, the high- and low-pressure cases had negative ROI's of -32.5% and -29.4%, respectively. In the second pricing strategy, we consider the eventuality of overproduction of solar and wind energy, when renewable energy sources comprise a majority of the supply. In this scenario, the opportunity cost of the excess electricity production would be zero, and the ROI of the high- and low-pressure cases are then positive at 29.9% and 31.8%, respectively. Though the latter is not reflective of the current economic reality, in the future it may become more relevant, and a design such as the one presented here should be considered as a potentially profitable solution.

Disciplines

Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering

Waste CO_2 to CO for Energy Storage

Analysis of the Feasibility of Solid Oxide Fuel Cell Technologies for Energy Storage Solutions

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April 28th, 2019

Dear Prof. Vohs and Prof. Vrana,

This spring, our senior design team set out to design an energy-storage process utilizing fuel cell technology to convert electricity to chemical fuel. The overarching goal of this process is to provide a means of efficient storage for excess energy-production from variable, renewable sources such as wind and solar energy. The profitability of the process is analyzed from a grid-balancing perspective, in which the price difference between on- and off-peak electricity demand is taken advantage of, and the intended application of excess energy storage, in which the input electricity has zero or negative opportunity cost. The latter scenario, in which potential energy production is foregone due to operating costs, is sometimes referred to as curtailment.

In this designed process, energy is stored by running an electrolytic cell that applies a potential to drive an energy-consuming reaction. When needed, the energy is dispensed by running a reverse process with a fuel cell that drives a current using an energy-producing reaction. Here, we use the reduction of carbon dioxide and the oxidation of carbon monoxide as the energy-storing and energy-producing reactions, respectively. This process's advantages include the side production of high purity oxygen gas and geographic invariance. Additionally, the process analyzed here does not use any fossil fuels and sources carbon dioxide sustainably.

The report analyzes the effect of different storage conditions on the overall profitability of the process. High-pressure storage reduces the capitalized cost of the storage tanks and overall size of the plant but reduces the efficiency of the energy-storage process, and therefore compromises the revenue. Here we show that it is optimal to store the carbon monoxide fuel at near-atmospheric conditions to maximize the efficiency and simplify the equipment needed.

Our analysis and evaluation show that the fuel cell energy storage process is not profitable for the purpose of grid balancing, as the price difference between on- and off-peak demand is not high enough to justify the operating costs for the optimized efficiency of the process. However, in the scenario where the input electricity has zero opportunity cost, such as in the case of overgeneration or curtailment, the process is profitable. We suggest that, when renewable sources of energy eventually become the primary source of electricity, this process should be revisited and considered for a potential energy-storage solution.

In this report, a detailed description of the optimized process, an analysis of the efficiency of the energy storage, an analysis of the costs and potential revenue of the design, and recommendations are included.

Sincerely,

Vignesh C. Bhethanabotla   Joseph C. Dennis   Mavis A. U Chen

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1. Abstract

In this report, we present a process design for the storage of electricity using solid oxide fuel cell (SOFC) technology to convert electrical energy to chemical fuel via the reduction of carbon dioxide. The goal of this project was to design a system that could alleviate the issues around the intermittent nature of renewable energy production, which must phase out the use of fossil fuels in the future. The overall process was developed for two storage strategies, and the economics feasibility of the design is considered and reported. The key aspect of this process is its reversible nature. Both the production and consumption of the chemical fuel are achieved in the same plant, both with the SOFC technology.

Two cases are presented. In both, carbon monoxide is produced via electrolysis during high-production hours for solar and wind power. Carbon dioxide is renewably sourced from fermentation plants. In the first case, the carbon monoxide is pressurized for storage at 2,000 psig. In the second case, the carbon monoxide is minimally compressed to 5 psig and stored at near atmospheric conditions. It was found that for the high-pressure storage case, the efficiency of the process was 53.5%, and in the low-pressure storage case, the efficiency was 54.6%.

Two pricing strategies were considered. The first assigned an opportunity cost of electricity storage to the off-peak electricity price. In this scenario, the high- and low-pressure cases had negative ROI’s of -32.5% and -29.4%, respectively. In the second pricing strategy, we consider the eventuality of overproduction of solar and wind energy, when renewable energy sources comprise a majority of the supply. In this scenario, the opportunity cost of the excess electricity production would be zero, and the ROI of the high- and low-pressure cases are then positive at

29.9% and 31.8%, respectively. Though the latter is not reflective of the current economic reality, in the future it may become more relevant, and a design such as the one presented here should be considered as a potentially profitable solution.

2. Introduction

2.1 Project Background

The use of fossil fuels continues to be integral to the energy sector. However, the use of fossil fuels must be curtailed to mitigate its contributions to climate change. While the efficacy of renewable and clean alternative energy production technologies has grown, they suffer from a risk of overgeneration during peak production hours and undergeneration during peak demand hours on a day-to-day basis. For example, solar energy plants waste potential electricity generation during midday when sunlight is strongest but demand for electricity tends to be lower. At the same time, demand for electricity tends to increase towards the evening and night, when solar energy production is low to zero. Variability is inherent to renewable energy sources such as this and necessitate the development of effective storage solutions. A representative diagram is shown in figure 2.1.1 to illustrate this concept.

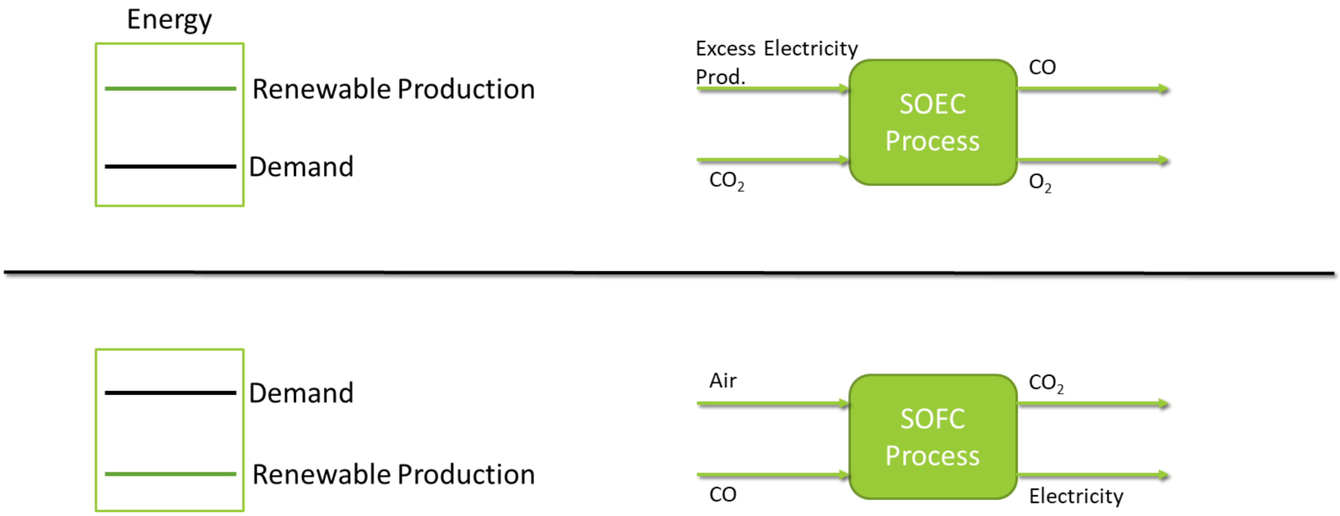
A model for commercial viability of energy storage is load shifting, a simple arbitrage practice that leverages the natural changes in production and demand throughout the day. During daylight hours, demand for electricity is typically lower, as people are out of their homes and in high-density buildings. During this time, renewable energy facilities are also generating power at their highest rates, driving down the price further by providing excess power in the market. This is called the off-peak period. At night, when populations return home and increase demand, the power supply from renewables decreases, leading to on-peak pricing. The marked difference in wholesale energy price-points between the two periods serves as the economic impetus behind many storage projects: store the energy when it can be acquired cheaply and sell it back when demand increases later in the day. The principle of load shifting is the basis for this project's first economic case, on-peak/off-peak pricing.

The second economic case uses a different set of underlying assumptions about the price of the acquired power. Oftentimes, renewable power plants are ordered or incentivized to stop production when there is an oversupply of energy in the market. This is called curtailment, and it is intended to avoid driving the price down to levels that are uneconomic or in some cases, negative. This is a common occurrence in areas with significant renewable energy generation buildout and will become increasingly common as renewables continue to increase their share of the power market. In these situations, the plants are unable to produce at their full capacity, with the curtailed energy essentially being wasted. From this standpoint, any power that can be stored instead of curtailed can effectively be thought of as free energy, or energy that would not otherwise generate revenue. For this project's second economic case, curtailment, the price of input energy is set to zero while the selling price remains at on-peak levels.

Chemical energy conversion provides an avenue of high energy and power density which would allow for solar and wind power plants to match demand without underproducing. Excess energy produced could be used to drive an endothermic reaction, storing energy in the form of chemical bonds. Then, when needed, the reverse reaction can be used to generate electricity. The challenge is to develop a system that achieves this forward and reverse process while minimizing lost energy; that is, maximizing the efficiency of the energy storage process. Solid oxide fuel cells (SOFCs) and solid oxide electrolytic cells (SOECs) can exploit redox reactions to generate electricity from exothermic reactions and store energy via endothermic reactions, respectively.

The conversion of CO_2 to CO is a potential chemical storage reaction made possible with this technology. Waste CO_2 from point sources can be used to generate high purity CO and co-product O_2 streams using SOFCs. CO can be stored and then reacted with oxygen when electricity is needed using SOECs. The efficiency and economics of this process, in addition to the specific process considerations, is analyzed and presented by this study to provide insight into the feasibility of this technology and application.

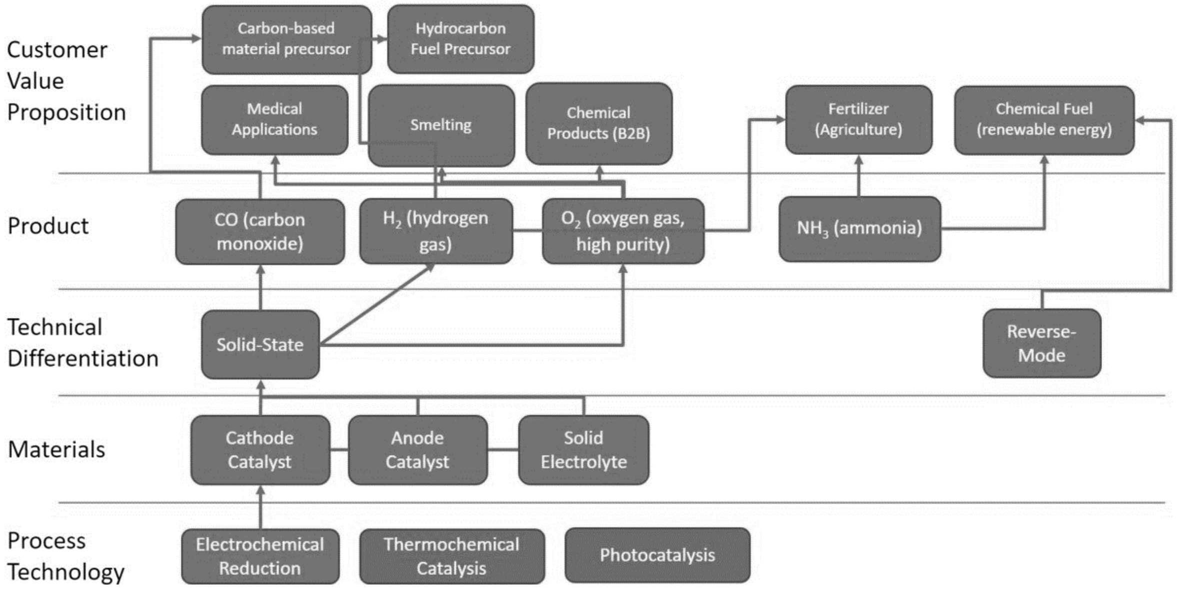
Figure 2.1.1: A schematic diagram illustrating the overall concept of the process design goal



2.3 Preliminary Process Synthesis

The process synthesis is driven by the technology focused innovation map, in Figure 2.3.1 below. Different alternatives and final products were assessed qualitatively to select the final process synthesis. As mentioned before, our focus is on green technology and electrochemical reduction was the targeted technology of interest.

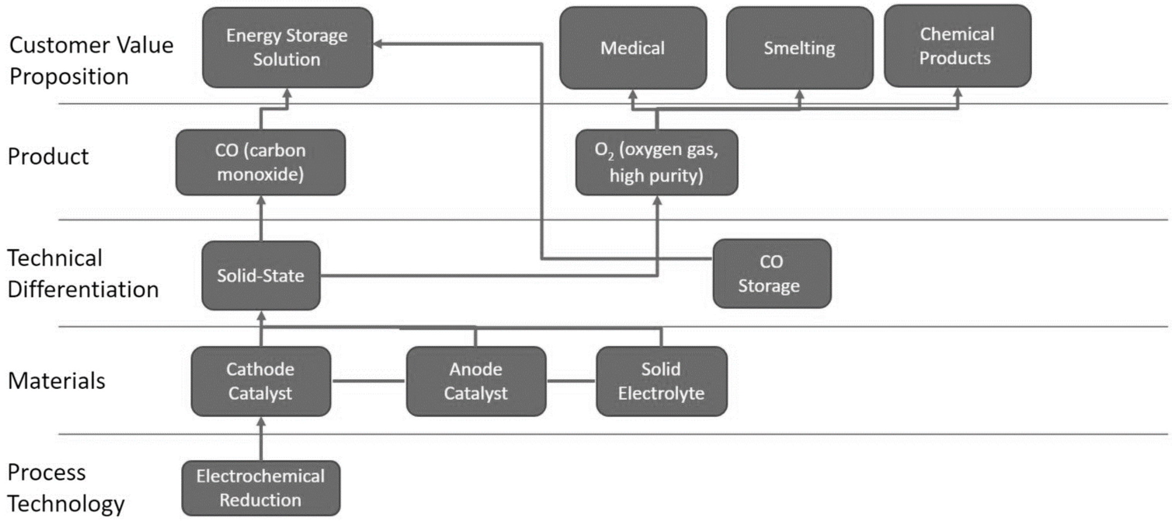
Figure 2.3.1: Preliminary innovation map



The initial final product that seemed promising was syngas production from electrochemical CO_2 reduction. Syngas has CO and H_2 as the primary components in the fuel. Globally, 6EJ of syngas is produced because of its substantial use as in intermediate, consuming 2% of the world's current energy consumption [1]. The syngas market is dominated by ammonia production. Another alternative was using the Fischer-Tropsch technique to produce clean synthetic fuel. The motivation behind creating syngas then producing clean synthetic gas using electrochemical reduction is to limit the carbon emissions from conventional methods. The ways to produce syngas is through steam reforming of natural gas and gasification of coal and biomass. Due to the current abundance of natural gas and goal, these methods are operated in large capacities and are convenient and highly profitable. Using electrochemical reduction for syngas production was unpromising in the economic environmental of current syngas production methods.

A shift to energy storage solution was made and the final innovation map is shown in Figure 2.3.2 below. The main components that we considered in the preliminary process synthesis are the modeling of the fuel cells, acquiring CO_2 as a raw material, and CO storage methods.

Figure 2.3.2: Final innovation map



SOEC and SOFC models were a combination of thermodynamic calculations and searching for industrialized models on the market, more information can be found in section 2.7: Assembly of Database. There were three main sources of CO_2 emissions that were considered: coal, natural gas or ethanol power plants. Ethanol power plant was the primary choice due to the high amounts and relatively pure CO_2 production. CO storage became the focus of our design. CO storage could be done in two ways: high pressure storage or low-pressure storage. These designs have impacts on plant size, equipment units and costing and safety measures. The main process design and flow sheets will present the analyses of the two cases.

2.4 Market and Competitive Analysis

With intensifying global efforts to address the climate crisis, increasing energy storage capacity to support build out of renewable power generation has been identified as one of the key strategies in reducing overall carbon dioxide emissions. According to Michigan University’s Center for Sustainable Systems, the United States currently has just over 31 GW of storage capacity installed, compared to 1098 GW of total power generation capacity, and less than 3% of power delivered within the US is cycled through an energy storage facility before use [2]. From these statistics, as well as multiple state governments issuing mandates to boost their renewable energy generation in the wake of the federal government pulling out of the Paris Climate Accords commitment, it is clear that demand for additional electricity storage capacity exists. Pumped hydroelectric storage dominates the sector globally, accounting for over 90% of storage capacity. However, expanding pumped hydroelectric is difficult because of extensive zoning requirements and environmental impact studies that must be completed before construction can begin; additionally, the geographical inflexibility of needing large amounts of water and natural elevation mean that it is not a solution that is readily scalable or widely deployable. Advanced lithium-ion batteries are gaining popularity across the world, especially because of their easy integration into behind-the-meter distributed generation systems, like residential solar installations. Even with costs projected to come down in the future, their dependence on rare metal components means that there is room for additional utility scale storage solutions. Other options include flywheels, compressed air storage and solar thermal storage. For more details about these technologies and their applications, please refer to Appendix A.

Fuel cells are a very attractive option for this space; they do not require expensive, precious metals for construction, can operate on extremely abundant fuel sources like carbon dioxide, and are not subject to the same geographical limitations as pumped hydroelectric storage. The modularity of the fuel cells also makes the solution naturally scalable for use in a wide range of plant sizes.

2.5 Customer Requirements

Energy storage can help address the intermittency of variable renewables like solar and wind. The US generated 4 billion MWh in 2017 and there were only 431 MWh of electrical storage available [3]. Our CO_2 Reduction energy storage solution utilizes electrochemical technologies, SOEC and SOFC. The energy storage mode takes the CO_2 emissions from an ethanol power plant and uses SOEC technology to reduce it to CO, then stored as fuel. In the energy production, stored CO is turned back into electricity using SOFC technology. While reversible fuel cell technologies exist (i.e. where the same cell can be used for the forward and reverse reaction), in this design we consider a plant with separate cells for forward and reverse-mode production due to the possibility of utilizing active materials and cell designs optimized for each of the reactions involved.

A common large-scale energy storage solution is pumped-hydro storage, which utilizes the gravitational force to generate electricity. Pumped hydro has large storage capacity and can be up to 85% efficient [2]. However, these systems are highly dependent of geographical location: natural rise in elevation and large amount of area. Pumped hydro is typically not readily available in the Midwest due to the flat geographical features.

CO_2 Feed Stream

The specification of our plant requires a steady input of carbon dioxide while in operation. The design is based on 60% of carbon dioxide emissions from an average size ethanol power plant in the United states, which equates to 410,100 lb CO_2/day. The CO_2 is transmitted by pipes will be stored at 25℃ and 1atm, readily as an input.

Oxygen Revenue Stream

High purity oxygen is a revenue stream from the energy storage mode. Due to the nature of the separated components in the SOEC, namely cathode, anode, and electrolyte, pure oxygen is obtained through an oxidation reaction on the anode side. With our plant process capacity, 149,100 lb of 99.9% pure oxygen is produced per day. The oxygen is then compressed and stored at 50℃ and 136 atm. The high purity oxygen from the plant can be sold at $90 per ton [4].

2.6 Competitive Patent Analysis

Electrochemical technologies, SOEC and SOFC, are primarily used in our design. Both technologies have been industrialized at different capacities. There are two major companies, Haldor Topsøe and Bloom Energy, that have the technologies commercialize and researched.

(i) Haldor Topsøe

Haldor Topsøe is a Danish high-performance catalysis company founded in 1940 [5]. The company's technology focuses within chemical processing, hydroprocessing and emissions management. The technology of interest for our design is Haldor Topsøe's carbon monoxide generator – eCOs™ [5]. The Solid Oxide Electrolytic Cell (SOEC) is the core to the eCOs™ units. The eCOs™ technology has produces levels of CO purity, around 99.5-99.9% vol pure, with minimal CO_2 contaminants and operates at 700-850℃ [6]. The total energy consumption on an eCOs™ unit is 6-8 kWh per Nm^3 CO produced and the design is operated on food/beverage grade CO_2 [1]. The brochure for the eCOs™ can be viewed in the appendix.

The first industrialized plant has been in operation in LaPorte, Texas since January 2016 with a plant capacity of $12Nm^3/hr$. Haldor Topsøe expected a 10 time increase in plant capacity by the end of 2017. The technology focuses on onsite and flexible production of CO based on customer specifications and demands. This eliminates the need for tube trailer/cylinder supply, which can be expensive due to the safety measures for transporting carbon monoxide. The current plant capacity for the eCOs™ is significantly lower than the plant capacity that our design would require to process 60% of the CO_2 emissions from an average ethanol plant.

(i) Bloom Energy

Bloom Energy, founded in 2001, is a green energy company that manufactures and markets solid oxide fuel cells. The main product from the company is the Bloom Energy Servers, which are energy generation platforms that utilizes proprietary solid oxide fuel cell technology. The system offers three designs at three different power outputs, 200kW, 250kW and 300kW [7]. The fuel cells utilize natural gas or biogas as input and produces near zero criteria pollutes. The efficiency of the system is reported as 53-65%. The system uses a stack configuration for fuel cells and is operated continuously. The fact sheet of the Bloom Energy Servers can be viewed in the appendix.

The company has customers from 500 sites globally. Aside from Bloom Energy Servers, they also provide other advanced services like integrated energy storage where SOFCs and lithium ion batteries are used in combination, and microgrid management which protects businesses from power outages. The company stretches further from providing traditional fuel cell power generation to a more marketable and holistic energy solution in the 21st century.

2.7 Assembly of Database

(i) Fuel Cell Technology

Solid Oxide Electrolytic Cell (SOEC) is the reverse fuel cell mode which converts electrical energy to chemical energy through an endothermic reaction. In the energy storage mode, excess electricity is used to electrolyze CO_2 to from CO, which the acts as fuel that is stored and used in the latter energy production mode. The excess electricity comes from solar and/or wind power plants during off-peak hours or for curtailment purposes. In SOEC, the electrolyte is a solid ceramic material and the electrodes are commonly composites of metallic nickel (Ni) and yttria-stabilized zirconia (YSZ) [1]. The electrochemical reactions on the electrodes in the SOEC can be expressed as:

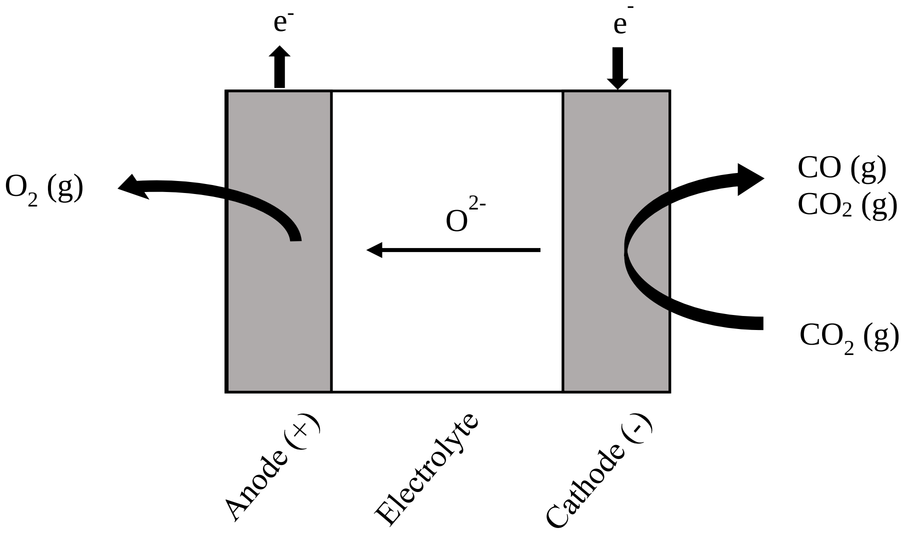
$$Cathode: \ CO_2 + 2e^- \rightarrow CO + O^{2-}$$

$$Anode: O^{2-} \rightarrow 0.5O_2 + 2e^-$$

$$Overall: CO_2 \rightarrow CO + 0.5O_2$$

On the cathode, carbon dioxide is reduced to carbon monoxide, where the electrons for the reaction are provided from external power source. On the anode, oxide ions are oxidized into molecular oxygen. Schematic diagram for SOEC is provided in Figure 2.7.1.

Figure 2.7.1: Schematic diagram for SOEC



A review paper by Küngas *et al* provides an overview of existing electrolysis technology for CO_2 reduction for CO production [8]. The system that we chose to model the SOEC from is presented in Ebbesen *et al* [9]. The cell has a strontium-doped lanthanum manganite (LSM) composite anode, nickel and yttria-stabilized zirconia composite cathode and a yttria-stabilized zirconia electrolyte. The performance of the SOEC system is presented in Table 2.7.1. The energetic efficiency (EE) represents the efficiency of the applied electric potential into the desired product, carbon monoxide. The parameter combines the effects of non-ideal selectivity and polarization losses. The electric power consumption (EPC) refers to the amount of electric energy required to produce 1 Nm^3 of CO.

Table 2.7.1: SOEC Model from Ebbesen *et al.*

Cell Composition	**LSM-YSZ|YSZ|Ni-YSZ**
EE	92%
EPC (kWh/Nm^3)	2.4

Solid Oxide Fuel Cell (SOFC) is a type of fuel cell that uses a solid ceramic electrolyte. It converts chemical energy of a fuel gas into electrical energy in an exothermic reaction. Unlike batteries, fuel cells do not run down or require recharging, which guarantees continuous power production as long as fuel and oxidants are supplied. Additionally, fuel cells are environmentally clean and have promising applications in commercial electricity generation. The electrochemical reactions on the electrodes in the SOFC can be expressed as:

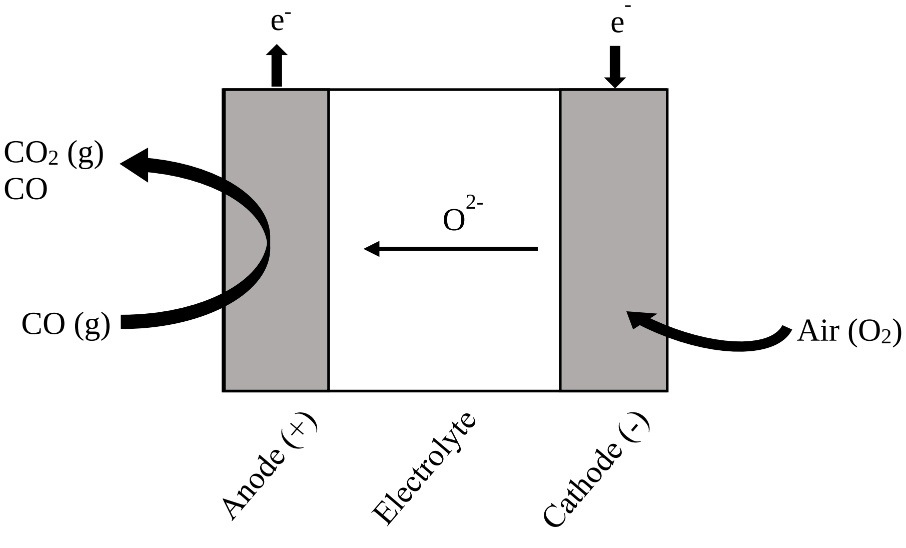
$$Cathode: 0.5O_2 + 2e^- \rightarrow O^{2-}$$

$$Anode: CO + O^{2-} \rightarrow CO_2 + 2e^-$$

$$Overall: CO + 0.5\ O_2 \rightarrow CO_2$$

On the anode, carbon monoxide is oxidized to carbon dioxide, where the electrons produce a current. On the cathode, molecular oxygen from air is reduced to oxide ions. Schematic diagram for SOFC is provided in Figure 2.7.2.

Figure 2.7.1: Schematic diagram for SOFC



Similar to the SOEC, the cell composition of the SOFC will also be a composite of Ni/YSZ and LSM/YSZ. The SOFC operations in this process is modeled by the thermodynamics of a fuel cell. The maximum amount of work done in the system is expressed by the Gibbs free energy of the system [10][11]. Therefore, the maximum electric output in a “perfect” fuel cell is the change in Gibbs free energy in the system. The Gibbs free energy is dependent on temperature and pressure. Since the SOFC will be operated at high temperatures, the Gibbs free energy of the chemicals in the reaction is listed in Table 2.7.2 below. Using Hess’s Law, the change in Gibbs free energy for the entire reaction is calculated to be –206.7 kJ/mol, which is comparable to the values in Kitazaki et al. [4]. The efficiency of typical SOFC cells can go up to ~60%, which is analogous to the industrial fuel cell models in Bloom Energy [12][13]. The power production from the SOFC could be obtained from the thermodynamics of a fuel cell, using the parameters above.

(ii) Primary Chemicals

The primary components of this process are listed in Table 2.7.2. This includes the inputs and outputs to the SOEC and SOFC systems and their relevant properties. For the SDS of all the chemicals, refer to Appendix C.

Table 2.7.2: Thermophysical Property and Cost for Primary Chemicals

Chemical	Molecular Weight (g/mol)	Density (kg/m^3)	ΔG°(kJ/mol) at 600℃	Cost ($ per ton)	Comments
Carbon Dioxide (CO_2)	44.01	1.98	-395.5	N/A	Input to SOEC, output to SOFC
Carbon Monoxide (CO)	28.01	1.25	-188.9	N/A	Output to SOEC, input to SOFC
Oxygen	32	1.43	0	90	Output to SOEC
Water	18.01	997	N/A	~0	Cooling water
Air	28.96	1.23	N/A	0	Input to SOFC

(iii) Toxicity

Carbon monoxide (CO) is a colorless, odorless and toxic gas. Due to its odorless and colorless nature, special precautions are required when hazardous concentrations are possible. CO is the source of fuel in our process. It is stored at 1 atm and 50℃ for the low-pressure design and stored at 136 atm and 50℃ for the high-pressure design. The lower flammability limit is 12.5% and upper flammability limit is 74.5%. For indoor storage of CO, the safety limit is 5ppm concentration in air. For this value, the plant should be nominally more than 2 km away from residential areas. The Midwest is a suitable region for the design due to the sparsely populated areas. For safety and handling procedures, refer to SDS on CO in Appendix C.

(iv) Cost of Chemicals

The raw material for this process is CO_2. However, since the CO_2 is sourced from the emissions of ethanol plants, there is no cost associated with acquiring the CO_2. In favorable sustainable initiatives or legislations, the CO_2 may even be a source of revenue for the plant, where ethanol power plants would pay to remove a portion of their CO_2 emission. The primary byproduct of the process is a pure O_2 stream produced form the CO_2 reduction reaction in the SOEC. The O_2 stream is 99.9% pure and can be sold as a commodity. With our plant capacity, 248487 lb of O_2 is produced per day. Since O_2 is a competitive commodity, the pricing will differ based on regions and time. An estimate of the pricing of O_2 is gathered from Intratec and scaled up by the producer price index. The pricing of O_2 in 2020 is estimated to be 14.42 cents/Nm^3, which is equivalent to $90/ton ($0.045/lb) [14].

(v) Ethanol Plant Emissions

The primary raw material, CO_2, is sourced from ethanol plant emissions. Emission data from ethanol plants in the US is gathered from the Greenhouse Gas Reporting Program (GHGRP) from the United States Environmental Protection Agency (EPA) [15]. The average CO_2 emission from an ethanol plant is calculated to be 683495 lb/day. To ensure a continuous supply of CO_2, 60% of the CO_2 emissions from an ethanol power plant is taken as the input to the process. Thus, the plant receives 410097 lb of CO_2 per day.

(vi) Process parameters

Table 2.7.3: Process utilities and parameters

Cooling Water	
Inlet Temperature	80°F
Outlet Temperature	125°F
Compressor Efficiency	
Isotropic Efficiency	72%
Mechanical Efficiency	80%

3. Overall Process Considerations

3.1 Material Balances

Table 3.1.1 shows the overall material balance for the process, which remains the same in all the designs. The basis of this material balance is the average emission of carbon dioxide from ethanol production plants in the target region (American Midwest). The design utilizes 60% of the waste carbon dioxide produced per day to account for the batch nature of fermentation processes.

Table 3.1.1: Overall Material Balance for total process

	lb/day	**lbmol/day**
Inputs		
CO2	410,097	9,318
Products		
CO	261,005	9,318
O2	149,092	4,659

3.2 Oxygen Profitability Analysis

Oxygen production tradeoff derivation

Due to the use of an electrolyte separator intrinsic to the SOFC and SOEC technology, high-purity oxygen gas is produced along with the carbon monoxide gas. Two options are presented for this product.

One option is to use the high-temperature gas to preheat the feed carbon dioxide stream and then cool and compress into storage tanks to be sold. High-purity oxygen is used in many industries, including industrial processes and medical applications. In order to sell this oxygen, the stream must be cooled and compressed for storage and transportation. This incurs an energy cost in the storage mode without increasing the extensive amount of electricity produced in the reverse mode. A market price of $90 / ton, obtained from Intratec Chemical commodity reports (14.42 cents / SCM) [1], is used for this analysis.

Another option is to use the high-temperature oxygen gas to preheat the feed carbon dioxide stream and subsequently vent the oxygen to the atmosphere. By venting the oxygen instead of compressing and storing it, less electricity needs to be inputted for storage, increasing the efficiency of the process relative to the other option.

An analysis on a per-kWhr basis is taken to determine which of these options is more profitable. First, the value of the extra efficiency gained by venting the oxygen stream as waste is considered. Here we refer to this strategy as “option 1.” The strategy of storing oxygen at 2000 psig to sell will be referred to as “option 2.”

$$\Delta\eta = \eta_1 - \eta_2$$

Where η_1 is the efficiency of the process with venting oxygen and η_2 is the efficiency of the process when oxygen is compressed to 2000 psig for storage. The opportunity cost of option 1 in dollars per kWh is therefore

$$r_1 = \Delta P * \Delta\eta$$

Where ΔP is the revenue per kWh of the electricity storage / distribution cycle and r_1 is the revenue per kWh gained by the energy savings of option 1 over option 2. Then, the revenue is multiplied by the capacity of the designed plant, C in kWh/cycle, in kWh, to determine the extensive revenue from the increased efficiency R_1, in USD/cycle.

$$R_1 = r_1 * C$$

Next, we turn to the added revenue of selling the high-purity oxygen stream. The amount of oxygen produced per storage-discharge cycle is calculated and reported in the material balance of the process. The amount, in tons/cycle, is denoted by M_{O2}. The price of oxygen gas, in USD / ton, is denoted by P_{O2}.

$$R_2 = M_{O2} * P_{O2}$$

In option 2, R_2 represents the added revenue from selling the oxygen gas, while R_1 is the opportunity cost of the loss of energy storage efficiency. The relevant input values for this analysis are reproduced in this section. The two economic scenarios presented are both analyzed in this manner.

In the first scenario, electricity is bought from the grid at off-peak prices to be sold at on-peak prices.

In the second scenario, the electricity is assumed to be 0 cost due to curtailment, which occurs when an amount of electricity that could be produced is not due to low demand. Effectively, this electricity would have zero or negative opportunity cost.

Here we consider the effect of pressurization of oxygen gas for the high- and low-pressure cases. In both cases, the economics of buying-selling and storage of curtailed electricity are considered. The specific values of efficiency and costing are calculated and reported in sections 4 and 5.

High-Pressure Process Design: On-Peak/Off-Peak Pricing

Variable	Value
η_1	0.5089
η_2	0.4899
ΔP (USD / kWh)	0.00889
C (kWh/cycle)	226590
M_{O2} (tons/cycle)	73.8
P_{O2} (USD / ton)	90

Table 3.2.1: Inputs for grid-balancing economic analysis, where electricity is bought at off-peak pricing and sold later at on-peak pricing

Calculating the opportunity cost of this scenario using the derived equations yields

Variable	Value
R_1 (USD/cycle)	38.27
R_2 (USD/cycle)	6642
ΔR (USD/cycle)	6603.72

Clearly, in this scenario the loss in electrical efficiency is dwarfed by the revenue of the oxygen stream after compression.

High Pressure Process Design: Curtailment Pricing

Variable	Value
η_1	0.546
η_2	0.535
ΔP (USD / kWh)	0.00889
C (kWh/cycle)	226590
M_{O2} (tons/cycle)	73.8
P_{O2} (USD / ton)	90

Table 3.2.2: Inputs for overgeneration mitigation economic analysis, where it is assumed that electricity input is solely from overgeneration and has no opportunity cost of utilization.

Calculating the revenue values using the same equations:

Variable	Value
R_1 (USD/cycle)	92.30
R_2 (USD/cycle)	6642
ΔR (USD/cycle)	6549.70

Here, the opportunity cost of the electricity spent on compressing the oxygen is higher, however it still is less than the potential oxygen revenue.

In the high-pressure design case, regardless of the electricity pricing, selling the purified oxygen as a byproduct is a more cost-effective strategy.

Low-Pressure Process Design: On-Peak/Off-Peak Pricing

Variable	Value
η_1	0.556
η_2	0.545
ΔP (USD / kWh)	0.00889
C (kWh/cycle)	226590
M_{O2} (tons/cycle)	73.8
P_{O2} (USD / ton)	90

Table 3.2.3: Inputs for grid-balancing economic analysis, where electricity is bought at off-peak pricing and sold later at on-peak pricing

Calculating the revenue of selling oxygen and venting oxygen strategies yields:

Variable	Value
R_1 (USD/cycle)	22.16
R_2 (USD/cycle)	6642
ΔR (USD/cycle)	6619.84

Again, the value of the oxygen stream is much higher than that of the electricity input to the compressor.

Low-Pressure Process Design: Curtailment Pricing

Variable	Value
η_1	0.556
η_2	0.545
ΔP (USD / kWh)	0.00889
C (kWh/cycle)	226590
M_{O2} (tons/cycle)	73.8
P_{O2} (USD / ton)	90

Table 3.2.4: Inputs for overgeneration mitigation economic analysis, where it is assumed that electricity input is solely from overgeneration and has no opportunity cost of utilization.

Calculating the revenue of selling oxygen and venting oxygen strategies yields:

Variable	Value
R_1 (USD/cycle)	92.30
R_2 (USD/cycle)	6642
ΔR (USD/cycle)	6549.70

The change in efficiency in the low-pressure case reduces the opportunity cost of the electricity used to run the oxygen compressor while maintaining the high daily revenue of the byproduct.

Oxygen Revenue Conclusions

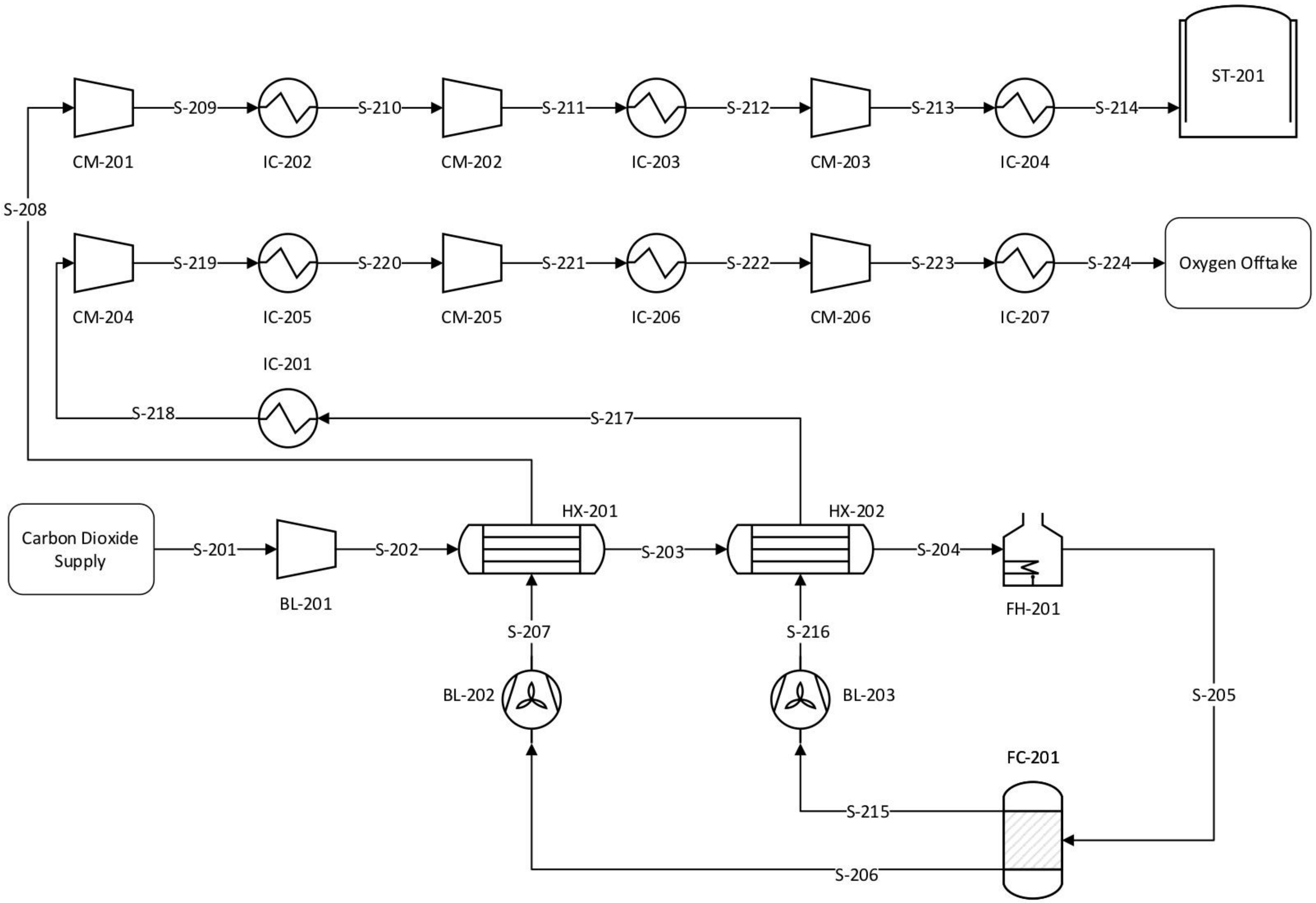
Clearly, regardless of the final design or pricing of electricity, selling oxygen as a byproduct is the correct design choice. This process design is therefore used for all economic and profitability analyses in this report.

4. Case 1: High-Pressure Storage Process Design

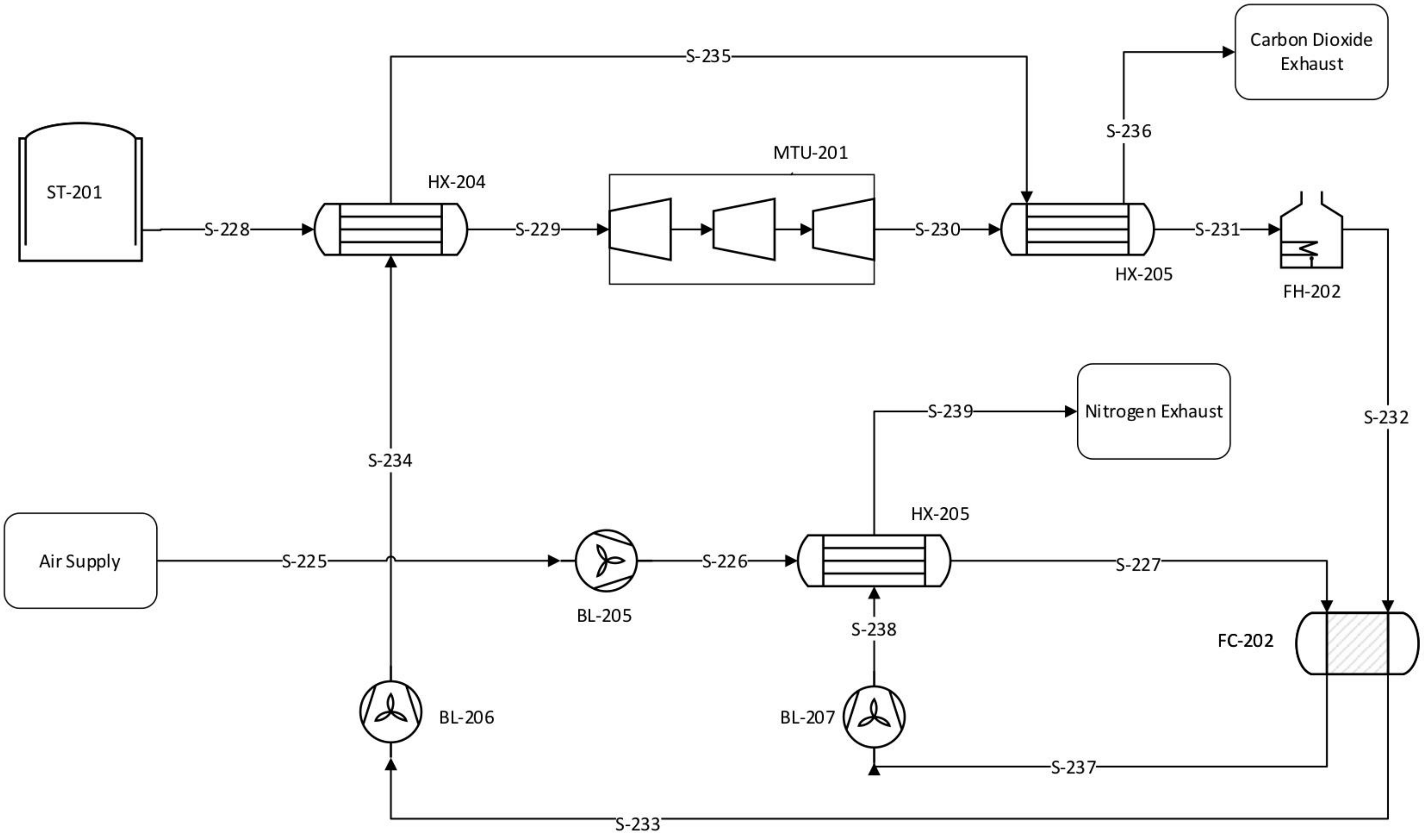
4.1 Process Flow Diagrams

Process flow diagrams are shown in this section, along with ASPEN stream reports listing relevant thermodynamic data.

High Pressure Energy Storage Process Flow Diagram



High Pressure Energy Production Process Flow Diagram



	Units	S-201	S-202	S-203	S-204	S-205
From			BL-201	HX-201	HX-202	FH-201
To		BL-201	HX-201	HX-202	FH-201	FC-201
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
Carbon Dioxide	lbmol/hr	388.2	388.2	388.2	388.2	388.2
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Water	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flow						
Carbon Dioxide	lb/hr	17083.7	17083.7	17083.7	17083.7	17083.7
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lb/hr	0.0	0.0	0.0	0.0	0.0
Water	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	388.2	388.2	388.2	388.2	388.2
Mass Flows	lb/hr	17083.7	17083.7	17083.7	17083.7	17083.7
Volume Flow	cuft/hr	151361.3	91919.1	253748.0	356052.3	496679.0
Temperature	F	77.0	198.3	1044.2	1223.4	1292.0
Pressure	psia	14.7	29.7	24.7	19.7	14.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-169196.3	-168077.9	-158591.4	-156340.1	-155462.6
Mass Enthalpy	Btu/lb	-3844.5	-3819.1	-3603.5	-3552.4	-3532.5
Enthalpy Flow	Btu/hr	-65678436.9	-65244315.2	-61561840.4	-60687915.9	-60347294.6
Molar Entropy	Btu/lbmol-R	0.7	1.2	10.6	12.5	13.6
Mass Entropy	Btu/lb-R	0.0	0.0	0.2	0.3	0.3
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.1	0.2	0.1	0.0	0.0

	Units	S-206	S-207	S-208	S-209	S-210
From		FC-201	BL-202	HX-201	CM-201	IC-202
To		BL-202	HX-201	CM-201	IC-202	CM-202
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
Carbon Dioxide	lbmol/hr	3.9	3.9	3.9	3.9	3.9
Carbon Monoxide	lbmol/hr	384.3	384.3	384.3	384.3	384.3
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Water	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flow						
Carbon Dioxide	lb/hr	170.8	170.8	170.8	170.8	170.8
Carbon Monoxide	lb/hr	10764.3	10764.3	10764.3	10764.3	10764.3
Oxygen	lb/hr	0.0	0.0	0.0	0.0	0.0
Water	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	388.2	388.2	388.2	388.2	388.2
Mass Flows	lb/hr	10935.2	10935.2	10935.2	10935.1	10935.1
Volume Flow	cuft/hr	496697.3	409414.9	191685.9	67066.4	34370.9
Temperature	F	1292.0	1475.3	216.3	754.4	122.4
Pressure	psia	14.7	19.7	14.7	75.6	70.6
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-39744.5	-38276.3	-47762.8	-43882.3	-48430.7
Mass Enthalpy	Btu/lb	-1410.9	-1358.7	-1695.5	-1557.7	-1719.2
Enthalpy Flow	Btu/hr	-15427985.8	-14858044.4	-18540519.2	-17034170.6	-18799761.9
Molar Entropy	Btu/lbmol-R	29.9	30.1	22.8	23.8	18.7
Mass Entropy	Btu/lb-R	1.1	1.1	0.8	0.8	0.7
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.0	0.0	0.1	0.2	0.3

	Units	S-211	S-212	S-213	S-214	S-215
From		CM-202	IC-203	CM-203	IC-204	FC-201
To		IC-203	CM-203	IC-204		BL-203
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
Carbon Dioxide	lbmol/hr	3.9	3.9	3.9	3.9	0.0
Carbon Monoxide	lbmol/hr	384.3	384.3	384.3	384.3	0.0
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0	192.1
Water	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flow						
Carbon Dioxide	lb/hr	170.8	170.8	170.8	170.8	0.0
Carbon Monoxide	lb/hr	10764.3	10764.3	10764.3	10764.3	0.0
Oxygen	lb/hr	0.0	0.0	0.0	0.0	6148.5
Water	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	388.2	388.2	388.2	388.2	192.1
Mass Flows	lb/hr	10935.1	10935.1	10935.1	10935.1	6148.5
Volume Flow	cuft/hr	11689.3	6347.3	2356.6	1271.2	245846.0
Temperature	F	617.0	122.4	597.3	121.2	1292.0
Pressure	psia	388.8	383.8	2000.0	2000.0	14.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-44887.3	-48480.2	-44979.5	-48687.0	9356.8
Mass Enthalpy	Btu/lb	-1593.4	-1721.0	-1596.7	-1728.3	292.4
Enthalpy Flow	Btu/hr	-17424305.3	-18818974.1	-17460098.8	-18899278.3	1797887.0
Molar Entropy	Btu/lbmol-R	19.6	15.2	16.2	11.5	8.9
Mass Entropy	Btu/lb-R	0.7	0.5	0.6	0.4	0.3
Molar Density	lbmol/cuft	0.0	0.1	0.2	0.3	0.0
Mass Density	lb/cuft	0.9	1.7	4.6	8.6	0.0

	Units	S-216	S-217	S-218	S-219	S-220
From		BL-203	HX-202	IC-201	CM-204	IC-205
To		HX-202	IC-201	CM-204	IC-205	CM-205
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
Carbon Dioxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lbmol/hr	192.1	192.1	192.1	192.1	192.1
Water	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flow						
Carbon Dioxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lb/hr	6148.5	6148.5	6148.5	6148.5	6148.5
Water	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	192.1	192.1	192.1	192.1	192.1
Mass Flows	lb/hr	6148.5	6148.5	6148.5	6148.5	6148.5
Volume Flow	cuft/hr	172888.5	159516.1	81588.3	28318.1	16961.6
Temperature	F	1610.1	1063.4	122.0	577.7	122.4
Pressure	psia	24.7	19.7	14.7	75.7	70.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	12026.9	7478.7	313.1	3644.2	304.6
Mass Enthalpy	Btu/lb	375.9	233.7	9.8	113.9	9.5
Enthalpy Flow	Btu/hr	2310954.8	1437030.3	60159.4	700232.8	58536.7
Molar Entropy	Btu/lbmol-R	9.3	7.2	0.6	1.5	-2.6
Mass Entropy	Btu/lb-R	0.3	0.2	0.0	0.0	-0.1
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.0	0.0	0.1	0.2	0.4

	Units	S-221	S-222	S-223	S-224
From		CM-205	IC-206	CM-206	IC-207
To		IC-206	CM-206	IC-207	
MIXED Substream					
Phase		Vapor	Vapor	Vapor	Vapor
Component Mole Flow					
Carbon Dioxide	lbmol/hr	0.0	0.0	0.0	0.0
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0
Oxygen	lbmol/hr	192.1	192.1	192.1	192.1
Water	lbmol/hr	0.0	0.0	0.0	0.0
Component Mass Flow					
Carbon Dioxide	lb/hr	0.0	0.0	0.0	0.0
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0
Oxygen	lb/hr	6148.5	6148.5	6148.5	6148.5
Water	lb/hr	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	192.1	192.1	192.1	192.1
Mass Flows	lb/hr	6148.5	6148.5	6148.5	6148.5
Volume Flow	cuft/hr	5664.5	3095.3	1120.0	590.0
Temperature	F	601.6	121.9	583.5	121.5
Pressure	psia	389.5	384.5	2005.0	2000.0
Molar Vapor Fraction		1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	3820.7	237.9	3655.4	-50.9
Mass Enthalpy	Btu/lb	119.4	7.4	114.2	-1.6
Enthalpy Flow	Btu/hr	734145.9	45713.6	702388.2	-9783.1
Molar Entropy	Btu/lbmol-R	-1.6	-6.0	-5.1	-9.8
Mass Entropy	Btu/lb-R	0.0	-0.2	-0.2	-0.3
Molar Density	lbmol/cuft	0.0	0.1	0.2	0.3
Mass Density	lb/cuft	1.1	2.0	5.5	10.4

	Units	S-225	S-226	S-227	S-228	S-229
From			BL-204	HX-203		HX-204
To		BL-204	HX-203	FC-202	HX-204	TU-201
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	384.3	384.3
Carbon Dioxide	lbmol/hr	0.0	0.0	0.0	3.9	3.9
Oxygen	lbmol/hr	192.9	192.9	192.9	0.0	0.0
Nitrogen	lbmol/hr	725.7	725.7	725.7	0.0	0.0
Component Mass Flow						
Carbon Monoxide	lb/hr	0.0	0.0	0.0	10764.3	10764.3
Carbon Dioxide	lb/hr	0.0	0.0	0.0	170.8	170.8
Oxygen	lb/hr	6172.7	6172.7	6172.7	0.0	0.0
Nitrogen	lb/hr	20329.1	20329.1	20329.1	0.0	0.0
Mole Flows	lbmol/hr	918.6	918.6	918.6	388.2	388.2
Mass Flows	lb/hr	26501.8	26501.8	26501.8	10935.2	10935.2
Volume Flow	cuft/hr	359937.7	301085.2	1175368.5	1273.2	4205.5
Temperature	F	77.0	141.8	1292.0	122.0	1473.8
Pressure	psia	14.7	19.7	14.7	2000.0	1995.0
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-2.9	449.2	8957.6	-48680.4	-38107.1
Mass Enthalpy	Btu/lb	-0.1	15.6	310.5	-1728.1	-1352.7
Enthalpy Flow	Btu/hr	-2647.7	412604.5	8228393.9	-18896688.5	-14792371.2
Molar Entropy	Btu/lbmol-R	1.0	1.2	9.6	11.5	20.9
Mass Entropy	Btu/lb-R	0.0	0.0	0.3	0.4	0.7
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.3	0.1
Mass Density	lb/cuft	0.1	0.1	0.0	8.6	2.6

	Units	S-230	S-231	S-232	S-233	S-234
From		TU-201	HX-205	FH-202	FC-202	BL-205
To		HX-205	FH-202	FC-202	BL-205	HX-204
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
Carbon Monoxide	lbmol/hr	384.3	384.3	384.3	3.8	3.8
Carbon Dioxide	lbmol/hr	3.9	3.9	3.9	384.3	384.3
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Nitrogen	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flow						
Carbon Monoxide	lb/hr	10764.3	10764.3	10764.3	107.6	107.6
Carbon Dioxide	lb/hr	170.8	170.8	170.8	16914.5	16914.5
Oxygen	lb/hr	0.0	0.0	0.0	0.0	0.0
Nitrogen	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	388.2	388.2	388.2	388.2	388.2
Mass Flows	lb/hr	10935.2	10935.2	10935.2	17022.2	17022.2
Volume Flow	cuft/hr	150122.7	227442.0	496697.3	496679.6	329580.2
Temperature	F	429.7	615.2	1292.0	1292.0	1493.2
Pressure	psia	24.7	19.7	14.7	14.7	24.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-46252.4	-44911.8	-39744.5	-154305.4	-151693.5
Mass Enthalpy	Btu/lb	-1641.9	-1594.3	-1410.9	-3518.8	-3459.3
Enthalpy Flow	Btu/hr	-17954203.3	-17433827.5	-15427985.8	-59898098.1	-58884239.4
Molar Entropy	Btu/lbmol-R	23.8	25.6	29.9	13.9	14.2
Mass Entropy	Btu/lb-R	0.8	0.9	1.1	0.3	0.3
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.1	0.0	0.0	0.0	0.1

	Units	S-235	S-236	S-237	S-238	S-239
From		HX-204	HX-205	FC-202	BL-206	HX-203
To		HX-205		BL-206	HX-203	
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flow						
Carbon Monoxide	lbmol/hr	3.8	3.8	0.0	0.0	0.0
Carbon Dioxide	lbmol/hr	384.3	384.3	0.0	0.0	0.0
Oxygen	lbmol/hr	0.0	0.0	2.7	2.7	2.7
Nitrogen	lbmol/hr	0.0	0.0	725.7	725.7	725.7
Component Mass Flow						
Carbon Monoxide	lb/hr	107.6	107.6	0.0	0.0	0.0
Carbon Dioxide	lb/hr	16914.5	16914.5	0.0	0.0	0.0
Oxygen	lb/hr	0.0	0.0	85.7	85.7	85.7
Nitrogen	lb/hr	0.0	0.0	20329.1	20329.1	20329.1
Mole Flows	lbmol/hr	388.2	388.2	728.4	728.4	728.4
Mass Flows	lb/hr	17022.2	17022.2	20414.7	20414.7	20414.7
Volume Flow	cuft/hr	231431.9	275821.3	931979.2	680716.0	259273.7
Temperature	F	634.6	513.7	1292.0	1603.0	160.3
Pressure	psia	19.7	14.7	14.7	23.7	18.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-162266.8	-163607.4	8853.4	11308.1	577.5
Mass Enthalpy	Btu/lb	-3700.4	-3730.9	315.9	403.5	20.6
Enthalpy Flow	Btu/hr	-62988556.7	-63508932.4	6448482.0	8236398.4	420609.0
Molar Entropy	Btu/lbmol-R	7.6	6.9	8.6	8.9	0.6
Mass Entropy	Btu/lb-R	0.2	0.2	0.3	0.3	0.0
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.1	0.1	0.0	0.0	0.1

4.2 Energy Balance and Utilities

Table 4.2.1: Utilities Summary for High Pressure Storage Mode

Equipment	Unit No.	Flow Rate (lb/hr)	Annual Flowrate (lb)	Price ($/lb)	Annual Cost ($)
Intercooler 1	IC-201	26,308.47	104,000,000	1.20E-05	$1,300
Intercooler 2	IC-202	34,029.43	134,000,000	1.20E-05	$1,600
Intercooler 3	IC-203	26,880.39	106,000,000	1.20E-05	$1,300
Intercooler 4	IC-204	27,738.28	110,000,000	1.20E-05	$1,300
Intercooler 5	IC-205	12,367.84	48,900,000	1.20E-05	$590
Intercooler 6	IC-206	13,268.62	52,500,000	1.20E-05	$630
Intercooler 7	IC-207	13,726.16	54,400,000	1.20E-05	$650
Total Cooling Water			611,000,000		$7,400

Equipment	Unit No.	Power (kW)	Annual Consumption (kWh)	Price ($/kWh)	Annual Cost ($)
Blower 1	BL-201	159.04	630,000	$0.03	$17,700
Blower 2	BL-202	208.79	827,000	$0.03	$23,300
Blower 3	BL-203	187.96	744,000	$0.03	$20,900
Compressor 1	CM-201	551.83	2,190,000	$0.03	$61,500
Compressor 2	CM-202	503.88	1,990,000	$0.03	$56,100
Compressor 3	CM-203	497.81	1,970,000	$0.03	$55,800
Compressor 4	CM-204	234.48	929,000	$0.03	$26,100
Compressor 5	CM-205	247.50	980,000	$0.03	$27,600
Compressor 6	CM-206	240.57	953,000	$0.03	$26,800
Pump 1	PU-201	0.84	3,300	$0.03	$100
Electrolytic Cell 1	FC-201	32,010.33	127,000,000	$0.03	$3,580,000.00
Total Electricity			138,000,000		$3,880,000.00

Equipment	**Unit No.**	**Heat Duty (Btu/hr)**	**Annual Consumption (lb)**	**Price ($/lb)**	**Annual Cost**
Fired Heater 1	FH-201	340,621.29	182,000.00	$0.09	$16,400

The bulk of the electricity consumed in the storage process (and the system overall) is related to the electrolytic cell, requiring 32,000 kW of power in order to operate. Pressure changers for the gas streams constitute almost the entirety of the rest of the demand, with the water pump requiring a negligible amount of power. The electricity is supplied at $0.028/kWh; for more details about the price determination, please refer to the Economic Analysis in section 6. The cooling water needed for the process is used for the intercoolers in the multistage compressors. The water enters at 80 F and is returned at 125 F. The price for the cooling water is $0.10 per thousand gallons, as defined in *Product and Process Design Principles*. The fired heater uses wood pellets as fuel, at a price of $180/ton and a heating value of 7429 Btu/hr. The total annual electricity cost is $3,880,000, the total annual cooling water cost is $7,400 and the total annual fired heating cost is $16,400.

Table 4.2.2: Utilities Summary for High Pressure Production Mode

Equipment	Unit No.	Power (kW)	Annual Consumption (kWh)	Price ($/kWh)	Annual Cost ($)
Blower 4	BL-204	152.12	602,000	$0.03	$17,000
Blower 5	BL-205	371.42	1,470,000	$0.03	$41,400
Blower 6	BL-206	654.98	2,590,000	$0.03	$73,000
M-Stage Turbine 1	MTU-201	(741.31)	(2,940,000)	$0.03	$(82,600)
Total Electricity			1,730,000		$48,800
Equipment	**Unit No.**	**Heat Duty (Btu/hr)**	**Annual Consumption (lb)**	**Price ($/lb)**	**Annual Cost**
Fired Heater 2	FH-202	2,005,841.74	1,070,000	$0.09	$96,300

The utilities needed for the production mode are electricity to power the air movers and fuel for the fired heater. The electricity demand is heavily offset by the power recovery in the multistage turbine, greatly reducing the net energy requirement for the process and improving the overall efficiency. Relatively, the price of heating is very high. This is due to the need for substantial reheating of the carbon monoxide stream after exiting the multistage turbine before it can be used in the fuel cell. The total annual electricity cost is $48,800 and the total annual fired heating cost is $96,300.

4.3 Process Description

High Pressure Storage

This section discusses the energy storage mode of the high-pressure carbon monoxide storage case, which operates for 12 hours a day during off-peak hours. 17083.7 lb/hr of pure carbon dioxide (S-201) is passed through a blower (BL-201) to increase its pressure from 14.7 psia to 29.7 psia. This is done in order to counteract the pressure drops (estimated to be 5 psi per unit) across the process units that follow. The pressurized carbon dioxide (S-202) enters a heat exchanger (HX-201) where it is heated from 198 F to 1044 F, and then into a second heat exchanger (HX-202) where it is heated to 1223 F, losing 10 psi across the two units. From there, it is passed through a fired heater (FH-201) in order to reach the final temperature of 1292 F. The final stream (S-205) enters the solid oxide electrolytic cell (FC-201) at 1292 F and 14.7 psia. The fuel cell converts the carbon dioxide into a nearly pure carbon monoxide stream and an oxygen stream. They are physically separated by the cell's configuration so there is no need for additional separation units or processes. The two streams are recycled for use in heating the carbon dioxide stream in HX-101 and HX-102, respectively.

The carbon monoxide stream (S-206) flows at 10935.2 lb/hr, containing 99% carbon monoxide and 1% carbon dioxide. It is flowed through a blower (BL-202) to counteract the pressure losses across the following equipment. With the pressure increased to 19.7 psia and a temperature of 1475 F (S-207), the stream enters HX-201 and is cooled by the countercurrent carbon dioxide stream, exiting the heat exchanger at 216 F (S-208). That stream is then sent to the multistage compressor system.

A multistage compressor system is incorporated to bring the carbon monoxide to 2000 psia for storage. It features three compressors (CM-201, CM-202 and CM-203) and three intercoolers (IC-202, IC-203 and IC-204). This was implemented in order to maximize the efficiency of the compression, as well as to keep the stream temperature within operable bounds. The compressors have approximately equal compression ratios. Each intercooler returns the carbon monoxide stream to 122 F. The final product carbon monoxide stream (S-214) is at 122 F and 2000 psia, the conditions needed for the storage tank (ST-201).

Running in parallel, 6148.5 lb/hr of pure oxygen (S-215) is flowed through a blower (BL-203) to counteract the pressure losses across the following equipment. With the pressure increased to 24.7 psia and a temperature of 1610 F (S-216), the stream enters HX-202 and is cooled by the countercurrent carbon dioxide stream, exiting the heat exchanger at 1063 F (S-217). The oxygen is further cooled by an intercooler (IC-201) to reach a temperature of 122 F (S-218) before being sent to the multistage compressor system.

A multistage compressor system is incorporated to bring the carbon monoxide to 2000 psia for storage. It features three compressors (CM-204, CM-205 and CM-206) and three intercoolers (IC-205, IC-206 and IC-207). This was implemented in order to maximize the efficiency of the compression, as well as to keep the stream temperature within operable bounds. The compressors have approximately equal compression ratios. Each intercooler returns the carbon monoxide stream to 122 F. The final product oxygen stream (S-224) is at 122 F and 2000 psia, the conditions needed in order to sell the oxygen commercially.

Finally, a stream of cooling water at 154,319.2 lb/hr, 80 F and 14.7 psia is used for the intercoolers. It is passed through a pump (PU-201), bringing it to 19.7 psia for use in the following processes. The master stream is then passed through a splitter which provides the required amounts of cooling water to each other unit processes. The intercooler streams are unnamed and unacknowledged in the process flow diagram and stream reports for the sake of simplicity and ease of following, but flowrates can be found in the Energy Balance and Utilities section.

High Pressure Production

This section discusses the energy production mode of the high-pressure carbon monoxide storage case, which operates for 12 hours a day during on-peak hours. 10935.2 lb/hr of 99% carbon monoxide and 1% carbon dioxide at 2000 psia and 122 F (S-228) from the storage tank is flowed through a heat exchanger (HX-104) to be preheated for the multistage turbine (MTU-201), where energy is recovered from gas expansion. The preheated stream enters the multistage turbine at 1473.8 F (S-229). The multistage turbine consists of three separate turbines. This was necessary because a single stage expansion with this pressure difference would result in liquid effluent in the turbine. Additionally, this increases the efficiency of the energy recovery. The preheating ensures that the stream does not fall outside of the range of operable temperatures over the course of the expansion. For details about the individual turbines, please refer to the specification sheet. Leaving the multistage turbine system, the carbon monoxide stream is at 429.7 F and 24.7 psia (S-230) and needs to be reheated before entering the fuel cell. It is flowed through a heat exchanger (HX-205), reaching 615.2 F, then sent to a fired heater (FH-202) to reach the fuel cell operating conditions of 1292 F and 14.7 psia (S-232).

Running in parallel, a stream of air pulled from the atmosphere flows at 26501.8 lb/hr, at atmospheric conditions of 77 F and 14.7 psia (S-128). It is flowed through a blower (BL-204) to increase the pressure in order to counteract the pressure drops across the following process units. BL-204 increases the stream pressure to 19.7 psia; the air stream then passes through a heat exchanger (HX-203) to complete its heating. The stream, at operating conditions of 1292 F and 14.7 psia (S-227) then enters the fuel cell.

The fuel cell converts the carbon monoxide and the oxygen from the air stream into carbon dioxide, releasing energy in the process. The nitrogen in the air is an inert and does not react. It produces two streams: one that is predominantly carbon dioxide with a small percentage of unreacted carbon monoxide flowing at 17022.2 lb/hr (S-233), and another that is predominantly nitrogen with a small percentage of unreacted oxygen flowing at 26501.8 lb/hr (S-237), both at 1292 F and 14.7 psia.

The nitrogen recycle stream is passed through a blower (BL-206) to reach a pressure of 23.7 psia and a temperature of 1603 F (S-234), then used in HX-203 to heat the air stream before being expelled to the atmosphere.

The carbon dioxide recycle stream is passed through a blower (BL-205) to reach a pressure of 24.7 psia and a temperature of 1493 F (S-133), then used in HX-204 to preheat the carbon monoxide stream before it enters the multistage turbine. Exiting HX-204, the carbon dioxide recycle stream is lowered to 634.6 F (S-235). It is used again to reheat the carbon monoxide stream in HX-205, before being expelled to the atmosphere.

4.4 Unit Descriptions

Table 4.4.1: High Pressure Storage Mode Equipment List

Unit No.	Unit Type	Function	Size	Material	Oper. T (F)	Oper. P (psia)
BL-201	Blower	Increase pressure of inlet carbon dioxide stream	Pc = 213.27 HP	Cast Iron	198.3	29.7
BL-202	Blower	Increase pressure of carbon monoxide stream	Pc = 279.994 HP	Cast Iron	1475.3	19.7
BL-203	Blower	Increase pressure of oxygen stream	Pc = 201.643 HP	Cast Iron	1610.1	24.7
CM-201	Compressor	Increase pressure of carbon monoxide stream	Pc = 740.017 HP	Carbon Steel	1610.1	24.7
CM-202	Compressor	Increase pressure of carbon monoxide stream	Pc = 675.719 HP	Carbon Steel	617.0	388.8
CM-203	Compressor	Bring carbon monoxide stream to storage condition pressure	Pc = 667.573 HP	Carbon Steel	597.3	2000.0
CM-204	Compressor	Increase pressure of oxygen stream	Pc = 314.448 HP	Carbon Steel	577.7	75.7
CM-205	Compressor	Increase pressure of oxygen stream	Pc = 331.906 HP	Carbon Steel	601.6	389.5
CM-206	Compressor	Bring oxygen stream to storage condition pressure	Pc = 322.604 HP	Carbon Steel	583.5	2005.0
FC-201	Fuel Cell	Convert carbon dioxide into carbon monoxide and oxygen		LSM-YSZ|YSZ|Ni-YSZ	1292.0	14.7
FH-201	Fired Heater	Heat carbon dioxide stream to fuel cell operating temp.	Q = 340621 Btu/hr	Stainless Steel	1292.0	14.7
HX-201	Heat Exchanger	Heat carbon dioxide stream while cooling carbon monoxide stream	A = 188.9991 sqft, Q = 873924 Btu/hr	Carbon Steel/Carbon Steel	1044.2	24.7
HX-202	Heat Exchanger	Heat carbon dioxide stream while cooling oxygen stream	A = 47.6987 sqft, Q = 1376870 Btu/hr	Carbon Steel/Carbon Steel	1223.4	19.7
IC-201	Intercooler	Cool oxygen stream before compression	A = 31.886 sqft, Q = 1765591 Btu/hr	Carbon Steel/Carbon Steel	122.0	14.7
IC-202	Intercooler	Cool carbon monoxide stream between compression stages	A = 54.20 sqft, Q = 1394668 Btu/hr	Carbon Steel/Carbon Steel	122.4	70.6
IC-203	Intercooler	Cool carbon monoxide stream between compression stages	A = 50.7837 sqft, Q = 1439179 Btu/hr	Carbon Steel/Carbon Steel	122.4	383.8
IC-204	Intercooler	Cool carbon monoxide stream to storage temp. conditions	A = 54.393 sqft, Q = 641696 Btu/hr	Carbon Steel/Carbon Steel	121.2	2000.0
IC-205	Intercooler	Cool oxygen stream between compression stages	A = 24.736 sqft, Q = 688432 Btu/hr	Carbon Steel/Carbon Steel	122.4	70.7
IC-206	Intercooler	Cool oxygen stream between compression stages	A = 25.716 sqft, Q = 712171 Btu/hr	Carbon Steel/Carbon Steel	121.9	384.5

IC-207	Intercooler	Cool oxygen stream to storage temp. conditions	A = 27.4149 sqft, Q = Btu/hr	Carbon Steel/Carbon Steel	121.5	2000.0
PU-201	Pump	Increase pressure of water for intercoolers	Pc = 0.90582 HP	Stainless Steel	80.0	19.7
ST-201	Storage Tank	Store carbon monoxide product stream			121.2	2000.0

Table 4.4.2: High Pressure Production Mode Equipment List

Unit No.	Unit Type	Function	Size	Material	Oper. T (F)	Oper. P (psia)
BL-204	Blower	Increase pressure of inlet air stream	Pc = 204 HP	Cast Iron	141.8	19.7
BL-205	Blower	Increase pressure of carbon monoxide waste stream	Pc = 498.07 HP	Cast Iron	1493.2	24.7
BL-206	Blower	Increase pressure of nitrogen waste stream	Pc = 878.34 HP	Cast Iron	1603.0	23.7
HX-203	Heat Exchanger	Heat inlet air stream to fuel cell operating conditions	A = 503.89 sqft, Q = 7815789 Btu/hr	Carbon Steel/Carbon Steel	1292.0	14.7
HX-204	Heat Exchanger	Preheat carbon monoxide stream for turbine decompression	A = 181.98 sqft, Q = 4104317 Btu/hr	Carbon Steel/Carbon Steel	1473.8	1995.0
HX-205	Heat Exchanger	Reheat carbon monoxide stream after decompression	A = 78.87 sqft, Q = 520375 Btu/hr	Carbon Steel/Carbon Steel	615.2	19.7
FC-202	Fuel Cell	Produce energy from converting carbon monoxide and oxygen into carbon dioxide		LSM-YSZ|YSZ|Ni-YSZ	1292.0	14.7
FH-202	Fired Heater	Heat carbon monoxide stream to fuel cell operating conditions	Q = 2005841 Btu/hr	Stainless Steel	1292.0	14.7
MTU-201	M-Stage Turbine	Recover energy from compressed carbon monoxide stream	Pc = -994.1 HP	Carbon Steel	429.7	24.7

High Pressure Storage

Blower 1 (BL-201)

Blower 1 is a centrifugal blower constructed with cast iron. It increases the pressure of the inlet carbon dioxide stream in order to offset pressure losses across the process units. The outlet stream leaves at 29.7 psia and 198.3 F. The net work of the compressor is 213.3 HP, with a bare module cost of $262,488. Please refer to section 4.5 for the specification sheet.

Blower 2 (BL-202)

Blower 2 is a centrifugal blower constructed with cast iron. It increases the pressure of the carbon dioxide stream in order to offset pressure losses across the process units. The outlet stream leaves at 19.7 psia and 1475.3 F. The net work of the compressor is 280.0 HP, with a bare module cost of $325,464. Please refer to section 4.5 for the specification sheet.

Blower 3 (BL-203)

Blower 3 is a centrifugal blower constructed with cast iron. It increases the pressure of the oxygen stream in order to offset pressure losses across the process units. The outlet stream leaves at 24.7 psia and 1610.1 F. The net work of the compressor is 201.6 HP, with a bare module cost of $251,117. Please refer to section 4.5 for the specification sheet.

Compressor 1 (CM-201)

Compressor 1 is a screw compressor constructed with carbon steel. It is the first of three units in a multi-stage compressor to bring the carbon dioxide stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 75.6 psia and 754.4 F. The net work of the compressor is 740.0 HP, with a bare module cost of $1,556,039. Please refer to section 4.5 for the specification sheet.

Compressor 2 (CM-202)

Compressor 2 is a reciprocating compressor constructed with carbon steel. It is the second of three units in a multi-stage compressor to bring the carbon dioxide stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 388.8 psia and 617.0 F. The net work of the compressor is 675.7.0 HP, with a bare module cost of $1,102,893. Please refer to section 4.5 for the specification sheet.

Compressor 3 (CM-203)

Compressor 3 is a reciprocating compressor constructed with carbon steel. It is the third of three units in a multi-stage compressor to bring the carbon dioxide stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 2000.0 psia and 597.3 F. The net work of the compressor is 667.6 HP, with a bare module cost of $1,086,562. Please refer to section 4.5 for the specification sheet.

Compressor 4 (CM-204)

Compressor 4 is a screw compressor constructed with carbon steel. It is the first of three units in a multi-stage compressor to bring the oxygen stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 75.7 psia and 577.7 F. The net work of the compressor is 314.4 HP, with a bare module cost of $837,150. Please refer to section 4.5 for the specification sheet.

Compressor 5 (CM-205)

Compressor 5 is a reciprocating compressor constructed with carbon steel. It is the second of three units in a multi-stage compressor to bring the oxygen stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 389.5 psia and 601.6 F. The net work of the compressor is 331.9 HP, with a bare module cost of $444,206. Please refer to section 4.5 for the specification sheet.

Compressor 6 (CM-206)

Compressor 6 is a reciprocating compressor constructed with carbon steel. It is the third of three units in a multi-stage compressor to bring the oxygen stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 2005.0 psia and 583.5 F. The net work of the compressor is 322.6 HP, with a bare module cost of $444,206. Please refer to section 4.5 for the specification sheet.

Fuel Cell (FC-201)

Fuel Cell 1 is the solid oxide electrolytic cell (SOEC) which reduces carbon dioxide to carbon monoxide and oxygen by using external electric supply. On the cathode side, carbon dioxide is being reduced to carbon monoxide and on the anode side, 99.9% pure molecular oxygen is being produced. The cell has a strontium-doped lanthanum manganite (LSM) composite anode, nickel and yttria-stabilized zirconia composite cathode and a yttria-stabilized zirconia electrolyte. The power consumption for this unit is 384.1 MWh. The SOEC is operated at 600℃ and 1 atm. The bare module cost of the unit is $6,207,642. Please refer to section 4.5 for the specification sheet.

Fired Heater (FH-201)

The fired heater uses wood pellets as fuel. Its purpose is to raise the temperature of the carbon dioxide stream to the operating conditions of the fuel cell, at a pressure of 14.7 psi and a temperature of 1292 F. It is based on a stainless steel constructed, shop fabricated unit with a heat duty of 340,621.3 Btu/hr. The bare module cost of the unit is $109,185. Please refer to section 4.5 for the specification sheet.

Heat Exchanger 1 (HX-201)

This heat exchanger uses the excess heat of the carbon monoxide stream in order to raise the temperature of the carbon dioxide stream bound for the fuel cell. This is an example of efficient heat integration, as the carbon monoxide stream must be cooled on its way to the multistage compressor as well. The carbon dioxide stream exits the heat exchanger at 1044.2 F; the carbon monoxide stream exits the heat exchanger at 216.3 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $36,356. Please refer to section 4.5 for the specification sheet.

Heat Exchanger 2 (HX-202)

This heat exchanger uses the excess heat of the oxygen stream in order to raise the temperature of the carbon dioxide stream bound for the fuel cell. This is an example of efficient heat integration, as the oxygen stream must be cooled on its way to the multistage compressor as well. The oxygen stream exits the heat exchanger at 1063.4 F; the carbon monoxide stream exits the heat exchanger at 1223.4 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $17,912. Please refer to section 4.5 for the specification sheet.

Intercooler 1 (IC-201)

Intercooler 1 cools the carbon monoxide stream to storage temperature conditions before entering the multistage compressor, in order to minimize the work required in the process and keep the stream from heating in inoperable temperatures. The stream is cooled from 1063.4 F to 122.0 F. For details on cooling water flowrates, please refer to the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $14,067. Please refer to section 4.5 for the specification sheet.

Intercooler 2 (IC-202)

Intercooler 2 cools the carbon monoxide stream in the multistage compressor, between CM-201 and CM-202, in order to minimize the work required in the process and keep the stream from heating in inoperable temperatures. The stream is cooled from 754.4 F to 122.0 F. For details on cooling water flowrates, please refer to the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $19,341. Please refer to section 4.5 for the specification sheet.

Intercooler 3 (IC-203)

Intercooler 3 cools the carbon monoxide stream in the multistage compressor, between CM-202 and CM-203, in order to minimize the work required in the process and keep the stream from heating in inoperable temperatures. The stream is cooled from 617.0 F to 122.0 F. For details on cooling water flowrates the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $18,599. Please refer to section 4.5 for the specification sheet.

Intercooler 4 (IC-204)

Intercooler 4 cools the carbon monoxide stream after its final compression stage in the multistage compressor, bringing it to storage temperature conditions. The stream is cooled from 583.5 F to 122.0 F. For details on cooling water flowrates the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $19,381. Please refer to section 4.5 for the specification sheet.

Intercooler 5 (IC-205)

Intercooler 5 cools the oxygen stream in the multistage compressor, between CM-204 and CM-205, in order to minimize the work required in the process and keep the stream from heating in inoperable temperatures. The stream is cooled from 577.7 F to 122.0 F. For details on cooling water flowrates the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $12,079. Please refer to section 4.5 for the specification sheet.

Intercooler 6 (IC-206)

Intercooler 6 cools the oxygen stream in the multistage compressor, between CM-205 and CM-206, in order to minimize the work required in the process and keep the stream from heating in inoperable temperatures. The stream is cooled from 601.6 F to 122.0 F. For details on cooling water flowrates the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $12,364. Please refer to section 4.5 for the specification sheet.

Intercooler 7 (IC-207)

Intercooler 7 cools the oxygen stream after its final compression stage in the multistage compressor, bringing it to storage temperature conditions. The stream is cooled from 583.5 F to 122.0 F. For details on cooling water flowrates the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $12,848. Please refer to section 4.5 for the specification sheet.

Pump 1 (PU-201)

Pump 1 is centrifugal water pump that pressurizes the cooling water used to regulate temperature throughout the process in the intercoolers. It brings the pressure from 14.7 psia to 19.7 psia in order to offset the pressure losses across the intercoolers. The size and specifications of the unit do not correspond to the correlations in *Product and Process Design Principles*, so a pricing approximation was used by comparing Pump 1 to a pump found online that can facilitate the required flowrate and operating pressure. Based on the cost of the AMT-4251-98 Centrifugal Pump, the bare module cost was calculated to be $8,015. Please refer to section 4.5 for the specification sheet.

Storage Tank 1 (ST-201)

The storage tank for the high-pressure process is designed to hold the carbon monoxide produced in the storage mode of the process at 2000 psig. The total volume of the container is 1200 m^3 or 317,000 gal. The tank is made of carbon steel and has a minimum thickness prescribed by the operating pressure. The weight is 3.6 million pounds, and the maximum pressure rating is 2200 psig.

High Pressure Production

Blower 4 (BL-204)

Blower 4 is a centrifugal blower constructed with cast iron. It increases the pressure of the inlet air stream in order to offset pressure losses across the process units. The outlet stream leaves at 19.7 psia and 141.8 F. The net work of the compressor is 204.0 HP, with a bare module cost of $169,745. Please refer to section 4.5 for the specification sheet.

Blower 5 (BL-205)

Blower 5 is a centrifugal blower constructed with cast iron. It increases the pressure of the waste carbon dioxide stream in order to offset pressure losses across the process units so that its excess heat can be used in a recycle loop before discarding. The outlet stream leaves at 24.7 psia and 1493.2 F. The net work of the compressor is 498.1 HP, with a bare module cost of $343,600. Please refer to section 4.5 for the specification sheet.

Blower 6 (BL-206)

Blower 5 is a centrifugal blower constructed with cast iron. It increases the pressure of the waste nitrogen stream in order to offset pressure losses across the process units so that its excess heat can be used in a recycle loop before discarding. The outlet stream leaves at 23.7 psia and 1603.0 F. The net work of the compressor is 498.1 HP, with a bare module cost of $537,880. Please refer to section 4.5 for the specification sheet.

Heat Exchanger 3 (HX-203)

This heat exchanger uses the excess heat of the nitrogen stream in order to raise the temperature of the air stream bound for the fuel cell. This is an example of efficient heat integration, as the nitrogen stream was to be discarded from the process otherwise. The air stream exits the heat exchanger at 1292 F; the carbon monoxide stream exits the heat exchanger at 160.3 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $44,567. Please refer to section 4.5 for the specification sheet.

Heat Exchanger 4 (HX-204)

This heat exchanger uses the excess heat of the carbon dioxide stream in order to raise the temperature of the carbon monoxide stream before it is expanded in the multistage turbine. By doing this, the need for reheaters between stages is eliminated, as the stream never falls below an operable temperature range. This is an example of efficient heat integration, as the carbon dioxide stream was to be discarded from the process otherwise. The carbon monoxide stream exits the heat exchanger at 1473.8 F; the carbon dioxide stream exits the heat exchanger at 634.6 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $36,420. Please refer to section 4.5 for the specification sheet.

Heat Exchanger 5 (HX-205)

This heat exchanger uses the excess heat of the carbon dioxide stream in order to raise the temperature of the expanded carbon monoxide stream bound for the fuel cell. This is an example of efficient heat integration, as the carbon dioxide stream was to be discarded from the process otherwise. The carbon monoxide stream exits the heat exchanger at 615.2 F; the carbon dioxide stream exits the heat exchanger at 513.7 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $24,223. Please refer to section 4.5 for the specification sheet.

Fuel Cell 2 (FC-202)

Fuel Cell 2 is the solid oxide fuel cell (SOFC) which generates electricity by converting carbon monoxide to carbon dioxide. On the cathode side, molecular oxygen from air is reduced to oxide ions and on the anode side, carbon monoxide is oxidized to carbon dioxide. The cell has a strontium-doped lanthanum manganite (LSM) composite anode, nickel and yttria-stabilized zirconia composite cathode and a yttria-stabilized zirconia electrolyte. The power production for this unit is 226.6 MWh. The SOFC is operated at 600°C and 1 atm. The bare module cost of the unit is $6,207,642. Please refer to section 4.5 for the specification sheet.

Fired Heater 2 (FH-202)

The fired heater uses wood pellets as fuel. Its purpose is to raise the temperature of the carbon monoxide stream to the operating conditions of the fuel cell, at a pressure of 14.7 psi and a temperature of 1292 F. It is based on a stainless steel constructed, shop fabricated unit with a heat duty of 2,005,841.75 Btu/hr. The bare module cost of the unit is $136,813. Please refer to section 4.5 for the specification sheet.

Multistage Turbine 1 (MTU-201)

The multistage turbine is implemented in order to recover energy from the highly pressurized carbon monoxide between storage in the tank and conversion in the fuel cell. Three stages had to be used because the temperature decrease across a single stage for this pressure difference was too large and would have resulted in liquid effluent. Additionally, expansion over multiple stages allows for greater recovery of energy, making the overall process more efficient as a result. The outlet stream exits at 429.7 F and 24.7 psia. The total work recovered by this unit is 994.1 HP. Each turbine is constructed with carbon steel; please refer to the specification sheet for details about the individual turbines

4.5 Specification Sheets

Specification sheets for the equipment listed in the process design are reported in this section.

Blower 1

Identification				
	Item	Blower 1	Date	4/12/20
	Item No.	BL-101	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of inlet carbon dioxide			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-101	S-102	
	Quantity (lb/hr)	17,083.7	17,083.7	
	Composition			
	Carbon Dioxide	17,083.7	17,083.7	
	Carbon Monoxide	-	-	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	77.0	165.8	
	Pressure (psi)	14.7	24.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Carbon Steel		
	Net Work (HP)	154.471		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$	63,378.21	
	CBM	$	203,444.05	

Blower 2

Identification				
	Item	Blower 2	Date	4/12/20
	Item No.	BL-202	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of carbon monoxide stream			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-206	S-207	
	Quantity (lb/hr)	10,935.2	10,935.2	
	Composition			
	Carbon Dioxide	170.8	170.8	
	Carbon Monoxide	10,764.3	10,764.32	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	1,292.0	1,475.3	
	Pressure (psi)	14.7	19.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	279.994		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$	101,390.76	
	CBM	$	325,464.33	

Blower 3

Identification				
	Item	Blower 3	Date	4/12/20
	Item No.	BL-203	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of oxygen stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-215	S-216	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	1,292.0	1,610.1	
	Pressure (psi)	14.7	24.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	201.643		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	78,229.68		
	CBM $	251,117.28		

Compressor 1

Identification				
	Item	Compressor 1	Date	4/12/20
	Item No.	CM-101	By	JD/MUC/VB
	No. Required	1		

Function	Increase pressure of carbon monoxide stream
Operation	12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		S-208B	S-209
Quantity (lb/hr)		10,935.1	10,935.15
Composition			
	Carbon Dioxide	170.8	170.84
	Carbon Monoxide	10,764.3	10,764.31
	Oxygen	-	-
	Water	-	-
Temperature (F)		216.3	754.4
Pressure (psi)		14.7	75.6
Vapor Fraction		1.0	1.0

Design Data	
Type	Screw Compressor
Material	Carbon Steel
Net Work (HP)	740.017
Isentropic Efficiency	0.72
Mechanical Efficiency	0.8

CP	$	484,747.65
CBM	$	1,556,039.95

Compressor 2

Identification

Item	Compressor 2	Date	4/12/20
Item No.	CM-102	By	JD/MUC/VB
No. Required	1		

Function Increase pressure of carbon monoxide stream

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		S-210	S-211
	Quantity (lb/hr)	10,935.1	10,935.15
	Composition		
	Carbon Dioxide	170.8	170.84
	Carbon Monoxide	10,764.3	10,764.31
	Oxygen	-	-
	Water	-	-
	Temperature (F)	122.4	617.0
	Pressure (psi)	70.6	388.8
	Vapor Fraction	1.0	1.0

Design Data

Type	Reciprocating Compressor
Material	Carbon Steel
Net Work (HP)	675.719
Isentropic Efficiency	0.72
Mechanical Efficiency	0.8

CP	$	343,580.41
CBM	$	1,102,893.10

Compressor 3

Identification				
	Item	Compressor 3	Date	4/12/20
	Item No.	CM-103	By	JD/MUC/VB
	No. Required	1		
Function	Bring carbon monoxide stream to storage condition pressure			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-212	S-213	
	Quantity (lb/hr)	10,935.1	10,935.15	
	Composition			
	Carbon Dioxide	170.8	170.84	
	Carbon Monoxide	10,764.3	10,764.31	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	122.4	597.3	
	Pressure (psi)	383.8	2,000.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Reciprocating Compressor		
	Material	Carbon Steel		
	Net Work (HP)	667.573		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$	338,492.87	
	CBM	$	1,086,562.12	

Compressor 4

Identification				
	Item	Compressor 4	Date	4/12/20
	Item No.	CM-104	By	JD/MUC/VB
	No. Required	1		

Function Increase pressure of oxygen stream

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		S-218B	S-219
	Quantity (lb/hr)	6,148.5	6,148.5
	Composition		
	Carbon Dioxide	-	-
	Carbon Monoxide	-	-
	Oxygen	6,148.5	6,148.5
	Water	-	-
	Temperature (F)	122.0	577.7
	Pressure (psi)	14.7	75.7
	Vapor Fraction	1.0	1.0

Design Data		
	Type	Screw Compressor
	Material	Carbon Steel
	Net Work (HP)	314.448
	Isentropic Efficiency	0.72
	Mechanical Efficiency	0.8

CP	$	260,794.59
CBM	$	837,150.62

Compressor 5

Identification				
	Item	Compressor 5	Date	4/12/20
	Item No.	CM-105	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of oxygen stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-220	S-221	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	122.4	601.6	
	Pressure (psi)	70.7	389.5	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Reciprocating Compressor		
	Material	Carbon Steel		
	Net Work (HP)	331.906		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	143,306.08		
	CBM $	460,012.53		

Compressor 6

Identification				
	Item	Compressor 6	Date	4/12/20
	Item No.	CM-106	By	JD/MUC/VB
	No. Required	1		
Function	Bring oxygen stream to storage condition pressure			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-222	S-223	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	121.9	583.5	
	Pressure (psi)	384.5	2,005.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Reciprocating Compressor		
	Material	Carbon Steel		
	Net Work (HP)	322.604		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$	138,382.07	
	CBM	$	444,206.46	

Fuel Cell 1

Identification

Item	Fuel Cell 1	Date	4/12/20
Item No.	FC-101	By	JD/MUC/VB
No. Required	1		

Function Convert carbon dioxide into carbon monoxide and oxygen

Operation 12 hours, daily

Materials Handled	**Inlet**	**Outlet 1**	**Outlet 2**
Stream ID	S-104	S-105	S-115
Quantity (lb/hr)	17,083.7	6,148.5	10,935.2
Composition			
Carbon Dioxide	17,083.7	-	170.8
Carbon Monoxide	-	-	10,764.3
Oxygen	-	6,148.5	-
Water	-	-	-
Temperature (F)	1,292.0	1,292.0	1,292.0
Pressure (psi)	14.7	14.7	14.7
Vapor Fraction	1.0	1.0	1.0

Design Data

Material	LSM-YSZ|YSZ|Ni-YSZ
Electricity Consumed (kW)	32010.33
Operating T (F)	1292.0
Operating P (psia)	14.7

CP	$	3,103,821.00
CBM	$	6,207,642.00

Fired Heater 1

Identification				
	Item	Fired Heater 1	Date	4/12/20
	Item No.	FH-201	By	JD/MUC/VB
	No. Required	1		
Function	Heat carbon dioxide stream to fuel cell operating temp.			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-204	S-205	
	Quantity (lb/hr)	17,083.7	17,083.7	
	Composition			
	Carbon Dioxide	17,083.7	17,083.7	
	Carbon Monoxide	-	-	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	1,223.4	1,292.0	
	Pressure (psi)	19.7	14.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Fired Heater		
	Material	Stainless Steel		
	Bare Module Type	Shop Fabricated		
	Heat Transfer (Btu/hr)	340621.3		
	CP $	34,014.15		
	CBM $	109,185.43		

Heat Exchanger 1

Identification

Item	Heat Exchanger 1	Date	4/12/20
Item No.	HX-201	By	JD/MUC/VB
No. Required	1		

Function Heat carbon dioxide stream while cooling carbon monoxide stream

Operation 12 hours, daily

Materials Handled	**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID	S-207	S-208A	S-202	S-203
Quantity (lb/hr)	10,935.2	10,935.2	17,083.7	17,083.7
Composition			-	-
Carbon Dioxide	170.8	170.8	17,083.7	17,083.7
Carbon Monoxide	10,764.3	10,764.3	-	-
Oxygen	-	-	-	-
Water	-	-	-	-
Temperature (F)	1,475.3	216.3	198.3	1,044.2
Pressure (psi)	19.7	14.7	29.7	24.7
Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	3682474.8
Heat Transfer Coefficient (Btu/hr-sqft-F)	149.7
Heat Transfer Area (sqft)	189.0

CP	$	11,468.80
CBM	$	36,356.09

Heat Exchanger 2

Identification

Item	Heat Exchanger 2	Date	4/12/20
Item No.	HX-202	By	JD/MUC/VB
No. Required	1		

Function Heat carbon dioxide stream while cooling oxygen stream

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID		S-216	S-217	S-203	S-204
	Quantity (lb/hr)	6,148.5	6,148.5	17,083.7	17,083.7
	Composition			-	-
	Carbon Dioxide	-	-	17,083.7	17,083.7
	Carbon Monoxide	-	-	-	-
	Oxygen	6,148.5	6,148.5	-	-
	Water	-	-	-	-
	Temperature (F)	1,610.1	1,063.4	1,044.2	1,223.4
	Pressure (psi)	24.7	19.7	24.7	19.7
	Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	873924.5
Heat Transfer Coefficient (Btu/hr-sqft-F)	149.7
Heat Transfer Area (sqft)	47.7

CP	$	5,650.66
CBM	$	17,912.61

Intercooler 1

Identification

	Item	Intercooler 1	Date	4/12/20
	Item No.	IC-201	By	JD/MUC/VB
	No. Required	1		

Function Cool oxygen stream before compression

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		S-217	S-218A
	Quantity (lb/hr)	6,148.5	6,148.5
	Composition		
	Carbon Dioxide	-	-
	Carbon Monoxide	-	-
	Oxygen	6,148.5	6,148.5
	Water	-	-
	Temperature (F)	1,063.4	122.0
	Pressure (psi)	19.7	14.7
	Vapor Fraction	1.0	1.0

Design Data

	Type	Shell and Tube
	Material	Carbon Steel/Carbon Steel
	Heat Transfer (Btu/lb)	1376870.9
	Heat Transfer Coefficient (Btu/hr-sqft-F)	149.7
	Heat Transfer Area (sqft)	31.9

Cold Utility		Cooling Water
CP	$	4,437.68
CBM	$	14,067.43

Intercooler 2

Identification

	Item	Intercooler 2	Date	4/12/20
	Item No.	IC-202	By	JD/MUC/VB
	No. Required	1		
Function	Cool carbon monoxide stream between compression stages			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-209	S-210	
	Quantity (lb/hr)	10,935.1	10,935.1	
	Composition			
	Carbon Dioxide	170.8	170.8	
	Carbon Monoxide	10,764.3	10,764.3	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	754.4	122.4	
	Pressure (psi)	75.6	70.6	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		1765591.4	
	Heat Transfer Coefficient (Btu/hr-sqft-F)		149.7	
	Heat Transfer Area (sqft)		54.2	
	Cold Utility	Cooling Water		
	CP	$ 6,101.49		
	CBM	$ 19,341.73		

Intercooler 3

Identification				
	Item	Intercooler 3	Date	4/12/20
	Item No.	IC-203	By	JD/MUC/VB
	No. Required	1		
Function	Cool carbon monoxide stream between compression stages			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-211	S-212	
	Quantity (lb/hr)	10,935.1	10,935.1	
	Composition			
	Carbon Dioxide	170.8	170.8	
	Carbon Monoxide	10,764.3	10,764.3	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	617.0	122.4	
	Pressure (psi)	388.8	383.8	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		1394668.8	
	Heat Transfer Coefficient (Btu/hr-sqft-F)		149.7	
	Heat Transfer Area (sqft)		50.8	
	Cold Utility	Cooling Water		
	CP	$	5,867.19	
	CBM	$	18,599.00	

Intercooler 4

Identification				
	Item	Intercooler 4	Date	4/12/20
	Item No.	IC-204	By	JD/MUC/VB
	No. Required	1		
Function	Cool carbon monoxide stream to storage temp. conditions			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-213	S-214	
	Quantity (lb/hr)	10,935.1	10,935.1	
	Composition			
	Carbon Dioxide	170.8	170.8	
	Carbon Monoxide	10,764.3	10,764.3	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	597.3	121.2	
	Pressure (psi)	2,000.0	2,000.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		1439179.5	
	Heat Transfer Coefficient (Btu/hr-sqft-F)		149.7	
	Heat Transfer Area (sqft)		54.4	
	Cold Utility	Cooling Water		
	CP $	6,113.94		
	CBM $	19,381.20		

Intercooler 5

Identification				
	Item	Intercooler 5	Date	4/12/20
	Item No.	IC-205	By	JD/MUC/VB
	No. Required	1		
Function	Cool oxygen stream between compression stages			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-219	S-220	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	577.7	122.4	
	Pressure (psi)	75.7	70.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		641696.0	
	Heat Transfer Coefficient (Btu/hr-sqft-F)		149.7	
	Heat Transfer Area (sqft)		24.7	
	Cold Utility	Cooling Water		
	CP	$ 3,810.60		
	CBM	$ 12,079.60		

Intercooler 6

Identification				
	Item	Intercooler 6	Date	4/12/20
	Item No.	IC-206	By	JD/MUC/VB
	No. Required	1		
Function	Cool oxygen stream between compression stages			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-221	S-222	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	601.6	121.9	
	Pressure (psi)	389.5	384.5	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		688432.3	
	Heat Transfer Coefficient (Btu/hr-sqft-F)		149.7	
	Heat Transfer Area (sqft)		25.7	
	Cold Utility	Cooling Water		
	CP	$ 3,900.48		
	CBM	$ 12,364.51		

Intercooler 7

Identification				
	Item	Intercooler 7	Date	4/12/20
	Item No.	IC-207	By	JD/MUC/VB
	No. Required	1		
Function	Cool oxygen stream to storage temp. conditions			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-223	S-224	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	583.5	121.5	
	Pressure (psi)	2,005.0	2,000.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		712171.3	
	Heat Transfer Coefficient (Btu/hr-sqft-F)		149.7	
	Heat Transfer Area (sqft)		27.4	
	Cold Utility	Cooling Water		
	CP	$ 4,053.10		
	CBM	$ 12,848.34		

Pump 1

Identification

Item	Pump 1	Date	4/12/20
Item No.	PU-201	By	JD/MUC/VB
No. Required	1		

Function Increase pressure of water for intercoolers

Operation 12 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID		
Quantity (lb/hr)	154,319.2	154,319.2
Composition		
Carbon Dioxide	-	-
Carbon Monoxide	-	-
Oxygen	-	-
Water	154,319.2	154,319.2
Temperature (F)	80.0	80.0
Pressure (psi)	14.7	19.7
Vapor Fraction	-	-

Design Data

Type	AMT 4251-98 Heavy Duty Straight Centrifugal Pump
Material	Stainless Steel
Net Work (HP)	0.90582
Isentropic Efficiency	0.72
Mechanical Efficiency	0.8

CP	$	2,497.00
CBM	$	8,015.37

Storage Tank 1

Identification				
	Item	Storage Tank 1	Date	4/12/20
	Item No.	ST-101	By	JD/MUC/VB
	No. Required	1		
Function		Store carbon monoxide product stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-214	S-202	
	Quantity (lb/hr)	10,935.1	17,083.68	
	Composition			
	Carbon Dioxide	170.8	17,083.68	
	Carbon Monoxide	10,764.3	-	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	121.2	198.3	
	Pressure (psi)	2,000.0	29.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Pressure Vessel		
	Material	Carbon Steel		
	Gas Volume (cuft)	5300		
	CP	$	3,788,872.00	
	CBM	$	9,472,180.00	

Blower 4

Identification				
	Item	Blower 4	Date	4/12/20
	Item No.	BL-204	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of inlet air stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-225	S-226	
	Quantity (lb/hr)	26,501.8	26,501.8	
	Composition			
	Carbon Monoxide	-	-	
	Carbon Dioxide	-	-	
	Oxygen	6,172.7	6,172.7	
	Nitrogen	20,329.1	20,329.1	
	Temperature (F)	77.0	141.8	
	Pressure (psi)	14.7	19.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	204		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	78,951.19		
	CBM $	253,433.33		

Blower 5

Identification

Item	Blower 5	Date	4/12/20
Item No.	BL-205	By	JD/MUC/VB
No. Required	1		

Function Increase pressure of carbon monoxide waste stream

Operation 12 hours, daily

Materials Handled	**Inlet**	**Outlet**
Stream ID	S-233	S-234
Quantity (lb/hr)	17,022.2	17,022.2
Composition		
Carbon Monoxide	107.6	107.6
Carbon Dioxide	16,914.5	16,914.5
Oxygen	-	-
Nitrogen	-	-
Temperature (F)	1,292.0	1,493.2
Pressure (psi)	14.7	24.7
Vapor Fraction	1.0	1.0

Design Data

Type	Centrifugal Blower
Material	Cast Iron
Net Work (HP)	498.077
Isentropic Efficiency	0.72
Mechanical Efficiency	0.8

CP	$	159,814.10
CBM	$	513,003.26

Blower 6

Identification				
	Item	Blower 6	Date	4/12/20
	Item No.	BL-206	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of nitrogen waste stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-237	S-238	
	Quantity (lb/hr)	20,414.7	20,414.7	
	Composition			
	Carbon Monoxide	-	-	
	Carbon Dioxide	-	-	
	Oxygen	85.7	85.7	
	Nitrogen	20,329.1	20,329.1	
	Temperature (F)	1,292.0	1,603.0	
	Pressure (psi)	14.7	23.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	878.347		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	250,176.84		
	CBM $	803,067.67		

Heat Exchanger 3

Identification

Item	Heat Exchanger 3	Date	4/12/20
Item No.	HX-203	By	JD/MUC/VB
No. Required	1		

Function Heat inlet air stream to fuel cell operating conditions

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID		S-238	S-239	S-226	S-227
	Quantity (lb/hr)	20,414.7	20,414.7	26,501.8	26,501.8
	Composition			-	-
	Carbon Monoxide	-	-	-	-
	Carbon Dioxide	-	-	-	-
	Oxygen	85.7	85.7	6,172.7	6,172.7
	Nitrogen	20,329.1	20,329.1	20,329.1	20,329.1
	Temperature (F)	1,603.0	160.3	141.8	1,292.0
	Pressure (psi)	23.7	18.7	19.7	14.7
	Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	7815789.4
Heat Transfer Coefficient (Btu/hr-ft2-F)	149.7
Heat Transfer Area (ft2)	503.9

CP	$	14,059.26
CBM	$	44,567.85

Heat Exchanger 4

Identification

Item	Heat Exchanger 4	Date	4/12/20
Item No.	HX-204	By	JD/MUC/VB
No. Required	1		

Function Preheat carbon monoxide stream for turbine decompression

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID		S-234	S-235	S-228	S-229
	Quantity (lb/hr)	17,022.2	17,022.2	10,935.2	10,935.2
	Composition			-	-
	Carbon Monoxide	107.6	107.6	10,764.3	10,764.3
	Carbon Dioxide	16,914.5	16,914.5	170.8	170.8
	Oxygen	-	-	-	-
	Nitrogen	-	-	-	-
	Temperature (F)	1,493.2	634.6	122.0	1,473.8
	Pressure (psi)	24.7	19.7	2,000.0	1,995.0
	Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	4104317.3
Heat Transfer Coefficient (Btu/hr-ft2-F)	149.7
Heat Transfer Area (ft2)	182.0

CP	$	11,489.03
CBM	$	36,420.22

Heat Exchanger 5

Identification

Item	Heat Exchanger 5	Date	4/12/20
Item No.	HX-205	By	JD/MUC/VB
No. Required	1		

Function Reheat carbon monoxide stream after decompression

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID		S-235	S-236	S-230	S-231
	Quantity (lb/hr)	17,022.2	17,022.2	10,935.2	10,935.2
	Composition			-	-
	Carbon Monoxide	107.6	107.6	10,764.3	10,764.3
	Carbon Dioxide	16,914.5	16,914.5	170.8	170.8
	Oxygen	-	-	-	-
	Nitrogen	-	-	-	-
	Temperature (F)	634.6	513.7	429.7	615.2
	Pressure (psi)	19.7	14.7	24.7	19.7
	Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	520375.8
Heat Transfer Coefficient (Btu/hr-ft2-F)	149.7
Heat Transfer Area (ft2)	78.9

CP	$	7,641.35
CBM	$	24,223.08

Fired Heater 2

Identification

Item	Fired Heater 2	Date	4/12/20
Item No.	FH-202	By	JD/MUC/VB
No. Required	1		

Function	Heat carbon monoxide stream to fuel cell operating conditions
Operation	12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		S-231	S-232
	Quantity (lb/hr)	10,935.2	10,935.2
	Composition		
	Carbon Monoxide	10,764.3	10,764.3
	Carbon Dioxide	170.8	170.8
	Oxygen	-	-
	Nitrogen	-	-
	Temperature (F)	615.2	1,292.0
	Pressure (psi)	19.7	14.7
	Vapor Fraction	1.0	1.0

Design Data

Type	Fired Heater
Material	Stainless Steel
Bare Module Type	Shop Fabricated
Heat Transfer (Btu/hr)	2005841.8

CP	$	136,813.57
CBM	$	439,171.56

Multistage Turbine 1

Identification				
	Item	Multistage Turbine 1	Date	4/12/20
	Item No.	MTU-201	By	JD/MUC/VB
	No. Required	1		
Function	Recover energy from compressed car bon monoxide stream			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-229	S-230	
	Quantity (lb/hr)	10,935.2	10,935.2	
	Composition			
	Carbon Monoxide	10,764.3	10,764.3	
	Carbon Dioxide	170.8	170.8	
	Oxygen	-	-	
	Nitrogen	-	-	
	Temperature (F)	1,473.8	429.7	
	Pressure (psi)	1,995.0	24.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Gas Expansion Turbine	Gas Expansion Turbine	Gas Expansion Turbine
	Material	Carbon Steel	Carbon Steel	Carbon Steel
	Net Work (HP)	-424.8	-323.3	-246.0
	Isentropic Efficiency	0.7	0.72	0.7
	Mechanical Efficiency	0.8	0.8	0.8
	CP $	80,719.92	64,704.11	51,857.16
	CBM $	201,799.79	161,760.28	129,642.89

Fuel Cell 2

Identification

Item	Fuel Cell 2	Date	4/12/20
Item No.	FC-202	By	JD/MUC/VB
No. Required	1		

Function	Convert carbon dioxide into carbon monoxide and oxygen
Operation	12 hours, daily

Materials Handled	**Inlet 1**	**Inlet 2**	**Outlet 1**	**Outlet 2**
Stream ID	S-227	S-232	S-233	S-237
Quantity (lb/hr)	26,501.8	10,935.2	17,022.2	20,414.7
Composition				
Carbon Dioxide	-	10,764.3	107.6	-
Carbon Monoxide	-	170.8	16,914.5	-
Oxygen	6,172.7	-	-	85.7
Water	20,329.1	-	-	20,329.1
Temperature (F)	1,292.0	1,292.0	1,292.0	1,292.0
Pressure (psi)	14.7	14.7	14.7	14.7
Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Material	LSM-YSZ|YSZ|Ni-YSZ
Electricity Supplied (kW)	18882.3
Operating T (F)	1292.0
Operating P (psi)	14.7

CP	$	3,103,821.00
CBM	$	6,207,642.00

4.6 Equipment Cost Summary

Equipment Description	**Type**	**Purchase Cost**	**Bare Module Factor**	**Bare Module Cost**
Name			(default 3.21 if blank)	
BL-201	Process Machinery	$81,800		$262,500
BL-202	Process Machinery	$101,400		$325,500
BL-203	Process Machinery	$78,200		$251,100
CM-201	Process Machinery	$484,700		$1,556,000
CM-202	Process Machinery	$343,600		$1,102,900
CM-203	Process Machinery	$338,500		$1,086,600
CM-204	Process Machinery	$260,800		$837,200
CM-205	Process Machinery	$143,300		$460,000
CM-206	Process Machinery	$138,400		$444,200
FC-201	Process Machinery	$3,103,800	2.00	$6,207,600
FH-201	Process Machinery	$34,000		$109,200
HX-201	Process Machinery	$11,500	3.17	$36,400
HX-202	Process Machinery	$5,700	3.17	$17,900
IC-201	Process Machinery	$4,400	3.17	$14,100
IC-202	Process Machinery	$6,100	3.17	$19,300
IC-203	Process Machinery	$5,900	3.17	$18,600
IC-204	Process Machinery	$6,100	3.17	$19,400
IC-205	Process Machinery	$3,800	3.17	$12,100
IC-206	Process Machinery	$3,900	3.17	$12,400
IC-207	Process Machinery	$4,100	3.17	$12,800

PU-201	Process Machinery	$2,500		$8,000
ST-201	Storage	$3,788,900	2.50	$9,472,200
BL-204	Process Machinery	$79,000		$253,400
BL-205	Process Machinery	$159,800		$513,000
BL-206	Process Machinery	$250,200		$803,100
HX-203	Process Machinery	$14,100	3.17	$44,600
HX-204	Process Machinery	$11,500	3.17	$36,400
HX-205	Process Machinery	$7,600	3.17	$24,200
FC-202	Process Machinery	$3,103,800	2.00	$6,207,600
FH-202	Process Machinery	$79,000		$253,400
MTU-201	Process Machinery	$169,700	2.50	$424,400
FS-201	Other Equipment	$17,000	1.92	$32,600
Total				**30,878,664**

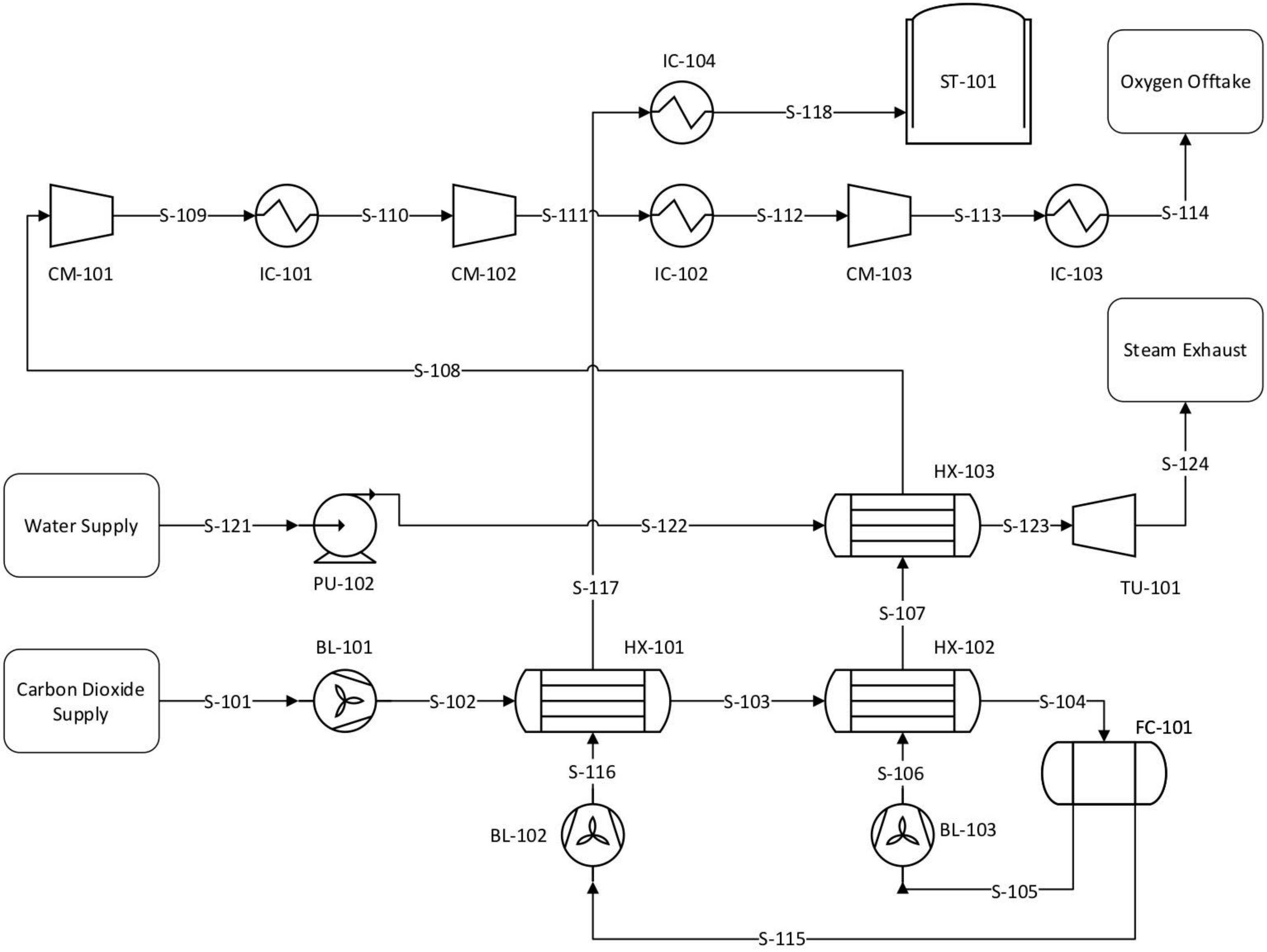
5. Case 2: Low-Pressure Storage Process Design

5.1 Process Flow Diagrams

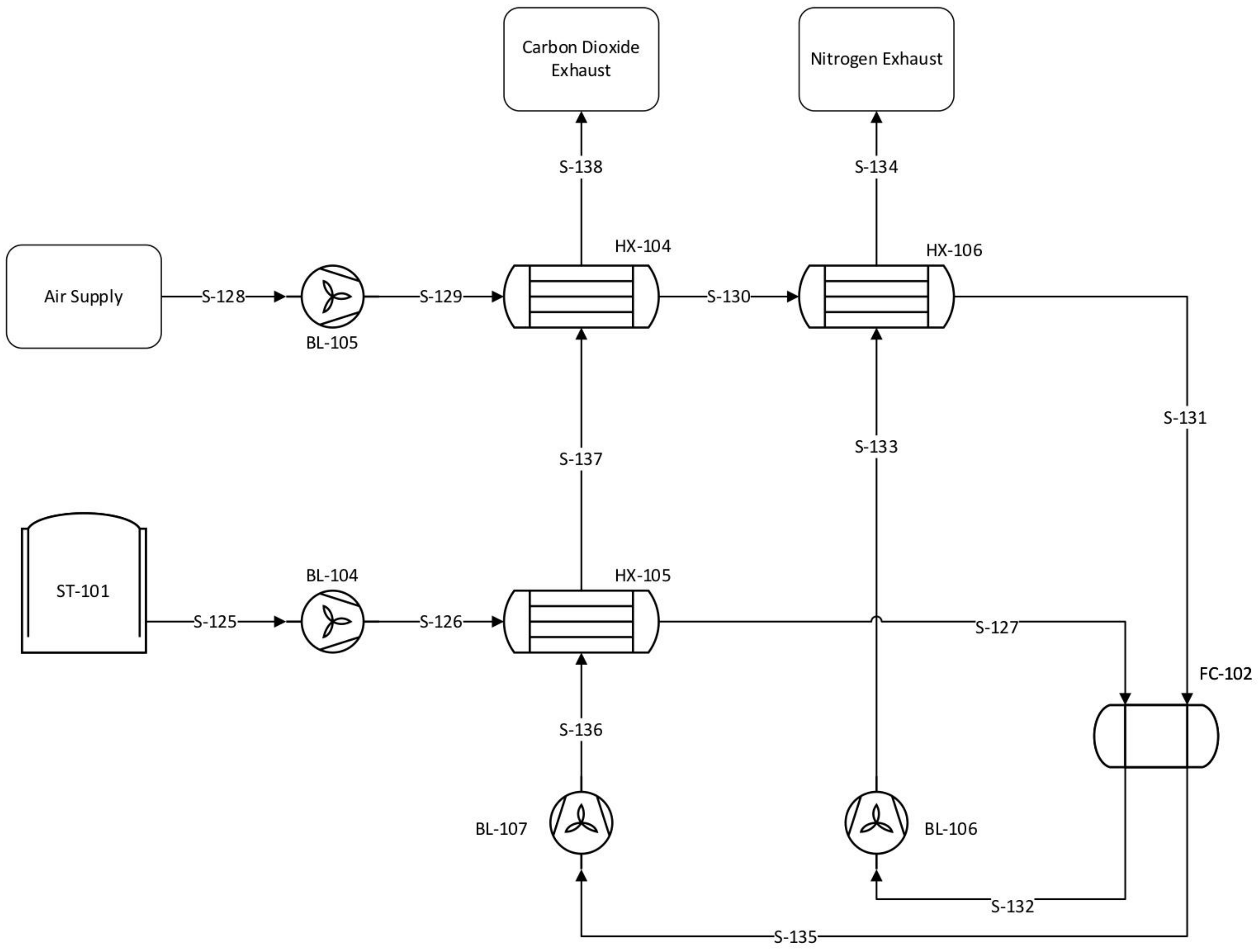
Process flow diagrams are shown in this section, along with ASPEN stream reports with relevant thermodynamic data.

Much of the equipment and process design remains the same from the high-pressure case presented in section 4. This process, however, is simplified and requires fewer pieces of equipment, notably fewer compressors and turbines due to the low storage pressure.

Low Pressure Energy Storage Process Flow Diagram



Low Pressure Energy Production Process Flow Diagram



	Units	S-101	S-102	S-103	S-104	S-105
From			BL-101	HX-101	HX-102	FC-101
To		BL-101	HX-101	HX-102	FC-101	BL-103
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flows						
Carbon Dioxide	lbmol/hr	388.2	388.2	388.2	388.2	0.0
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0	192.1
Water	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flows						
Carbon Dioxide	lb/hr	17083.7	17083.7	17083.7	17083.7	0.0
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lb/hr	0.0	0.0	0.0	0.0	6148.5
Water	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	388.2	388.2	388.2	388.2	192.1
Mass Flows	lb/hr	17083.7	17083.7	17083.7	17083.7	6148.5
Volume Flow	cuft/hr	151361.3	104953.9	354510.8	496679.0	245846.0
Temperature	F	77.0	165.8	1216.2	1292.0	1292.0
Pressure	psia	14.7	24.7	19.7	14.7	14.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-169196.3	-168386.3	-156432.7	-155462.6	9356.8
Mass Enthalpy	Btu/lb	-3844.5	-3826.1	-3554.5	-3532.5	292.4
Enthalpy Flow	Btu/hr	-65678436.9	-65364003.8	-60723883.6	-60347294.6	1797887.0
Molar Entropy	Btu/lbmol-R	0.7	1.0	12.4	13.6	8.9
Mass Entropy	Btu/lb-R	0.0	0.0	0.3	0.3	0.3
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.1	0.2	0.0	0.0	0.0

	Units	S-106	S-107	S-108	S-109	S-110
From		BL-103	HX-102	HX-103	CM-101	IC-101
To		HX-102	HX-103	CM-101	IC-101	CM-102
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flows						
Carbon Dioxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lbmol/hr	192.1	192.1	192.1	192.1	192.1
Water	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flows						
Carbon Dioxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lb/hr	6148.5	6148.5	6148.5	6148.5	6148.5
Water	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	192.1	192.1	192.1	192.1	192.1
Mass Flows	lb/hr	6148.5	6148.5	6148.5	6148.5	6148.5
Volume Flow	cuft/hr	152196.6	163674.4	60862.6	22582.7	13745.9
Temperature	F	1731.2	1500.1	122.1	545.8	121.3
Pressure	psia	29.7	24.7	19.7	92.0	87.0
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	13057.1	11097.2	312.4	3401.1	293.1
Mass Enthalpy	Btu/lb	408.0	346.8	9.8	106.3	9.2
Enthalpy Flow	Btu/hr	2508900.8	2132311.8	60035.0	653507.8	56322.5
Molar Entropy	Btu/lbmol-R	9.4	8.9	0.0	0.9	-3.0
Mass Entropy	Btu/lb-R	0.3	0.3	0.0	0.0	-0.1
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.0	0.0	0.1	0.3	0.4

	Units	S-111	S-112	S-113	S-114	S-115
From		CM-102	IC-102	CM-103	IC-103	FC-101
To		IC-102	CM-103	IC-103	B7	BL-102
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flows						
Carbon Dioxide	lbmol/hr	0.0	0.0	0.0	0.0	3.9
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0	384.3
Oxygen	lbmol/hr	192.1	192.1	192.1	192.1	0.0
Water	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Component Mass Flows						
Carbon Dioxide	lb/hr	0.0	0.0	0.0	0.0	170.8
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0	10764.3
Oxygen	lb/hr	6148.5	6148.5	6148.5	6148.5	0.0
Water	lb/hr	0.0	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	192.1	192.1	192.1	192.1	388.2
Mass Flows	lb/hr	6148.5	6148.5	6148.5	6148.5	10935.2
Volume Flow	cuft/hr	4954.4	2802.2	1084.5	591.6	496697.3
Temperature	F	563.2	122.0	550.8	122.7	1292.0
Pressure	psia	429.4	424.4	2005.0	2000.0	14.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	3523.8	230.5	3395.9	-40.2	-39744.5
Mass Enthalpy	Btu/lb	110.1	7.2	106.1	-1.3	-1410.9
Enthalpy Flow	Btu/hr	677084.6	44290.7	652514.0	-7728.2	-15427985.8
Molar Entropy	Btu/lbmol-R	-2.1	-6.2	-5.3	-9.7	29.9
Mass Entropy	Btu/lb-R	-0.1	-0.2	-0.2	-0.3	1.1
Molar Density	lbmol/cuft	0.0	0.1	0.2	0.3	0.0
Mass Density	lb/cuft	1.2	2.2	5.7	10.4	0.0

	Units	S-116	S-117	S-118	S-119	S-120
From		BL-102	HX-101	IC-104		PU-101
To		HX-101	IC-104		PU-101	SP-101
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Liquid	Liquid
Component Mole Flows						
Carbon Dioxide	lbmol/hr	3.9	3.9	3.9	0.0	0.0
Carbon Monoxide	lbmol/hr	384.3	384.3	384.3	0.0	0.0
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Water	lbmol/hr	0.0	0.0	0.0	2269.1	2269.1
Component Mass Flows						
Carbon Dioxide	lb/hr	170.8	170.8	170.8	0.0	0.0
Carbon Monoxide	lb/hr	10764.3	10764.3	10764.3	0.0	0.0
Oxygen	lb/hr	0.0	0.0	0.0	0.0	0.0
Water	lb/hr	0.0	0.0	0.0	40878.2	40878.2
Mole Flows	lbmol/hr	388.2	388.2	388.2	2269.1	2269.1
Mass Flows	lb/hr	10935.2	10935.2	10935.2	40878.2	40878.2
Volume Flow	cuft/hr	310184.9	108781.2	123004.5	659.9	659.9
Temperature	F	1750.4	185.0	121.9	80.0	80.0
Pressure	psia	29.7	24.7	19.7	14.7	19.7
Molar Vapor Fraction		1.0	1.0	1.0	0.0	0.0
Molar Liquid Fraction		0.0	0.0	0.0	1.0	1.0
Molar Enthalpy	Btu/lbmol	-36030.3	-47983.9	-48425.5	-124205.2	-124204.9
Mass Enthalpy	Btu/lb	-1279.0	-1703.3	-1719.0	-6894.4	-6894.4
Enthalpy Flow	Btu/hr	-13986220.3	-18626340.5	-18797756.0	-281832274.1	-281831510.9
Molar Entropy	Btu/lbmol-R	30.4	21.5	21.2	-40.8	-40.8
Mass Entropy	Btu/lb-R	1.1	0.8	0.8	-2.3	-2.3
Molar Density	lbmol/cuft	0.0	0.0	0.0	3.4	3.4
Mass Density	lb/cuft	0.0	0.1	0.1	62.0	62.0

	Units	S-121	S-122	S-123	S-124
From		SP-101	PU-102	HX-103	TU-101
To		PU-102	HX-103	TU-101	
MIXED Substream					
Phase		Liquid	Liquid	Liquid	Liquid
Component Mole Flows					
Carbon Dioxide	lbmol/hr	0.0	0.0	0.0	0.0
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0
Water	lbmol/hr	63.5	63.5	63.5	63.5
Component Mass Flows					
Carbon Dioxide	lb/hr	0.0	0.0	0.0	0.0
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0
Oxygen	lb/hr	0.0	0.0	0.0	0.0
Water	lb/hr	1143.8	1143.8	1143.8	1143.8
Mole Flows	lbmol/hr	63.5	63.5	63.5	63.5
Mass Flows	lb/hr	1143.8	1143.8	1143.8	1143.8
Volume Flow	cuft/hr	18.5	18.5	2407.0	55081.6
Temperature	F	80.0	80.3	1482.1	730.1
Pressure	psia	19.7	547.4	547.4	14.7
Molar Vapor Fraction		0.0	0.0	1.0	1.0
Molar Liquid Fraction		1.0	1.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-124204.9	-124169.4	-91531.6	-98499.6
Mass Enthalpy	Btu/lb	-6894.4	-6892.4	-5080.8	-5467.6
Enthalpy Flow	Btu/hr	-7886156.3	-7883902.4	-5811625.6	-6254048.6
Molar Entropy	Btu/lbmol -R	-40.8	-40.8	-6.6	-4.0
Mass Entropy	Btu/lb-R	-2.3	-2.3	-0.4	-0.2
Molar Density	lbmol/cuft	3.4	3.4	0.0	0.0
Mass Density	lb/cuft	62.0	61.9	0.5	0.0

	Units	S-125	S-126	S-127	S-128	S-129
From			BL-104	HX-105		BL-105
To		BL-104	HX-105	FC-102	BL-105	HX-104
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flows						
Carbon Monoxide	lbmol/hr	384.3	384.3	384.3	0.0	0.0
Carbon Dioxide	lbmol/hr	3.9	3.9	3.9	0.0	0.0
Oxygen	lbmol/hr	0.0	0.0	0.0	192.9	192.9
Nitrogen	lbmol/hr	0.0	0.0	0.0	725.7	725.7
Component Mass Flows						
Carbon Monoxide	lb/hr	10764.3	10764.3	10764.3	0.0	0.0
Carbon Dioxide	lb/hr	170.8	170.8	170.8	0.0	0.0
Oxygen	lb/hr	0.0	0.0	0.0	6172.7	6172.7
Nitrogen	lb/hr	0.0	0.0	0.0	20329.1	20329.1
Mole Flows	lbmol/hr	388.2	388.2	388.2	918.6	918.6
Mass Flows	lb/hr	10935.2	10935.2	10935.2	26501.8	26501.8
Volume Flow	cuft/hr	164901.1	137889.2	496697.3	359937.7	261662.8
Temperature	F	122.0	192.0	1292.0	77.0	195.6
Pressure	psia	14.7	19.7	14.7	14.7	24.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-48424.2	-47934.1	-39744.5	-2.9	825.2
Mass Enthalpy	Btu/lb	-1719.0	-1701.6	-1410.9	-0.1	28.6
Enthalpy Flow	Btu/hr	-18797238.5	-18607019.1	-15427985.8	-2647.7	758040.0
Molar Entropy	Btu/lbmol-R	21.8	22.0	29.9	1.0	1.4
Mass Entropy	Btu/lb-R	0.8	0.8	1.1	0.0	0.0
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.1	0.1	0.0	0.1	0.1

	Units	S-130	S-131	S-132	S-133	S-134
From		HX-104	HX-106	FC-102	BL-106	HX-106
To		HX-106	FC-102	BL-106	HX-106	
MIXED Substream						
Phase		Vapor	Vapor	Vapor	Vapor	Vapor
Component Mole Flows						
Carbon Monoxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Carbon Dioxide	lbmol/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lbmol/hr	192.9	192.9	2.7	2.7	2.7
Nitrogen	lbmol/hr	725.7	725.7	725.7	725.7	725.7
Component Mass Flows						
Carbon Monoxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Carbon Dioxide	lb/hr	0.0	0.0	0.0	0.0	0.0
Oxygen	lb/hr	6172.7	6172.7	85.7	85.7	85.7
Nitrogen	lb/hr	20329.1	20329.1	20329.1	20329.1	20329.1
Mole Flows	lbmol/hr	918.6	918.6	728.4	728.4	728.4
Mass Flows	lb/hr	26501.8	26501.8	20414.7	20414.7	20414.7
Volume Flow	cuft/hr	530977.2	1175207.3	931979.2	759606.3	573883.0
Temperature	F	600.6	1291.8	1292.0	1492.5	618.8
Pressure	psia	19.7	14.7	14.7	20.1	14.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	3711.5	8955.7	8853.4	10427.7	3813.8
Mass Enthalpy	Btu/lb	128.6	310.4	315.9	372.0	136.1
Enthalpy Flow	Btu/hr	3409377.0	8226653.4	6448482.0	7595152.9	2777876.5
Molar Entropy	Btu/lbmol-R	5.3	9.6	8.6	8.8	5.0
Mass Entropy	Btu/lb-R	0.2	0.3	0.3	0.3	0.2
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.0	0.0	0.0	0.0	0.0

	Units	S-135	S-136	S-137	S-138
From		FC-102	BL-107	HX-105	HX-104
To		BL-107	HX-105	HX-104	
MIXED Substream					
Phase		Vapor	Vapor	Vapor	Vapor
Component Mole Flows					
Carbon Monoxide	lbmol/hr	3.8	3.8	3.8	3.8
Carbon Dioxide	lbmol/hr	384.3	384.3	384.3	384.3
Oxygen	lbmol/hr	0.0	0.0	0.0	0.0
Nitrogen	lbmol/hr	0.0	0.0	0.0	0.0
Component Mass Flows					
Carbon Monoxide	lb/hr	107.6	107.6	107.6	107.6
Carbon Dioxide	lb/hr	16914.5	16914.5	16914.5	16914.5
Oxygen	lb/hr	0.0	0.0	0.0	0.0
Nitrogen	lb/hr	0.0	0.0	0.0	0.0
Mole Flows	lbmol/hr	388.2	388.2	388.2	388.2
Mass Flows	lb/hr	17022.2	17022.2	17022.2	17022.2
Volume Flow	cuft/hr	496679.6	329580.2	275085.2	190481.1
Temperature	F	1292.0	1493.2	840.6	213.8
Pressure	psia	14.7	24.7	19.7	14.7
Molar Vapor Fraction		1.0	1.0	1.0	1.0
Molar Liquid Fraction		0.0	0.0	0.0	0.0
Molar Enthalpy	Btu/lbmol	-154305.4	-151693.5	-159883.2	-166713.4
Mass Enthalpy	Btu/lb	-3518.8	-3459.3	-3646.0	-3801.8
Enthalpy Flow	Btu/hr	-59898098.1	-58884239.4	-62063272.7	-64714609.6
Molar Entropy	Btu/lbmol-R	13.9	14.2	9.6	3.1
Mass Entropy	Btu/lb-R	0.3	0.3	0.2	0.1
Molar Density	lbmol/cuft	0.0	0.0	0.0	0.0
Mass Density	lb/cuft	0.0	0.1	0.1	0.1

5.2 Energy Balances and Utilities

Table 5.2.1: Utilities Summary for Low Pressure Storage Mode

Equipment	Unit No.	Flow Rate (lb/hr)	Annual Flowrate (lb)	Price ($/lb)	Annual Cost ($)
Intercooler 1	IC-101	11,509.96	45,600,000	1.20E-05	$550
Intercooler 2	IC-102	12,196.26	48,300,000	1.20E-05	$580
Intercooler 3	IC-103	12,725.29	50,400,000	1.20E-05	$600
Intercooler 4	IC-104	3,302.86	13,100,000	1.20E-05	$160
Heat Exchanger 3	HX-103	1,143.85	4,530,000	1.20E-05	$60
Total Cooling Water			161,000,000		$1,950

Equipment	Unit No.	Power (kW)	Annual Consumption (kWh)	Price ($/kWh)	Annual Cost ($)
Blower 1	BL-101	115.19	456,000	$0.03	$12,800
Blower 2	BL-102	528.18	2,090,000	$0.03	$58,900
Blower 3	BL-103	260.47	1,030,000	$0.03	$29,000
Compressor 1	CM-101	217.41	861,000	$0.03	$24,200
Compressor 2	CM-102	227.41	900,000	$0.03	$25,300
Compressor 3	CM-103	222.82	882,000	$0.03	$24,800
Pump 1	PU-101	0.22	890	$0.03	$25
Pump 2	PU-102	0.66	2,600	$0.03	$80
Turbine 1	TU-101	(103.73)	(411,000)	$0.03	$(11,600)
Electrolytic Cell	FC-101	32,010.33	127,000,000	$0.03	$3,570,000
Total Electricity			133,000,000		$3,730,000

As with the high-pressure case, the main consumer of power in the low-pressure case is the electrolytic cell, with its power demand being two orders of magnitude more than any of the other units. Outside of that, air movers and compressors constitute the bulk of the demand once again. The turbine implemented in the cogeneration unit recovers a portion of the energy spent heating the process streams. The cooling water provided to the process is used for the intercoolers in the multistage compressor systems and as the working fluid in the cogeneration unit. The total annual electricity cost is $3,730,000 and the total annual cooling water cost is $1,950

Table 5.2.2: Utilities Summary for Low Pressure Production Mode

Equipment	Unit No.	Power (kW)	Annual Consumption (kWh)	Price ($/kWh)	Annual Cost ($)
Blower 4	BL-104	69.68	275,000	$0.03	$7,700
Blower 5	BL-105	278.67	1,103,000	$0.03	$31,000
Blower 6	BL-106	420.07	1,660,000	$0.03	$46,800
Blower 7	BL-107	371.42	1,470,000	$0.03	$41,400
Total Electricity			4,510,000		$127,000

The only utility needed for the low-pressure production mode is electricity to power the air movers. The total annual electricity cost is $127,000.

5.3 Process Description

Low Pressure Storage

This section discusses the energy storage mode of the low-pressure carbon monoxide storage case, which operates for 12 hours a day during off-peak hours. 17083.7 lb/hr of pure carbon dioxide (S-101) is passed through a blower (BL-101) to increase its pressure from 14.7 psia to 24.7 psia. This is done in order to counteract the pressure drops (estimated to be 5 psi per unit) across the process units that follow. The pressurized carbon dioxide (S-102) enters a heat exchanger (HX-101) where it is heated from 166 F to 1216 F, and then into a second heat exchanger (HX-102) where it is brought to the final electrolytic cell operating temperature of 1292 F, losing 10 psi across the two units. The final stream (S-104) enters the solid oxide electrolytic cell (FC-101) at 1292 F and 14.7 psia.

The fuel cell converts the carbon dioxide into a nearly pure carbon monoxide stream and an oxygen stream. They are physically separated by the cell's configuration so there is no need for additional separation units or processes. The two streams are recycled for use in heating the carbon dioxide stream in HX-101 and HX-102, respectively.

The carbon monoxide stream (S-115) flows at 10935.2 lb/hr, containing 99% carbon monoxide and 1% carbon dioxide. It is flowed through a blower (BL-102) to counteract the pressure losses across the following equipment. With the pressure increased to 29.7 psia and a temperature of 1750 F (S-116), the stream enters HX-101 and is cooled by the countercurrent carbon dioxide stream, exiting the heat exchanger at 185 F (S-117). The carbon monoxide stream is further cooled with Intercooler 4 (IC-104) to a final temperature of 122 F and a pressure of 19.7 psia (S-118) for storage in the floating head tank (ST-101).

Running in parallel, 6148.5 lb/hr of pure oxygen (S-105) is flowed through a blower (BL-103) to counteract the pressure losses across the following equipment. With the pressure increased to 29.7 psia and a temperature of 1731 F (S-106), the stream enters HX-102 and is cooled by the countercurrent carbon dioxide stream, exiting the heat exchanger at 1500 F (S-107).

The oxygen stream is then used as part of a cogeneration process. The hot oxygen stream flowed through a heat exchanger (HX-103) with pressurized water as the countercurrent stream. Leaving the cogeneration heat exchanger, the stream reaches 122 F (S-108). From there, the oxygen must be compressed to 2000 psia in order to be sold. A multistage compressor system is incorporated to facilitate this process, with three compressors (CM-101, CM-102 and CM-103) and three intercoolers (IC-101, IC-102, and IC-103). This was implemented in order to maximize the efficiency of the compression, as well as to keep the stream temperature within operable bounds. Each intercooler returns the oxygen stream to 122 F. The final product oxygen stream (S-114) is at 122 F and 2000 psia, the standard conditions needed to sell the product.

Finally, a stream of cooling water (S-119) at 40878.2 lb/hr, 80 F and 14.7 psia is used for the intercoolers and the cogeneration process. It is passed through a pump (PU-101), bringing it to 19.7 psia for use in the following processes. The master stream is then passed through a splitter which provides the required amounts of cooling water to each other unit processes. The intercooler streams are unnamed and unacknowledged in the process flow diagram and stream reports for the sake of simplicity and ease of following, but flowrates can be found in the Energy Balance and Utilities section. The stream going to the cogeneration process (S-121) flows at 1143.8 lb/hr and enters an additional pump (PU-102) that increases the pressure to 547.4

psia. The stream then enters HX-103 and is heated by the oxygen stream. The water stream is evaporated into steam, exiting the heat exchanger with a vapor fraction of 1 and a temperature of 1482 F (S-123). Finally, the vapor stream is flowed through a turbine (TU-101) and expanded in order to recover the energy put into the process.

Low Pressure Production

This section discusses the energy production mode of the low-pressure carbon monoxide storage case, which operates for 12 hours a day during on-peak hours. 10935.2 lb/hr of 99% carbon monoxide and 1% carbon dioxide (S-125) from the storage tank is passed through a blower (BL-104) to increase its pressure to 19.7 psia. This is done in order to counteract the pressure drops (estimated to be 5 psi per unit) across the process units that follow. The pressurized carbon monoxide (S-122) enters a heat exchanger (HX-105) where it is heated from 192 F to 1292 F (S-127) and then enters the fuel cell.

Running in parallel, a stream of air pulled from the atmosphere flows at 26501.8 lb/hr, at atmospheric conditions of 77 F and 14.7 psia (S-128). It is flowed through a blower (BL-105) to increase the pressure in order to counteract the pressure drops across the following process units. BL-105 increases the stream pressure to 24.7 psia; the air stream then passes through two heat exchangers in series (HX-104 and HX-106), bringing the temperature to 601 F and 1292 F, respectively. The stream, at operating conditions of 1292 F and 14.7 psia (S-131) then enters the fuel cell.

The fuel cell converts the carbon monoxide and the oxygen from the air stream into carbon dioxide, releasing energy in the process. The nitrogen in the air is an inert and does not react. It produces two streams: one that is predominantly carbon dioxide with a small percentage of unreacted carbon monoxide flowing at 17022.2 lb/hr (S-135), and another that is predominantly nitrogen with a small percentage of unreacted oxygen flowing at 26501.8 lb/hr (S-132), both at 1292 F and 14.7 psia.

The nitrogen recycle stream is passed through a blower (BL-106) to reach a pressure of 19.7 psia and a temperature of 1492 F (S-133), then used in HX-106 to heat the air stream before being expelled to the atmosphere.

The carbon recycle dioxide stream is passed through a blower (BL-107) to reach a pressure of 24.7 psia and a temperature of 1493 F (S-133), then used in HX-105 and HX-104 to heat the carbon monoxide and air streams before being expelled to the atmosphere.

5.4 Unit Descriptions

Table 5.4.1: Low Pressure Storage Mode Equipment List

Unit No.	Unit Type	Function	Size	Material	Oper. T (F)	Oper. P (psia)
BL-101	Blower	Increase pressure of inlet carbon dioxide	Pc = 154.471 HP	Cast Iron	165.8	24.7
BL-102	Blower	Increase pressure of carbon monoxide stream	Pc = 708.294 HP	Cast Iron	1750.4	29.7
BL-103	Blower	Increase pressure of oxygen stream	Pc = 349.299 HP	Cast Iron	1731.2	29.7
CM-101	Compressor	Increase pressure of oxygen stream	Pc = 291.555 HP	Carbon Steel	1750.4	29.7
CM-102	Compressor	Increase pressure of oxygen stream	Pc = 304.961 HP	Carbon Steel	563.2	429.4
CM-103	Compressor	Bring oxygen stream to storage pres. conditions	Pc = 298.801 HP	Carbon Steel	550.8	2005.0
FC-101	Fuel Cell	Convert carbon dioxide into carbon monoxide and oxygen		LSM-YSZ|YSZ|Ni-YSZ	1292.0	14.7
HX-101	Heat Exchanger	Heat carbon monoxide stream while cooling carbon dioxide stream	A = 200.05 sqft, Q = 4640120 Btu/hr	Carbon Steel/Carbon Steel	1216.2	19.7
HX-102	Heat Exchanger	Heat carbon dioxide stream while cooling oxygen stream	A = 7.0677 sqft, Q = 376588 Btu/hr	Carbon Steel/Carbon Steel	1292.0	14.7
HX-103	Heat Exchanger	Cool oxygen stream while producing steam for cogeneration	A = 141.323 sqft, Q = 2072276 Btu/hr	Carbon Steel/Carbon Steel	1482.1	547.4
IC-101	Intercooler	Cool oxygen stream between compression stages	A = 24.407 sqft, Q = 597185. Btu/hr	Carbon Steel/Carbon Steel	121.3	87.0
IC-102	Intercooler	Cool oxygen stream between compression stages	A = 25.022 sqft, Q = 632793 Btu/hr	Carbon Steel/Carbon Steel	122.0	424.4

IC-103	Intercooler	Cool oxygen stream to storage temp. conditions	A = 26.4719 sqft, Q = 660242 Btu/hr	Carbon Steel/Carbon Steel	122.7	2000.0
IC-104	Intercooler	Cool carbon monoxide stream to storage temp. conditions	A = 22.7094 sqft, Q = 171415Btu/hr	Carbon Steel/Carbon Steel	121.9	19.7
PU-101	Pump	Increase pressure of water for intercoolers and cogeneration	Pc = 0.29 HP	Cast Iron	80.0	19.7
PU-102	Pump	Increase pressure of water stream for cogeneration	Pc = 0.885 HP	Cast Iron	80.3	547.4
TU-101	Turbine	Recover energy from cogeneration process	Pc = -139.1 HP	Carbon Steel	730.1	14.7
ST-101	Storage Tank	Store carbon monoxide product stream			121.9	19.7

Table 5.4.2: Low Pressure Production Mode Equipment List

Unit No.	Unit Type	Function	Size	Material	Oper. T (F)	Oper. P (psia)
BL-104	Blower	Increase pressure of inlet carbon monoxide stream	Pc = 74.7 HP	Cast Iron	192.0	19.7
BL-105	Blower	Increase pressure of inlet air stream	Pc = 373 HP	Cast Iron	195.6	24.7
BL-106	Blower	Increase pressure of nitrogen waste stream	Pc = 563 HP	Cast Iron	1492.5	20.1
BL-107	Blower	Increase pressure of waste carbon dioxide stream	Pc = 498 HP	Cast Iron	1493.2	24.7
HX-104	Heat Exchanger	Heat carbon monoxide stream	A = 205.89 sqft, Q = 2651336 Btu/hr	Carbon Steel/Carbon Steel	600.6	19.7
HX-105	Heat Exchanger	Heat inlet air stream to fuel cell operating temp.	A = 55.55 sqft, Q = 3179033 Btu/hr	Carbon Steel/Carbon Steel	1292.0	14.7
HX-106	Heat Exchanger	Heat air stream to fuel cell operating temp.	A = 423.2 sqft, Q = 4817276 Btu/hr	Carbon Steel/Carbon Steel	1291.8	14.7
FC-102	Fuel Cell	Convert carbon monoxide and oxygen into carbon dioxide		LSM-YSZ|YSZ|Ni-YSZ	1292.0	14.7

Low Pressure Storage

Blower 1 (BL-101)

Blower 1 is a centrifugal blower constructed with cast iron. It increases the pressure of the inlet carbon dioxide stream in order to offset pressure losses across the process units. The outlet stream leaves at 24.7 psia and 165.8 F. The net work of the compressor is 154.5 HP, with a bare module cost of $203,444. Please refer to section 5.5 for the specification sheet.

Blower 2 (BL-102)

Blower 2 is a centrifugal blower constructed with cast iron. It increases the pressure of the carbon monoxide stream in order to offset pressure losses across the process units. The outlet stream leaves at 29.7 psia and 1750.4 F. The net work of the compressor is 708.3 HP, with a bare module cost of $677,523. Please refer to section 5.5 for the specification sheet.

Blower 3 (BL-103)

Blower 2 is a centrifugal blower constructed with cast iron. It increases the pressure of the oxygen stream in order to offset pressure losses across the process units. The outlet stream leaves at 29.7 psia and 1731.2 F. The net work of the compressor is 708.3 HP, with a bare module cost of $387,598. Please refer to section 5.5 for the specification sheet.

Compressor 1 (CM-101)

Compressor 1 is a screw compressor constructed with carbon steel. It is the first of three units in a multi-stage compressor to bring the oxygen stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 92.0 psia and 545.8 F. The net work of the compressor is 291.6 HP, with a bare module cost of $674,226. Please refer to section 5.5 for the specification sheet.

Compressor 2 (CM-102)

Compressor 2 is a reciprocating compressor constructed with carbon steel. It is the second of three units in a multi-stage compressor to bring the oxygen stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 2005.0 psia and 550.8 F. The net work of the compressor is 305.0 HP, with a bare module cost of $414,516. Please refer to section 5.5 for the specification sheet.

Compressor 3 (CM-103)

Compressor 3 is a reciprocating compressor constructed with carbon steel. It is the third of three units in a multi-stage compressor to bring the carbon dioxide stream to storage pressure conditions, designed to reduce losses from compression and maintain operable temperature conditions. The outlet stream leaves at 2000.0 psia and 597.3 F. The net work of the compressor is 298.8 HP, with a bare module cost of $404,241. Please refer to section 5.5 for the specification sheet.

Fuel Cell 1 (FC-101)

Fuel Cell 1 is the solid oxide electrolytic cell (SOEC) which reduces carbon dioxide to carbon monoxide and oxygen by using external electric supply. On the cathode side, carbon dioxide is being reduced to carbon monoxide and on the anode side, 99.9% pure molecular oxygen is being produced. The cell has a strontium-doped lanthanum manganite (LSM) composite anode, nickel and yttria-stabilized zirconia composite cathode and a yttria-stabilized zirconia electrolyte. The power consumption for this unit is 384.1 MWh. The SOEC is operated at 600℃ and 1 atm. The bare module cost of the unit is $6,207,642. Please refer to section 4.5 for the specification sheet.

Heat Exchanger 1 (HX-101)

This heat exchanger uses the excess heat of the carbon monoxide stream in order to raise the temperature of the carbon dioxide stream bound for the fuel cell. This is an example of efficient heat integration, as the carbon monoxide stream must be cooled on its way to the multistage compressor as well. The carbon dioxide stream exits the heat exchanger at 1216.2 F; the carbon monoxide stream exits the heat exchanger at 185.0 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $36,356. Please refer to the specification sheet in section 5.5.

Heat Exchanger 2 (HX-102)

This heat exchanger uses the excess heat of the oxygen stream in order to raise the temperature of the carbon dioxide stream bound for the fuel cell. This is an example of efficient heat integration, as the oxygen stream must be cooled on its way to the multistage compressor as well. The carbon dioxide stream exits the heat exchanger at 1292 F; the oxygen stream exits the heat exchanger at 1500.1 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $5,696. Please refer to section 5.5 for the specification sheet.

Heat Exchanger 3 (HX-103)

This heat exchanger uses the excess heat of the oxygen stream in order to produce high-pressure steam from cooling water in a process called cogeneration. The steam's energy can be recovered with a turbine, increasing the overall efficiency of the process. In the process, the oxygen is decreased in temperature to storage temperature conditions. The inlet water stream is fully converted to steam, and exits the heat exchanger at 1482.1 F; the carbon monoxide stream exits the heat exchanger at 122.1 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $34,370. Please refer to section 5.5 for the specification sheet.

Intercooler 1 (IC-101)

Intercooler 5 cools the oxygen stream in the multistage compressor, between CM-101 and CM-102, in order to minimize the work required in the process and keep the stream from heating in inoperable temperatures. The stream is cooled from 545.8 F to 121.3.0 F. For details on cooling water flowrates, please refer to the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $11,982. Please refer to section 5.5 for the specification sheet.

Intercooler 2 (IC-102)

Intercooler 2 cools the oxygen stream in the multistage compressor, between CM-102 and CM-103, in order to minimize the work required in the process and keep the stream from heating in inoperable temperatures. The stream is cooled from 563.2 F to 122.0 F. For details on cooling water flowrates, please refer to the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $12,163. Please refer to section 5.5 for the specification sheet.

Intercooler 3 (IC-103)

Intercooler 3 cools the oxygen stream after its final compression stage in the multistage compressor, bringing it to storage temperature conditions. The stream is cooled from 550.8 F to 122.7 F. For details on cooling water flowrates, please refer to the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $12,581. Please refer to section 5.5 for the specification sheet.

Intercooler 4 (IC-104)

Intercooler 4 cools the carbon monoxide stream to storage temperature conditions. The stream is cooled from 185.0 F to 121.9 F. For details on cooling water flowrates, please refer to the Energy Balance and Utilities section. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The intercooler is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $11,475. Please refer to section 5.5 for the specification sheet.

Pump 1 (PU-101)

Pump 1 is centrifugal water pump that pressurizes the cooling water used to regulate temperature throughout the process in the intercoolers and the water used in the cogeneration process. The stream is then flowed through a splitter to provide the required amounts of water to each component. The pump brings the stream pressure from 14.7 psia to 19.7 psia in order to offset the pressure losses across the intercoolers. The size and specifications of the unit as determined by ASPEN do not correspond to the correlations in *Product and Process Design Principles*, so a pricing approximation was used by comparing Pump 1 to a pump found online that can facilitate the required flowrate and operating pressure. Based on the cost of the Barmessa End-Suction Centrifugal Pump, the bare module cost was calculated to be $2,927. Please refer to section 5.5 for the specification sheet.

Pump 2 (PU-102)

Pump 2 is a water pump that pressurizes the cooling water used in the cogeneration process. The pump brings the stream pressure from 14.7 psia to 547.4 psia. This was determined to be the optimal pressure for maximum energy output in the turbine without having the stream produce liquid effluent after expansion. The size and specifications of the unit as determined by ASPEN do not correspond to the correlations in *Product and Process Design Principles*, so a pricing approximation was used by comparing Pump 2 to a pump found online that can facilitate the required flowrate and operating pressure. Based on the cost of the Aeromist Direct Drive Misting Pump, the bare module cost was calculated to be $5,261. Please refer to section 5.5 for the specification sheet.

Turbine 1 (TU-101)

The turbine is implemented as part of the cogeneration process; at this step, the pressurized and heated steam is expanded in order to recovery its energy. Because of the relatively small flowrate and energy to be recovered, only a single stage is needed for this process. The outlet stream exits at 429.7 F and 24.7 psia. The total work recovered by this unit is 994.1 HP. Each turbine is constructed with carbon steel; please refer to the specification sheet for details about the individual turbines.

Storage Tank 1 (ST-101)

The storage tank in the low-pressure process is designed to hold the carbon monoxide produced in the storage mode at slightly above 1 atmosphere pressure (5 psig). The total volume of the storage tank is 1.6E+5 m^3 or 42 M gal. The storage tank is a floating head tank designed to maintain pressure with a moveable roof.

Low Pressure Production

Blower 4 (BL-104)

Blower 4 is a centrifugal blower constructed with cast iron. It increases the pressure of carbon monoxide stream leaving the storage tank in order to offset pressure losses across the process units. The outlet stream leaves at 19.7 psia and 192.0 F. The net work of the compressor is 74.6 HP, with a bare module cost of $114,670. Please refer to section 5.5 for the specification sheet.

Blower 5 (BL-105)

Blower 5 is a centrifugal blower constructed with cast iron. It increases the pressure of the inlet air stream in order to offset pressure losses across the process units. The outlet stream leaves at 24.7 psia and 195.6 F. The net work of the compressor is 373.7 HP, with a bare module cost of $408,837. Please refer to section 5.5 for the specification sheet.

Blower 6 (BL-106)

Blower 6 is a centrifugal blower constructed with cast iron. It increases the pressure of the waste nitrogen stream in order to offset pressure losses across the process units so that its excess heat can be used in a recycle loop before discarding. The outlet stream leaves at 20.1 psia and 1492.5 F. The net work of the compressor is 563.3 HP, with a bare module cost of $565,398. Please refer to section 5.5 for the specification sheet.

Blower 7 (BL-107)

Blower 7 is a centrifugal blower constructed with cast iron. It increases the pressure of the waste carbon dioxide stream in order to offset pressure losses across the process units so that its excess heat can be used in a recycle loop before discarding. The outlet stream leaves at 24.7 psia and

1493.2 F. The net work of the compressor is 498.1 HP, with a bare module cost of $513,003. Please refer to section 5.5 for the specification sheet.

Heat Exchanger 4 (HX-104)

This heat exchanger uses the excess heat of the carbon dioxide stream in order to raise the temperature of the air stream bound for the fuel cell. This is an example of efficient heat integration, as the carbon dioxide stream was to be discarded from the process otherwise. The air stream exits the heat exchanger at 600.6 F; the carbon monoxide stream exits the heat exchanger at 213.8 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $36,729. Please refer to section 5.5 for the specification sheet.

Heat Exchanger 5 (HX-105)

This heat exchanger uses the excess heat of the carbon dioxide stream in order to raise the temperature of the carbon monoxide stream bound for the fuel cell. This is an example of efficient heat integration, as the carbon dioxide stream was to be discarded from the process otherwise. The carbon monoxide stream exits the heat exchanger at 1292 F; the carbon dioxide stream exits the heat exchanger at 840.6 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $19,629. Please refer to section 5.5 for the specification sheet.

Heat Exchanger 6 (HX-106)

This heat exchanger uses the excess heat of the waste nitrogen stream in order to raise the temperature of the air stream bound for the fuel cell. This is an example of efficient heat integration, as the nitrogen stream was to be discarded from the process otherwise. The air stream exits the heat exchanger at 1291.8 F; the carbon dioxide stream exits the heat exchanger at 618.8 F. The heat transfer surface area and heat transfer coefficient were calculated by ASPEN. The heat exchanger is modeled as a carbon steel shell and tube heat exchanger, with a bare module cost of $42,389. Please refer to section 5.5 for the specification sheet.

Fuel Cell 2 (FC-102)

Fuel Cell 2 is the solid oxide fuel cell (SOFC) which generates electricity by converting carbon monoxide to carbon dioxide. On the cathode side, molecular oxygen from air is reduced to oxide ions and on the anode side, carbon monoxide is oxidized to carbon dioxide. The cell has a strontium-doped lanthanum manganite (LSM) composite anode, nickel and yttria-stabilized zirconia composite cathode and a yttria-stabilized zirconia electrolyte. The power production for this unit is 226.6 MWh. The SOFC is operated at 600°C and 1 atm. The bare module cost of the unit is $6,207,642. Please refer to section 4.5 for the specification sheet.

5.5 Specification Sheets

Specification sheets for equipment listed in this process design are reported in this section.

Blower 1

Identification				
	Item	Blower 1	Date	4/12/20
	Item No.	BL-101	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of inlet carbon dioxide			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-101	S-102	
	Quantity (lb/hr)	17,083.7	17,083.7	
	Composition			
	Carbon Dioxide	17,083.7	17,083.7	
	Carbon Monoxide	-	-	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	77.0	165.8	
	Pressure (psi)	14.7	24.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Carbon Steel		
	Net Work (HP)	154.471		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	63,378.21		
	CBM $	203,444.05		

Blower 2

Identification				
	Item	Blower 2	Date	4/12/20
	Item No.	BL-102	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of carbon monoxide stream			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-115	S-116	
	Quantity (lb/hr)	10,935.2	10,935.2	
	Composition			
	Carbon Dioxide	170.8	170.8	
	Carbon Monoxide	10,764.3	10,764.3	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	1,292.0	1,750.4	
	Pressure (psi)	14.7	29.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Carbon Steel		
	Net Work (HP)	708.294		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	211,066.63		
	CBM $	677,523.90		

Blower 3

Identification				
	Item	Blower 3	Date	4/12/20
	Item No.	BL-103	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of oxygen stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-105	S-106	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	1,292.0	1,731.2	
	Pressure (psi)	14.7	29.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Carbon Steel		
	Net Work (HP)	349.299		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	120,747.12		
	CBM $	387,598.25		

Compressor 1

Identification				
	Item	Compressor 1	Date	4/12/20
	Item No.	CM-101	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of oxygen stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-108	S-109	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	122.1	545.8	
	Pressure (psi)	19.7	92.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Screw Compressor		
	Material	Carbon Steel		
	Net Work (HP)	291.555		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	210,039.39		
	CBM $	674,226.46		

Compressor 2

Identification				
	Item	Compressor 2	Date	4/12/20
	Item No.	CM-102	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of oxygen stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-110	S-111	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	121.3	563.2	
	Pressure (psi)	87.0	429.4	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Reciprocating Compressor		
	Material	Carbon Steel		
	Net Work (HP)	304.961		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	129,132.79		
	CBM $	414,516.26		

Compressor 3

Identification				
	Item	Compressor 3	Date	4/12/20
	Item No.	CM-103	By	JD/MUC/VB
	No. Required	1		
Function	Bring oxygen stream to storage pres. conditions			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-112	S-113	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	122.0	550.8	
	Pressure (psi)	424.4	2,005.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Reciprocating Compressor		
	Material	Carbon Steel		
	Net Work (HP)	298.801		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$ 125,931.96		
	CBM	$ 404,241.59		

Fuel Cell 1

Identification

Item	Fuel Cell 1	Date	4/12/20
Item No.	FC-101	By	JD/MUC/VB
No. Required	1		

Function Convert carbon dioxide into carbon monoxide and oxygen

Operation 12 hours, daily

Materials Handled	**Inlet**	**Outlet 1**	**Outlet 2**
Stream ID	S-104	S-105	S-115
Quantity (lb/hr)	17,083.7	6,148.5	10,935.2
Composition			
Carbon Dioxide	17,083.7	-	170.8
Carbon Monoxide	-	-	10,764.3
Oxygen	-	6,148.5	-
Water	-	-	-
Temperature (F)	1,292.0	1,292.0	1,292.0
Pressure (psi)	14.7	14.7	14.7
Vapor Fraction	1.0	1.0	1.0

Design Data

Material	LSM-YSZ|YSZ|Ni-YSZ
Electricity Consumed (kW)	32010.33
Operating T (F)	1292.0
Operating P (psi)	14.7

CP	$	3,103,821.00
CBM	$	6,207,642.00

Heat Exchanger 1

Identification

	Item	Heat Exchanger 1	Date	4/12/20
	Item No.	HX-101	By	JD/MUC/VB
	No. Required	1		

Function Heat carbon monoxide stream while cooling carbon dioxide stream

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID		S-116	S-117	S-102	S-103
	Quantity (lb/hr)	10,935.2	10,935.2	17,083.7	17,083.7
	Composition			-	-
	Carbon Dioxide	170.8	170.8	17,083.7	17,083.7
	Carbon Monoxide	10,764.3	10,764.3	-	-
	Oxygen	-	-	-	-
	Water	-	-	-	-
	Temperature (F)	1,750.4	185.0	165.8	1,216.2
	Pressure (psi)	29.7	24.7	24.7	19.7
	Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

	Type	Shell and Tube
	Material	Carbon Steel/Carbon Steel
	Heat Transfer (Btu/lb)	4640120.2
	Heat Transfer Coefficient (Btu/hr-ft2-F)	149.7
	Heat Transfer Area (ft2)	200.1

CP	$	11,545.02
CBM	$	36,597.71

Heat Exchanger 2

Identification

Item	Heat Exchanger 2	Date	4/12/20
Item No.	HX-102	By	JD/MUC/VB
No. Required	1		

Function Heat carbon dioxide stream while cooling oxygen stream

Operation 12 hours, daily

Materials Handled	**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID	S-106	S-107	S-103	S-104
Quantity (lb/hr)	6,148.5	6,148.5	17,083.7	17,083.7
Composition			-	-
Carbon Dioxide	-	-	17,083.7	17,083.7
Carbon Monoxide	-	-	-	-
Oxygen	6,148.5	6,148.5	-	-
Water	-	-	-	-
Temperature (F)	1,731.2	1,500.1	1,216.2	1,292.0
Pressure (psi)	29.7	24.7	19.7	14.7
Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	376589.0
Heat Transfer Coefficient (Btu/hr-ft2-F)	149.7
Heat Transfer Area (ft2)	7.1

CP	$	1,797.06
CBM	$	5,696.68

Heat Exchanger 3

Identification

Item	Heat Exchanger 3	Date	4/12/20
Item No.	HX-103	By	JD/MUC/VB
No. Required	1		

Function Cool oxygen stream while producing steam for cogeneration

Operation 12 hours, daily

Materials Handled	**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID	S-107	S-108A	S-122	S-123
Quantity (lb/hr)	6,148.5	6,148.5	1,143.8	1,143.8
Composition			-	-
Carbon Dioxide	-	-	-	-
Carbon Monoxide	-	-	-	-
Oxygen	6,148.5	6,148.5	-	-
Water	-	-	1,143.8	1,143.8
Temperature (F)	1,500.1	122.1	80.3	1,482.1
Pressure (psi)	24.7	19.7	547.4	547.4
Vapor Fraction	1.0	1.0	-	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	2072276.8
Heat Transfer Coefficient (Btu/hr-ft2-F)	149.7
Heat Transfer Area (ft2)	141.3

CP	$	34,371.89
CBM	$	108,958.90

Intercooler 1

Identification				
	Item	Intercooler 1	Date	4/12/20
	Item No.	IC-101	By	JD/MUC/VB
	No. Required	1		
Function	Cool oxygen stream between compression stages			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-109	S-110	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	545.8	121.3	
	Pressure (psi)	92.0	87.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		597185.3	
	Heat Transfer Coefficient (Btu/hr-ft2-F)		149.7	
	Heat Transfer Area (ft2)		24.4	
	Cold Utility	Cooling Water		
	CP $	3,780.11		
	CBM $	11,982.94		

Intercooler 2

Identification				
	Item	Intercooler 2	Date	4/12/20
	Item No.	IC-102	By	JD/MUC/VB
	No. Required	1		
Function	Cool oxygen stream between compression stages			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-111	S-112	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	563.2	122.0	
	Pressure (psi)	429.4	424.4	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		632793.9	
	Heat Transfer Coefficient (Btu/hr-ft2-F)		149.7	
	Heat Transfer Area (ft2)		25.0	
	Cold Utility	Cooling Water		
	CP $	3,837.04		
	CBM $	12,163.41		

Intercooler 3

Identification				
	Item	Intercooler 3	Date	4/12/20
	Item No.	IC-103	By	JD/MUC/VB
	No. Required	1		
Function	Cool oxygen stream to storage temp. conditions			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-113	S-114	
	Quantity (lb/hr)	6,148.5	6,148.5	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	6,148.5	6,148.5	
	Water	-	-	
	Temperature (F)	550.8	122.7	
	Pressure (psi)	2,005.0	2,000.0	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type		Shell and Tube	
	Material		Carbon Steel/Carbon Steel	
	Heat Transfer (Btu/lb)		660242.2	
	Heat Transfer Coefficient (Btu/hr-ft2-F)		149.7	
	Heat Transfer Area (ft2)		26.5	
	Cold Utility	Cooling Water		
	CP	$	3,968.87	
	CBM	$	12,581.31	

Intercooler 4

Identification

Item	Intercooler 4	Date	4/12/20
Item No.	IC-104	By	JD/MUC/VB
No. Required	1		

Function	Cool carbon monoxide stream to storage temp. conditions
Operation	12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		S-117	S-118
	Quantity (lb/hr)	10,935.2	10,935.2
	Composition		
	Carbon Dioxide	170.8	170.84
	Carbon Monoxide	10,764.3	########
	Oxygen	-	-
	Water	-	-
	Temperature (F)	185.0	121.9
	Pressure (psi)	24.7	19.7
	Vapor Fraction	1.0	1.0

Design Data		
	Type	Shell and Tube
	Material	Carbon Steel/Carbon Steel
	Heat Transfer (Btu/lb)	171415.4
	Heat Transfer Coefficient (Btu/hr-ft2-F)	149.7
	Heat Transfer Area (ft2)	22.7
	Cold Utility	Cooling Water

CP	$	3,620.09
CBM	$	11,475.68

Pump 1

Identification				
	Item	Pump 1	Date	4/12/20
	Item No.	PU-101	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of water for intercoolers and cogeneration			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-119	S-120	
	Quantity (lb/hr)	40,878.2	40,878.2	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	-	-	
	Water	40,878.2	40,878.2	
	Temperature (F)	80.0	80.0	
	Pressure (psi)	14.7	19.7	
	Vapor Fraction	-	-	
Design Data				
	Type	Barmessa End-Suction Centrifugal Pump		
	Material	Cast Iron		
	Net Work (HP)	0.29993		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$ 912.00		
	CBM	$ 2,927.52		

Pump 2

Identification

Item	Pump 2	Date	4/12/20
Item No.	PU-102	By	JD/MUC/VB
No. Required	1		

Function	Increase pressure of water stream for cogeneration
Operation	12 hours, daily

Materials Handled		**Inlet**	**Outlet**
Stream ID		S-121	S-122
	Quantity (lb/hr)	1,143.8	1,143.8
	Composition		
	Carbon Dioxide	-	-
	Carbon Monoxide	-	-
	Oxygen	-	-
	Water	1,143.8	1,143.8
	Temperature (F)	80.0	80.3
	Pressure (psi)	19.7	547.4
	Vapor Fraction	-	-

Design Data

Type	Aeromist Direct Drive Misting Pump
Material	Cast Iron
Net Work (HP)	0.88581
Isentropic Efficiency	0.72
Mechanical Efficiency	0.8

CP	$	1,639.02
CBM	$	5,261.25

Turbine 1

Identification				
	Item	Turbine 1	Date	4/12/20
	Item No.	TU-101	By	JD/MUC/VB
	No. Required	1		
Function		Recover energy from cogeneration process		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-123	S-124	
	Quantity (lb/hr)	1,143.8	1,143.8	
	Composition			
	Carbon Dioxide	-	-	
	Carbon Monoxide	-	-	
	Oxygen	-	-	
	Water	1,143.8	1,143.8	
	Temperature (F)	1,482.1	730.1	
	Pressure (psi)	547.4	14.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Gas Expansion Turbine		
	Material	Carbon Steel		
	Net Work (HP)	-139.103		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	32,677.88		
	CBM $	81,694.69		

Storage Tank 1

Identification				
	Item	Storage Tank 1	Date	4/12/20
	Item No.	ST-101	By	JD/MUC/VB
	No. Required	1		
Function		Store carbon monoxide product stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-118	S-125	
	Quantity (lb/hr)	10,935.2	10,935.2	
	Composition			
	Carbon Dioxide	170.8	10,764.3	
	Carbon Monoxide	10,764.3	170.8	
	Oxygen	-	-	
	Water	-	-	
	Temperature (F)	121.9	122.0	
	Pressure (psi)	19.7	14.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Floating Head		
	Material	Carbon Steel		
	Gas Volume (gal)	42000000.0		
	CP	$	14,700,000.00	
	CBM	$	36,750,000.00	

Blower 4

Identification				
	Item	Blower 4	Date	4/12/20
	Item No.	BL-104	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of inlet carbon monoxide stream			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-125	S-126	
	Quantity (lb/hr)	10,935.2	10,935.2	
	Composition			
	Carbon Monoxide	10,764.3	10,764.3	
	Carbon Dioxide	170.8	170.8	
	Oxygen	-	-	
	Nitrogen	-	-	
	Temperature (F)	122.0	192.0	
	Pressure (psi)	14.7	19.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	74.759		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$	35,722.76	
	CBM	$	114,670.06	

Blower 5

Identification				
	Item	Blower 5	Date	4/12/20
	Item No.	BL-105	By	JD/MUC/VB
	No. Required	1		
Function		Increase pressure of inlet air stream		
Operation		12 hours, daily		
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-128	S-129	
	Quantity (lb/hr)	26,501.8	26,501.8	
	Composition			
	Carbon Monoxide	-	-	
	Carbon Dioxide	-	-	
	Oxygen	6,172.7	6,172.7	
	Nitrogen	20,329.1	20,329.1	
	Temperature (F)	77.0	195.6	
	Pressure (psi)	14.7	24.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	373.702		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP	$	127,363.78	
	CBM	$	408,837.75	

Blower 6

Identification				
	Item	Blower 6	Date	4/12/20
	Item No.	BL-106	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of nitrogen waste stream			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-132	S-133	
	Quantity (lb/hr)	20,414.7	20,414.7	
	Composition			
	Carbon Monoxide	-	-	
	Carbon Dioxide	-	-	
	Oxygen	85.7	85.7	
	Nitrogen	20,329.1	20,329.1	
	Temperature (F)	1,292.0	1,492.5	
	Pressure (psi)	14.7	20.1	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	563.323		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	176,136.47		
	CBM $	565,398.06		

Blower 7

Identification				
	Item	Blower 7	Date	4/12/20
	Item No.	BL-107	By	JD/MUC/VB
	No. Required	1		
Function	Increase pressure of waste carbon dioxide stream			
Operation	12 hours, daily			
Materials Handled		**Inlet**	**Outlet**	
Stream ID		S-135	S-136	
	Quantity (lb/hr)	17,022.2	17,022.2	
	Composition			
	Carbon Monoxide	107.6	107.6	
	Carbon Dioxide	16,914.5	16,914.5	
	Oxygen	-	-	
	Nitrogen	-	-	
	Temperature (F)	1,292.0	1,493.2	
	Pressure (psi)	14.7	24.7	
	Vapor Fraction	1.0	1.0	
Design Data				
	Type	Centrifugal Blower		
	Material	Cast Iron		
	Net Work (HP)	498.077		
	Isentropic Efficiency	0.72		
	Mechanical Efficiency	0.8		
	CP $	159,814.10		
	CBM $	513,003.26		

Heat Exchanger 4

Identification

Item	Heat Exchanger 4	Date	4/12/20
Item No.	HX-104	By	JD/MUC/VB
No. Required	1		

Function	Heat carbon monoxide stream
Operation	12 hours, daily

Materials Handled		**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID		S-137	S-138	S-129	S-130
	Quantity (lb/hr)	17,022.2	17,022.2	26,501.8	26,501.8
	Composition			-	-
	Carbon Monoxide	107.6	107.6	-	-
	Carbon Dioxide	16,914.5	16,914.5	-	-
	Oxygen	-	-	6,172.7	6,172.7
	Nitrogen	-	-	20,329.1	20,329.1
	Temperature (F)	840.6	213.8	195.6	600.6
	Pressure (psi)	19.7	14.7	24.7	19.7
	Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	2651337.0
Heat Transfer Coefficient (Btu/hr-sqft-F)	149.7
Heat Transfer Area (sqft)	205.9

CP	$	11,586.70
CBM	$	36,729.83

Heat Exchanger 5

Identification

Item	Heat Exchanger 5	Date	4/12/20
Item No.	HX-105	By	JD/MUC/VB
No. Required	1		

Function Heat inlet air stream to fuel cell operating temp.

Operation 12 hours, daily

Materials Handled		**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID		S-136	S-137	S-126	S-127
	Quantity (lb/hr)	17,022.2	17,022.2	10,935.2	10,935.2
	Composition			-	-
	Carbon Monoxide	107.6	107.6	10,764.3	10,764.3
	Carbon Dioxide	16,914.5	16,914.5	170.8	170.8
	Nitrogen	-	-	-	-
	Nitrogen	-	-	-	-
	Temperature (F)	1,493.2	840.6	192.0	1,292.0
	Pressure (psi)	24.7	19.7	19.7	14.7
	Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	3179033.3
Heat Transfer Coefficient (Btu/hr-sqft-F)	149.7
Heat Transfer Area (sqft)	55.6

CP	$	6,192.22
CBM	$	19,629.34

Heat Exchanger 6

Identification

Item	Heat Exchanger 6	Date	4/12/20
Item No.	HX-106	By	JD/MUC/VB
No. Required	1		

Function	Heat air stream to fuel cell operating temp.
Operation	12 hours, daily

Materials Handled	**Inlet**	**Outlet**	**Inlet**	**Outlet**
Stream ID	S-133	S-134	S-130	S-131
Quantity (lb/hr)	20,414.7	20,414.7	26,501.8	26,501.8
Composition			-	-
Carbon Monoxide	-	-	-	-
Carbon Dioxide	-	-	-	-
Oxygen	85.7	85.7	6,172.7	6,172.7
Nitrogen	20,329.1	20,329.1	20,329.1	20,329.1
Temperature (F)	1,492.5	618.8	600.6	1,291.8
Pressure (psi)	20.1	14.7	19.7	14.7
Vapor Fraction	1.0	1.0	1.0	1.0

Design Data

Type	Shell and Tube
Material	Carbon Steel/Carbon Steel
Heat Transfer (Btu/lb)	4817276.4
Heat Transfer Coefficient (Btu/hr-sqft-F)	149.7
Heat Transfer Area (sqft)	423.2

CP	$	13,372.10
CBM	$	42,389.56

Fuel Cell 2

Identification					
	Item	Fuel Cell 2	Date	4/12/20	
	Item No.	FC-102	By	JD/MUC/VB	
	No. Required	1			
Function	Convert carbon dioxide into carbon monoxide and oxygen				
Operation	12 hours, daily				
Materials Handled		**Inlet 1**	**Inlet 2**	**Outlet 1**	**Outlet 2**
Stream ID		S-127	S-131	S-132	S-135
	Quantity (lb/hr)	10,935.2	26,501.8	20,414.7	17,022.2
	Composition				
	Carbon Dioxide	10,764.3	-	-	107.6
	Carbon Monoxide	170.8	-	-	16,914.5
	Oxygen	-	6,172.7	85.7	-
	Water	-	20,329.1	20,329.1	-
	Temperature (F)	1,292.0	1,291.8	1,292.0	1,292.0
	Pressure (psi)	14.7	14.7	14.7	14.7
	Vapor Fraction	1.0	1.0	1.0	1.0
Design Data					
	Material	LSM-YSZ|YSZ|Ni-YSZ			
	Electricity Supplied (kW)	18,882.30			
	Operating T (F)	1292.0			
	Operating P (psi)	14.7			
	CP $	3,103,821.00			
	CBM $	6,207,642.00			

5.6 Equipment Cost Summary

Equipment Costs				
Equipment Description	Type	Purchase Cost	Bare Module Factor	Bare Module Cost
Name	(must be filled-in!)		(default 3.21 if blank)	
BL-101	Process Machinery	$63,300		$203,400
BL-102	Process Machinery	$211,000		$677,500
BL-103	Process Machinery	$120,700		$387,600
CM-101	Process Machinery	$210,000		$674,200
CM-102	Process Machinery	$129,100		$414,500
CM-103	Process Machinery	$125,900		$404,200
FC-101	Process Machinery	$3,103,800	2.00	$6,207,600
HX-101	Process Machinery	$11,600	3.17	$36,600
HX-102	Process Machinery	$1,800	3.17	$5,700
HX-103	Process Machinery	$10,800	3.17	$34,400
IC-101	Process Machinery	$3,800	3.17	$12,00
IC-102	Process Machinery	$3,800	3.17	$12,200
IC-103	Process Machinery	$3,900	3.17	$12,600
IC-104	Process Machinery	$3,600	3.17	$11,500
PU-101	Process Machinery	$900		$2,900
PU-102	Process Machinery	$1,600		$5,300
TU-101	Process Machinery	$32,700	2.50	$81,700
ST-101	Storage	$14,700,000	2.50	$36,750,000
BL-104	Process Machinery	$35,700		$114,600
BL-105	Process Machinery	$127,400		$408,800

BL-106	Process Machinery	$176,100		$565,400
BL-107	Process Machinery	$159,800		$513,000
FC-202	Process Machinery	$3,103,800	2.00	$6,207,600
HX-104	Process Machinery	$11,600	3.17	$36,700
HX-105	Process Machinery	$6,100	3.17	$19,600
HX-106	Process Machinery	$13,400	3.17	$42,400
FS-101	Other Equipment	$17,00	1.92	$32,600
Total				**53,874,800**

6. Economic Analyses

6.1 Profitability Analyses for On-Peak / Off-Peak Pricing Scenario

The economic model of this project centers around the idea of load shifting, a simple arbitrage practice in which storage systems intake electricity during low demand periods when power is inexpensive, and supply power back to the grid when demand is higher and a better price and can be obtained in the market. Although spot market energy prices change in real time in actuality, this project simplifies real-world conditions into two pricing periods: on-peak and off-peak, both taking equal parts of the day. Prices for each period were determined by analyzing real time energy pricing information for the year of 2019, provided by MISO, the independent system operator for the region where this project would be constructed (see Appendix D for a sample report). On-peak and off-peak prices were calculated by aggregating and averaging the prices from periods typically considered to fall in those categories: noon to 2pm for off-peak and 6pm to 8pm for on-peak. The prices were determined to be $37.03/MWh for on-peak energy and $28.14/MWh for off-peak energy, or $0.037/kWh on-peak and $0.028 for off-peak.

The profitability of the energy storage plant using off-peak pricing for charging and process electricity was evaluated using the Profitability Analysis Spreadsheet (see Appendix). Due in large part to the marginal difference in energy prices between the two periods, the project does not forecast profitability for either the high pressure or low-pressure cases. At the selling price of $37.03/MWh of energy produced, the high-pressure case’s NPV is -$8,758,200, with a third year of production ROI of -32.47%. The low-pressure case’s NPV is -$8,186,300, with a third year of production ROI of -29.43%. More information on the ROI summaries for the high-pressure and low-pressure cases are given in Table 6.1.1 and Table 6.1.2, respectively.

In order to achieve a breakeven ROI of 0.00% for the high-pressure case, the selling price for on-peak power would have to reach $67.96/MWh, which is 83.5% higher than the current calculated price. In order to achieve a breakeven ROI of 0.00% for the low-pressure case, the selling price for on-peak power would have to reach $65.06/MWh, which is 75.7% higher than the current calculated price.

The low-pressure case is marginally more profitable than the high-pressure case; this is due to the differences in equipment and utilities requirements between the two scenarios. Neither provides a positive return on investment, with drastically higher on-peak prices needed in order to achieve a breakeven point.

Table 6.1.1: On-Peak/Off-Peak Pricing Profitability Summary for High Pressure Case

ROI Analysis (Third Production Year)	
Annual Sales	$ 2,492,000
Annual Costs	$ (4,030,000)
Depreciation	$ (302,000)
Income Tax	$ 497,069,000
Net Earnings	$ (1,344,000)
Total Capital Investment	$ 4,139,000
ROI	-32.47%
Internal Rate of Return (IRR)	
Net Present Value (NPV)	$ (8,758,200)

Table 6.1.2: On-Peak/Off-Peak Pricing Profitability Summary for Low Pressure Case

ROI Analysis (Third Production Year)	
Annual Sales	$ 2,492,000
Annual Costs	$ (3,858,000)
Depreciation	$ (302,000)
Income Tax	$ 450,000
Net Earnings	$ (1,218,000)
Total Capital Investment	$ 4,139,000
Return on Investment (ROI)	-29.43%
Internal Rate of Return (IRR)	
Net Present Value (NPV)	$ 8,186,000

6.2 Profitability Analyses for Curtailment Pricing Scenario

As more renewables are added onto the grid, there is an increasing amount of oversupply due to the variability of wind and solar energy. During the brightest hours of the day, solar energy tends to oversupply for the required power input from the grid. Curtailment is a method to manage the oversupply; it is a means to reduce the output of a renewable source below what it could have otherwise produced. Curtailment has been on the rise in several part of the world. In 2019, California alone, wind and solar curtailment was approximately 1 million MWh of power that could have be produced compared to only 187000 MWh curtailed in 2015 [17]. Curtailment itself is counterintuitive solution to over generation, since it doesn't meet economic goals, when investments does not lead to maximum renewable power production. The main ways of curtailment are self-scheduled cuts, economic curtailment or ISO dispatch. Economic curtailment is the target for our design; this is when the market finds a place for low-priced or even negative-priced energy. In the on-peak/off-peak case, low-priced energy was used. In this case, negative-priced energy is used.

This section presents the profitability analyses of curtailment on our design. The main parameter that is changed is the buying price of electricity. Here, the electricity price would be $0/kwh from solar and wind power plants. The overall profitability of the high pressure and low-pressure case for curtailment are evaluated using the Profitability Analysis Spreadsheet (see Appendix B for full summary). A summary of the results is shown in Table 6.2.1 and Table 6.2.2 below.

From Table 6.2.1 and Table 6.2.2, the return of investment (ROI) is 29.9% in the high-pressure case for curtailment and 31.8% in the low-pressure case for curtailment. The low-pressure case has a slightly higher ROI, due to the cheaper annual cost, mostly the variability in equipment costing from two cases. From the profitability measures and efficiency calculations in previous sections, the low-pressure storage case has better performance than the high-pressure storage case, but not by a drastic measure.

Unlike the on peak/off peak design, curtailment allows a profitable design shown in the positive return in investment, regardless of CO storage pressure. However, this scenario of buying electricity at $0 due to curtailments is not feasible in our current energy and economic environment. In the future, where renewables dominate the energy production industry, there may be a higher chance of adopting the curtailment design. This would be a turning point for our design since it would yield profitable measures and possibly be implemented over conventional energy storage methods.

Table 6.2.1: Curtailment Profitability Summary for High Pressure Storage

ROI Analysis (Third Production Year)	
Annual Sales	$ 2,492,000
Annual Costs	$ (492,000)
Depreciation	$ (302,000)
Income Tax	$ (458,000)
Net Earnings	$ 1,239,000
Total Capital Investment	$ 4,139,000
ROI	29.93%
Internal Rate of Return (IRR)	28.18%
Net Present Value (NPV)	$ 2,973,000

Table 6.2.2: Curtailment Profitability Summary for Low Pressure Storage

ROI Analysis (Third Production Year)	
Annual Sales	$ 2,492,000
Annual Costs	$ (386,000)
Depreciation	$ (302,000)
Income Tax	$ (487,000)
Net Earnings	$ 1,316,000
Total Capital Investment	$ 4,139,000
ROI	31.80%
Internal Rate of Return (IRR)	29.59%
Net Present Value (NPV)	$ 3,325,000

7. Additional Considerations

7.1 Environmental Considerations

This process seeks to improve the feasibility of a majority renewable electricity production supply. A benefit of this goal is the reduction of carbon output by traditional electricity producing plants, such as coal power plants. By sourcing the input CO_2 from fermentation, the process is net carbon neutral, since the original source of carbon dioxide was supplied by an input feedstock to the fermentation process and not fossil fuels. Additionally, by reducing the reliance of the grid on coal and other fossil fuel power plants, their contribution to other pollutants, such as sulfurous and nitrous oxides, would be mitigated.

7.2 Safety Considerations

Many of the chemical species used in the process are non-toxic and non-hazardous. Some, however, require special safety considerations

High-purity oxygen gas is produced in the energy-storing mode of the process. This gas is flammable, causing or potentially intensifying fires.

Carbon monoxide gas is produced and stored in the energy-storing mode of the process and used as an input in the energy-producing mode of the process. This species is flammable and acutely toxic. Indoors, it has a maximum safe limit of 50 ppm. A large amount of CO is stored on-site, though in both the high- and low-pressure cases it is stored in an outdoor erected structure.

Emergency venting equipment is fitted to the process to deal with possible leaks. The cost of this equipment is accounted for in this analysis.

Some of the equipment, notably the fuel cells and electrolyzer cells, operate at very high temperatures (up to 700 Celsius). In the event of a burst pipe or malfunction of operating equipment, injury may occur. Safe handling practices must be put into place for operating engineers. Care must be taken during operation of the plant to ensure that the SOFC and SOEC, as well as other operating equipment, stay below critical temperatures.

Safety information of all chemical species used in the process are included in this report.

7.3 Location Considerations

An advantage of this technology and process is its geographic invariance. That is, this process could feasibly be fit to any location near a source of CO_2 and with access to the grid.

Due to the operating conditions of the plant, it is best to have it away from residential areas or important wildlife habitats. In the event of catastrophic failure of the storage tanks, it was calculated that a minimum distance of 2 kilometers was sufficient to ensure the safety of the surrounding areas.

8. Conclusions

8.1 Summary of Cases

Table 8.1.1 shows the efficiencies and capacities of the two designed energy storage processes.

Process Design	Storage Capacity (MWhr)	Efficiency
High-Pressure Storage Design	226.5	53.5%
Low-Pressure Storage Design	226.5	54.6%

Table 8.1.2 shows the expected ROIs of each process design for on-peak/off-peak pricing and curtailment pricing of input electricity for storage.

Process Design	ROI for On-Peak/Off-Peak Pricing	ROI for Curtailment Pricing
High Pressure Storage Design	-32.5%	29.93%
Low-Pressure Storage Design	-29.4%	31.80%

8.2 Recommendations

After a study of the potential energy-storage processes made possible by fuel cell and electrolytic cell technologies. By utilizing waste CO_2 from fermentation plants, a simplified process was able to be developed for a net-carbon-neutral storage solution. Using average waste CO_2 numbers from typical ethanol production plants, it was shown that an energy storage facility could be developed with a high capacity in excess of 250 MWhr per cycle.

The optimal strategy for storage of the chemical fuel, CO gas, was around 1 atmosphere storage using floating-head tanks. While compressed storage reduced the cost of storage, the recovery of energy from the compression created a more costly inefficiency and added more process equipment, leading to a lower profitability of the plant.

This high-capacity chemical fuel storage solution is not likely to be profitable in the current economic landscape. The price differential between on-peak and off-peak electricity is not high enough to justify the cost of the plant and process. However, if renewable power plants become more prevalent, overgeneration will likely become a larger economic factor, and the availability of zero-opportunity cost or negative-opportunity cost energy at off-peak hours would likely become a reality. In this case, the process described in this report would likely be profitable and a viable solution to this problem. In the eventuality that fossil fuel energy production is phased out, this energy storage solution should be revisited to provide a net-carbon-neutral, viable storage process.

9. References

1. El-Nagar, R. A.; Ghanem, laa A. Syngas Production, Properties, and Its Importance. *IntechOpen* **2019**.
2. U.S. Grid Energy Storage Factsheet. http://css.umich.edu/factsheets/us-grid-energy-storage-factsheet (accessed Apr 17, 2020).
3. Zablocki, A. Fact Sheet: Energy Storage (2019). https://www.eesi.org/papers/view/energy-storage-2019 (accessed Apr 13, 2020).
4. Oxygen Prices: Utilities Cost Database. https://www.intratec.us/chemical-markets/oxygen-price (accessed Apr 13, 2020).
5. eCOs - Haldor Topsoe. https://info.topsoe.com/ecos (accessed Apr 13, 2020).
6. Mittal, C.; Hadsbjerg, C.; Blennow, P. Small-Scale CO from CO2 Using Electrolysis. *Chemical Engineering World* **2017**, 44–46.
7. Bloom Energy Server ES5-300kW. https://www.bloomenergy.com/datasheets/energy-server-es5-300kw (accessed Apr 13, 2020).
8. Küngas, R. Review—Electrochemical CO2 Reduction for CO Production: Comparison of Low- and High-Temperature Electrolysis Technologies. *Journal of The Electrochemical Society* **2020**, *167* (4), 044508.
9. Ebbesen, S. D.; Mogensen, M. Electrolysis of Carbon Dioxide in Solid Oxide Electrolysis Cells. *Journal of Power Sources* **2009**, *193* (1), 349–358.
10. Khotseng, L. Fuel Cell Thermodynamics. *Thermodynamics and Energy Engineering* **2019**.
11. Kitazaki, Y.; Shimonosono, T.; Hirata, Y.; Sameshima, S.; Yamaji, K. Solid Oxide Fuel Cell Using CO-H2O Mixed Gas Fuel. *Journal of the Ceramic Society of Japan* **2018**, *126* (10), 794–800.
12. Stambouli, A.; Traversa, E. Solid Oxide Fuel Cells (SOFCs): A Review of an Environmentally Clean and Efficient Source of Energy. *Renewable and Sustainable Energy Reviews* **2002**, *6* (5), 433–455.
13. Bloom Energy Server ES5-300kW. https://www.bloomenergy.com/datasheets/energy-server-es5-300kw (accessed Apr 13, 2020).
14. Oxygen Prices: Utilities Cost Database. https://www.intratec.us/chemical-markets/oxygen-price (accessed Apr 13, 2020).
15. GHGRP Miscellaneous Combustion. https://www.epa.gov/ghgreporting/ghgrp-miscellaneous-combustion#2018-subsector (accessed Apr 13, 2020).
16. California ISO. http://www.caiso.com/informed/Pages/ManagingOversupply.aspx (accessed Apr 15, 2020).
17. Safety Data Information From: AirGas SDS

9. Acknowledgments

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Appendix A

Current Commercial Fuel Cell Technology

Bloom Energy – Energy Server^{TM} 5

Bloomenergy

PRODUCT DATASHEET

Energy Server™ 5

Always On, Clean Energy
Using Patented Solid Oxide
Fuel Cell Technology

The Energy Server 5 provides combustion-free electric power with these benefits

Clean
Our systems produce near zero criteria pollutants (NOx, SOx, and particulate matter) and far fewer carbon emissions than legacy technologies.

Reliable
Bloom Energy Servers are designed around a modular architecture of simple repeating elements. This enables us to generate power 24 x 7 x 365 and can be configured to eliminate the need for traditional backup power equipment.

Resilient
Our system operates at very high availability due to its fault-tolerant design and use of the robust natural gas pipeline system. Bloom Energy Servers have survived extreme weather events and other incidences and have continued providing power to our customers.

Simple Installation and Maintenance
Our Energy Servers are 'plug and play' and have been designed in compliance with a variety of safety standards. Bloom Energy manages all aspects of installation, operation and maintenance of the systems.

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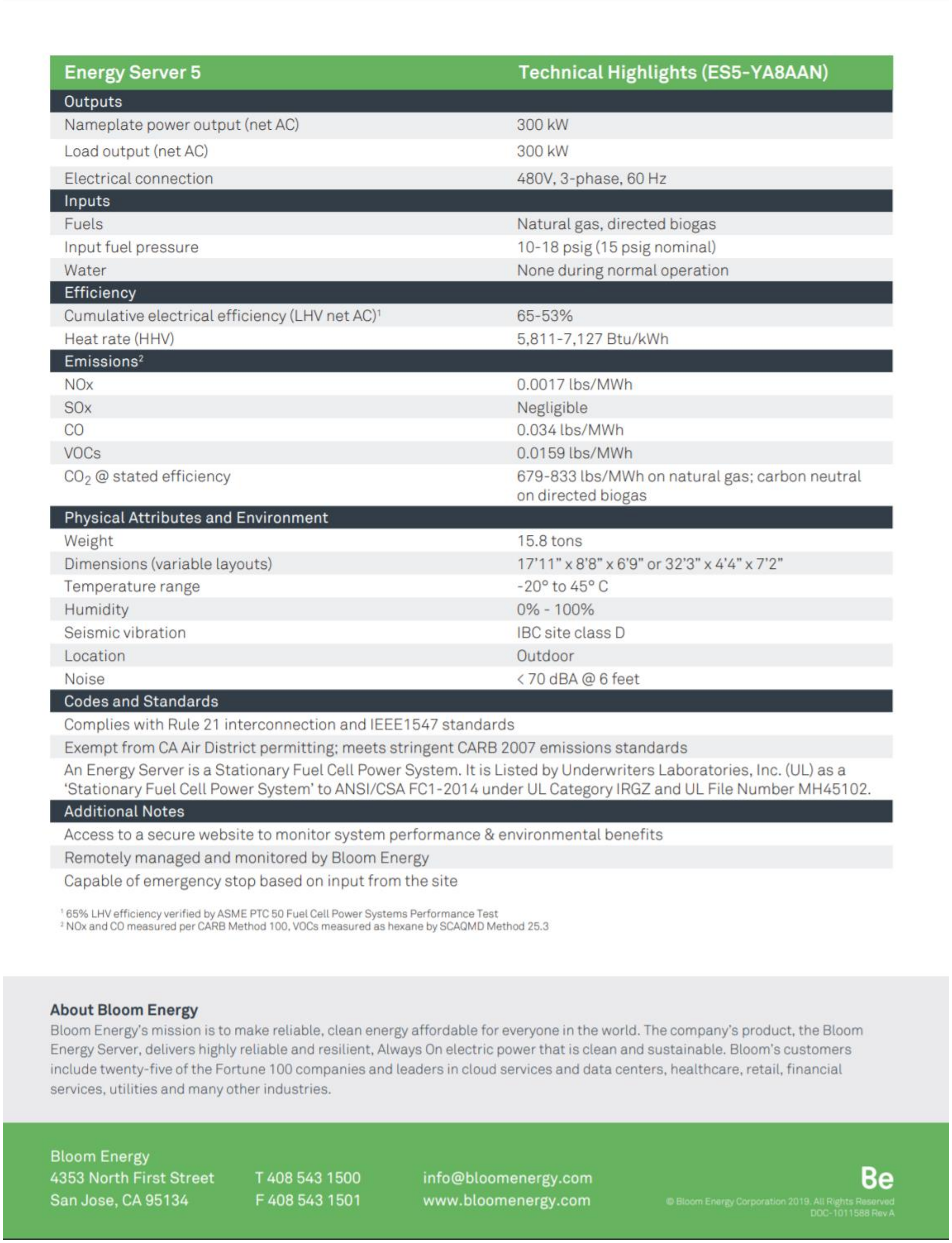

Energy Server 5	Technical Highlights (ES5-YA8AAN)
Outputs	
Nameplate power output (net AC)	300 kW
Load output (net AC)	300 kW
Electrical connection	480V, 3-phase, 60 Hz
Inputs	
Fuels	Natural gas, directed biogas
Input fuel pressure	10-18 psig (15 psig nominal)
Water	None during normal operation
Efficiency	
Cumulative electrical efficiency (LHV net AC)[1]	65-53%
Heat rate (HHV)	5,811-7,127 Btu/kWh
Emissions[2]	
NOx	0.0017 lbs/MWh
SOx	Negligible
CO	0.034 lbs/MWh
VOCs	0.0159 lbs/MWh
CO_2 @ stated efficiency	679-833 lbs/MWh on natural gas; carbon neutral on directed biogas
Physical Attributes and Environment	
Weight	15.8 tons
Dimensions (variable layouts)	17'11" x 8'8" x 6'9" or 32'3" x 4'4" x 7'2"
Temperature range	-20° to 45° C
Humidity	0% - 100%
Seismic vibration	IBC site class D
Location	Outdoor
Noise	< 70 dBA @ 6 feet
Codes and Standards	
Complies with Rule 21 interconnection and IEEE1547 standards	
Exempt from CA Air District permitting; meets stringent CARB 2007 emissions standards	
An Energy Server is a Stationary Fuel Cell Power System. It is Listed by Underwriters Laboratories, Inc. (UL) as a 'Stationary Fuel Cell Power System' to ANSI/CSA FC1-2014 under UL Category IRGZ and UL File Number MH45102.	
Additional Notes	
Access to a secure website to monitor system performance & environmental benefits	
Remotely managed and monitored by Bloom Energy	
Capable of emergency stop based on input from the site	

[1] 65% LHV efficiency verified by ASME PTC 50 Fuel Cell Power Systems Performance Test
[2] NOx and CO measured per CARB Method 100, VOCs measured as hexane by SCAQMD Method 25.3

About Bloom Energy

Bloom Energy's mission is to make reliable, clean energy affordable for everyone in the world. The company's product, the Bloom Energy Server, delivers highly reliable and resilient, Always On electric power that is clean and sustainable. Bloom's customers include twenty-five of the Fortune 100 companies and leaders in cloud services and data centers, healthcare, retail, financial services, utilities and many other industries.

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DOC-1011588 Rev A

Halder Topsoe -- eCOs™

eCOs™ CO production

Produce your own CO
B'e**CO**s™ it's **better**

Get CO on-demand at the touch of a button

HALDOR TOPSØE

Haldor Topsoe

Say goodbye **to uncertainty**

If you're like most companies that depend on an uninterrupted supply of CO, you probably know the challenges and hassles involved in sourcing CO.

The number of CO suppliers is limited. Transportation costs are ever increasing. Production shortages and bad traffic or weather only add to delivery headaches.

We discovered a cure.

eCOs™ onsite CO production.
B'eCOs™ its 100% predictable
The solution is a stand-alone eCOs™ on-site CO production unit.

eCOs™ delivers a steady supply of affordable CO, on-demand. An eCOs™ plant is a safe, reliable CO generator located on your own premises. It delivers the exact supply of the right volumes and purity levels that your business needs.

Tailored to your business
Topsoe will help you minimize costs with an optimally-designed supply system calibrated to your company's usage profile.

Together with you, we'll discover your gas usage patterns. We will also estimate the impact of future gas requirements into consideration to identify potential cost savings. An eCOs™ solution can be customized to produce CO at 99.999 vol% purity.

Turn to eCOs™ for:

- As easy as START/STOP operation
- On-demand production
- Only pay for what you use. Save money
- Multiple sizes and purity options up to 99.999 vol%
- Full replacement of tube trailer or cylinder supply
- Zero transportation and safe toxic gas storage
- Reduced carbon footprint compared to delivered gases

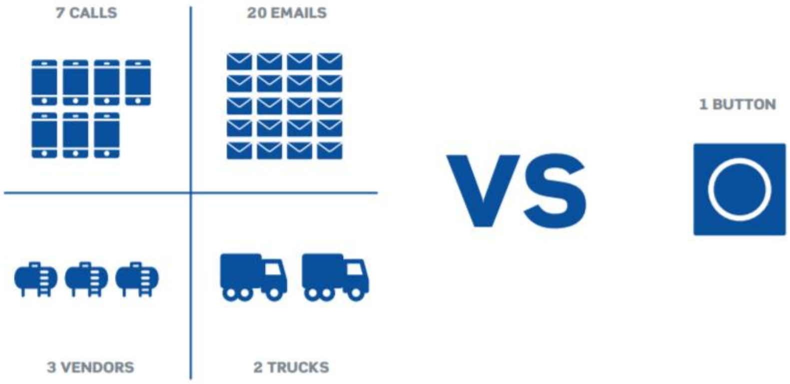
Performance.
Unconditionally guaranteed
eCOs™ stands for "electrolytic Carbon Monoxide solution." At its heart is a solid oxide electrolysis cell (SOEC) that efficiently reduces CO_2 to CO. Any remaining unconverted CO_2 is removed from the CO product gas using a combination of PSA and polisher units.

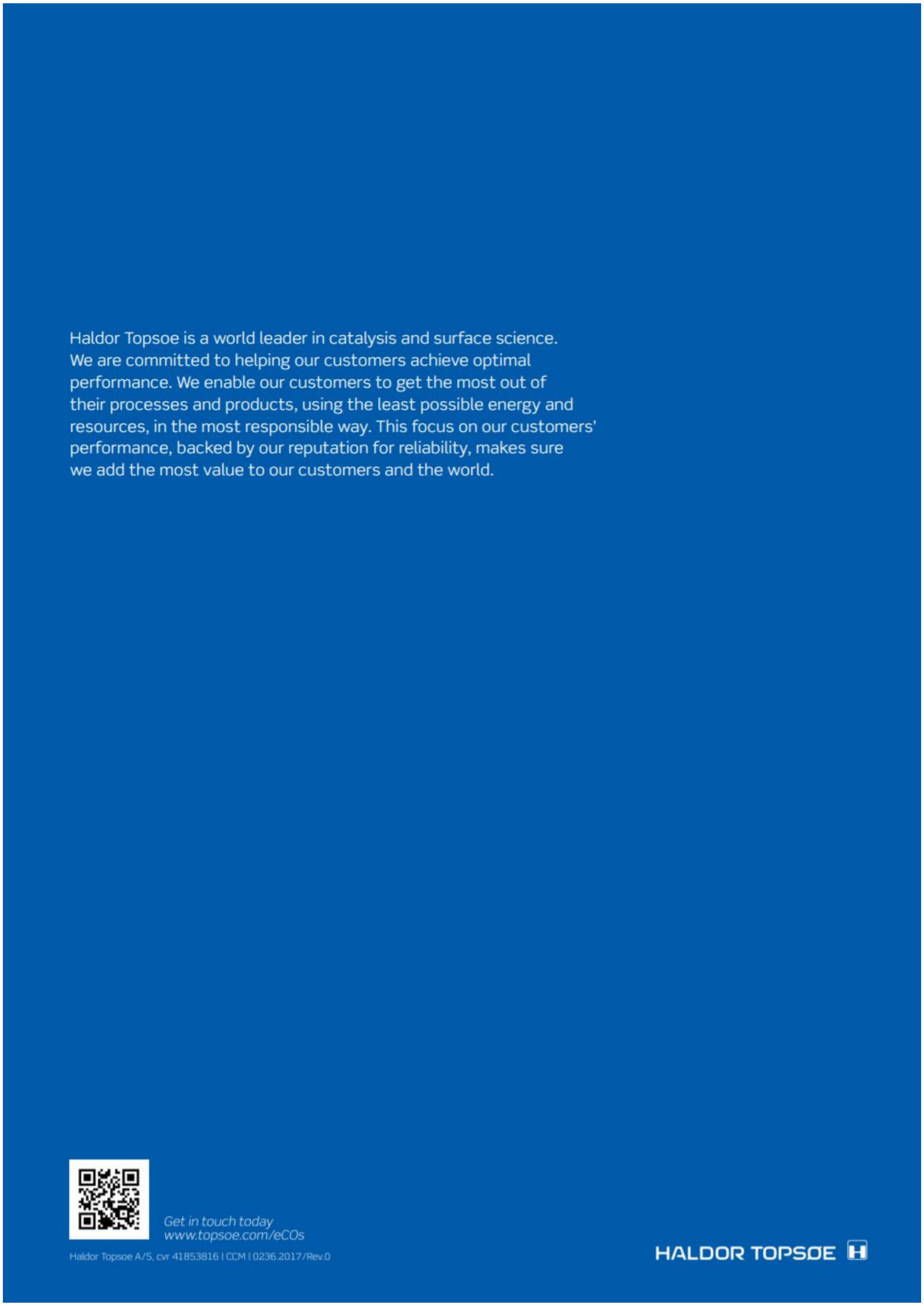
We deliver eCOs™ units as a stand-alone unit with power, CO_2 and product gas connections. Our eCOs™ technology guarantees high levels of purity, producing CO at the desired assay with minimal contaminants and CO_2 as the main contaminant.

Only pay for what you **use**

When you install an eCOs™ unit from Topsoe, you get the exact purity and quality of CO you want, on-site and on-demand. Better yet, with our leasing program you only pay for what you use.

Talk to us. Get a quote.
See how much time and money you could save.





Haldor Topsoe is a world leader in catalysis and surface science. We are committed to helping our customers achieve optimal performance. We enable our customers to get the most out of their processes and products, using the least possible energy and resources, in the most responsible way. This focus on our customers' performance, backed by our reputation for reliability, makes sure we add the most value to our customers and the world.

Get in touch today
www.topsoe.com/eCOs

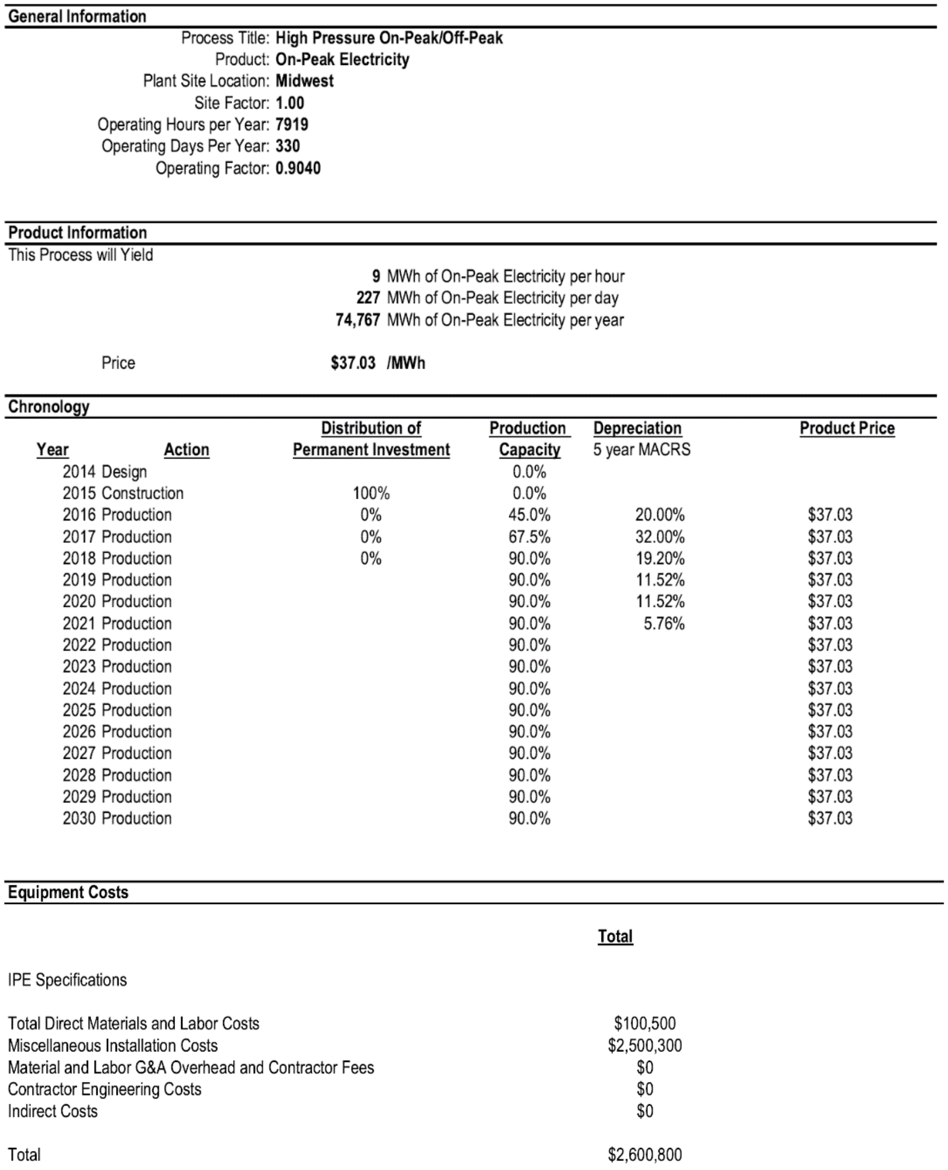
Haldor Topsoe A/S, cvr 41853816 | CCM | 0236.2017/Rev.0

HALDOR TOPSØE

Appendix B

Profitability Spreadsheet Analyses

On peak/Off-peak (High Pressure Storage)



General Information

Process Title: **High Pressure On-Peak/Off-Peak**
Product: **On-Peak Electricity**
Plant Site Location: **Midwest**
Site Factor: **1.00**
Operating Hours per Year: **7919**
Operating Days Per Year: **330**
Operating Factor: **0.9040**

Product Information

This Process will Yield

9 MWh of On-Peak Electricity per hour
227 MWh of On-Peak Electricity per day
74,767 MWh of On-Peak Electricity per year

Price **$37.03 /MWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2014	Design		0.0%		
2015	Construction	100%	0.0%		
2016	Production	0%	45.0%	20.00%	$37.03
2017	Production	0%	67.5%	32.00%	$37.03
2018	Production	0%	90.0%	19.20%	$37.03
2019	Production		90.0%	11.52%	$37.03
2020	Production		90.0%	11.52%	$37.03
2021	Production		90.0%	5.76%	$37.03
2022	Production		90.0%		$37.03
2023	Production		90.0%		$37.03
2024	Production		90.0%		$37.03
2025	Production		90.0%		$37.03
2026	Production		90.0%		$37.03
2027	Production		90.0%		$37.03
2028	Production		90.0%		$37.03
2029	Production		90.0%		$37.03
2030	Production		90.0%		$37.03

Equipment Costs

	Total
IPE Specifications	
Total Direct Materials and Labor Costs	$100,500
Miscellaneous Installation Costs	$2,500,300
Material and Labor G&A Overhead and Contractor Fees	$0
Contractor Engineering Costs	$0
Indirect Costs	$0
Total	$2,600,800

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:
1	Carbon Dioxide	lb	1454.2447 lb per MWh of On-Peak Electricity	$0.000E+00 per lb

Total Weighted Average: $0.000E+00 per MWh of On-Peak Electricity

Byproducts

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price
1	Oxygen	lb	528.69504 lb per MWh of On-Peak Electricity	$0.045 per lb

Total Weighted Average: $23.791 per MWh of On-Peak Electricity

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost
1	High Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
2	Low Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
3	Process Water	gal	0 gal per MWh of On-Peak Electricit	$0.000E+00 per gal
4	Cooling Water	lb	8172.4598 lb per MWh of On-Peak Electricity	$1.200E-05 per lb
5	Electricity	MWh	1.868 MWh per MWh of On-Peak Electri	$28.140 per MWh
6	Fire Heater Fuel	lb	16.726715 lb per MWh of On-Peak Electricity	$0.090 per lb

Total Weighted Average: $54.169 per MWh of On-Peak Electricity

Variable Costs

General Expenses:

Selling / Transfer Expenses:	**3.00% of Sales**
Direct Research:	**4.80% of Sales**
Allocated Research:	**0.50% of Sales**
Administrative Expense:	**2.00% of Sales**
Management Incentive Compensation:	**1.25% of Sales**

Working Capital

Accounts Receivable	⇨	**30**	**Days**
Cash Reserves (excluding Raw Materials)	⇨	**30**	**Days**
Accounts Payable	⇨	**30**	**Days**
On-Peak Electricity Inventory	⇨	**4**	**Days**
Raw Materials	⇨	**2**	**Days**

Variable Cost Summary

Variable Costs at 100% Capacity:

General Expenses			
Selling / Transfer Expenses:		$	83,059
Direct Research:		$	132,894
Allocated Research:		$	13,843
Administrative Expense:		$	55,372
Management Incentive Compensation:		$	34,608
Total General Expenses		$	319,776
Raw Materials	$0.000000 per MWh of On-Peak Electr		$0
Byproducts	$23.791277 per MWh of On-Peak Electr		($1,778,801)
Utilities	$54.179568 per MWh of On-Peak Electr		$4,050,841
Total Variable Costs		**$**	**2,591,816**

Fixed Cost Summary

Operations		
Direct Wages and Benefits	$	416,000
Direct Salaries and Benefits	$	62,400
Operating Supplies and Services	$	24,960
Technical Assistance to Manufacturing	$	300,000
Control Laboratory	$	325,000
Total Operations	**$**	**1,128,360**
Maintenance		
Wages and Benefits	$	151,913
Salaries and Benefits	$	37,978
Materials and Services	$	151,913
Maintenance Overhead	$	7,596
Total Maintenance	**$**	**349,399**
Operating Overhead		
General Plant Overhead:	$	47,449
Mechanical Department Services:	$	16,039
Employee Relations Department:	$	39,429
Business Services:	$	49,454
Total Operating Overhead	**$**	**152,370**
Property Taxes and Insurance		
Property Taxes and Insurance:	$	67,517
Other Annual Expenses		
Rental Fees (Office and Laboratory Space):	$	-
Licensing Fees:	$	-
Miscellaneous:	$	-
Total Other Annual Expenses	**$**	**-**
Total Fixed Costs	**$**	**1,697,646**

Investment Summary

Installed Equipment Costs:		
Total Direct Materials and Labor Costs	$ 100,500	
Miscellaneous Installation Costs	$ 2,500,300	
Material and Labor G&A Overhead and Contractor Fees	$ -	
Contractor Engineering Costs	$ -	
Indirect Costs	$ -	
Total:		**$ 2,600,800**
Direct Permanent Investment		
Cost of Site Preparations:	$ 130,040	
Cost of Service Facilities:	$ 130,040	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		**$ 2,860,880**
Total Depreciable Capital		
Cost of Contingencies & Contractor Fees	$ 514,958	
Total Depreciable Capital		**$ 3,375,838**
Total Permanent Investment		
Cost of Land:	$ 67,517	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 337,584	
Total Permanent Investment - Unadjusted		$ 3,780,939
Site Factor		1.00
Total Permanent Investment		**$ 3,780,939**

Working Capital

	2015	2016	2017
Accounts Receivable	$ 102,401	$ 51,201	$ 51,201
Cash Reserves	$ 212,615	$ 106,308	$ 106,308
Accounts Payable	$ (149,826)	$ (74,913)	$ (74,913)
On-Peak Electricity Inventory	$ 13,653	$ 6,827	$ 6,827
Raw Materials	$ -	$ -	$ -
Total	**$ 178,844**	**$ 89,422**	**$ 89,422**
Present Value at 15%	*$ 155,517*	*$ 67,616*	*$ 58,796*

Total Capital Investment	**$ 4,062,868**

Cash Flow Summary

Year	Percentage of Design Capacity	Product Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Depletion Allowance	Taxible Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 15%
2014	0%		-	-	-	-	-	-	-	-	-	-	-	-
2015	0%		-	(3,780,900)	(178,800)	-	-	-	-	-	-	-	(3,959,800)	(3,443,300)
2016	45%	$37.03	1,245,900	-	(89,400)	(1,166,300)	(1,697,600)	(675,200)	-	(2,293,300)	619,200	(1,674,100)	(1,088,300)	(4,266,200)
2017	68%	$37.03	1,868,800	-	(89,400)	(1,749,500)	(1,697,600)	(1,080,300)	-	(2,658,600)	717,800	(1,940,800)	(949,900)	(4,890,800)
2018	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	(648,200)	-	(2,186,700)	590,400	(1,596,300)	(948,100)	(5,432,900)
2019	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	(388,900)	-	(1,927,400)	520,400	(1,407,000)	(1,018,100)	(5,939,100)
2020	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	(388,900)	-	(1,927,400)	520,400	(1,407,000)	(1,018,100)	(6,379,200)
2021	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	(194,400)	-	(1,733,000)	467,900	(1,265,100)	(1,070,600)	(6,781,700)
2022	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(7,148,900)
2023	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(7,468,100)
2024	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(7,745,800)
2025	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(7,987,200)
2026	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(8,197,100)
2027	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(8,379,600)
2028	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(8,538,300)
2029	90%	$37.03	2,491,800	-	-	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(1,123,100)	(8,676,400)
2030	90%	$37.03	2,491,800	-	357,700	(2,332,600)	(1,697,600)	-	-	(1,538,500)	415,400	(1,123,100)	(765,400)	(8,758,200)

Profitability Measures

The Internal Rate of Return (IRR) for this project is Negative IRR

The Net Present Value (NPV) of this project in 2014 is $ (8,758,200)

ROI Analysis (Third Production Year)

Annual Sales	**2,491,758**
Annual Costs	**(4,030,280)**
Depreciation	**(302,475)**
Income Tax	**497,069**
Net Earnings	**(1,343,928)**
Total Capital Investment	**4,138,627**
ROI	**-32.47%**

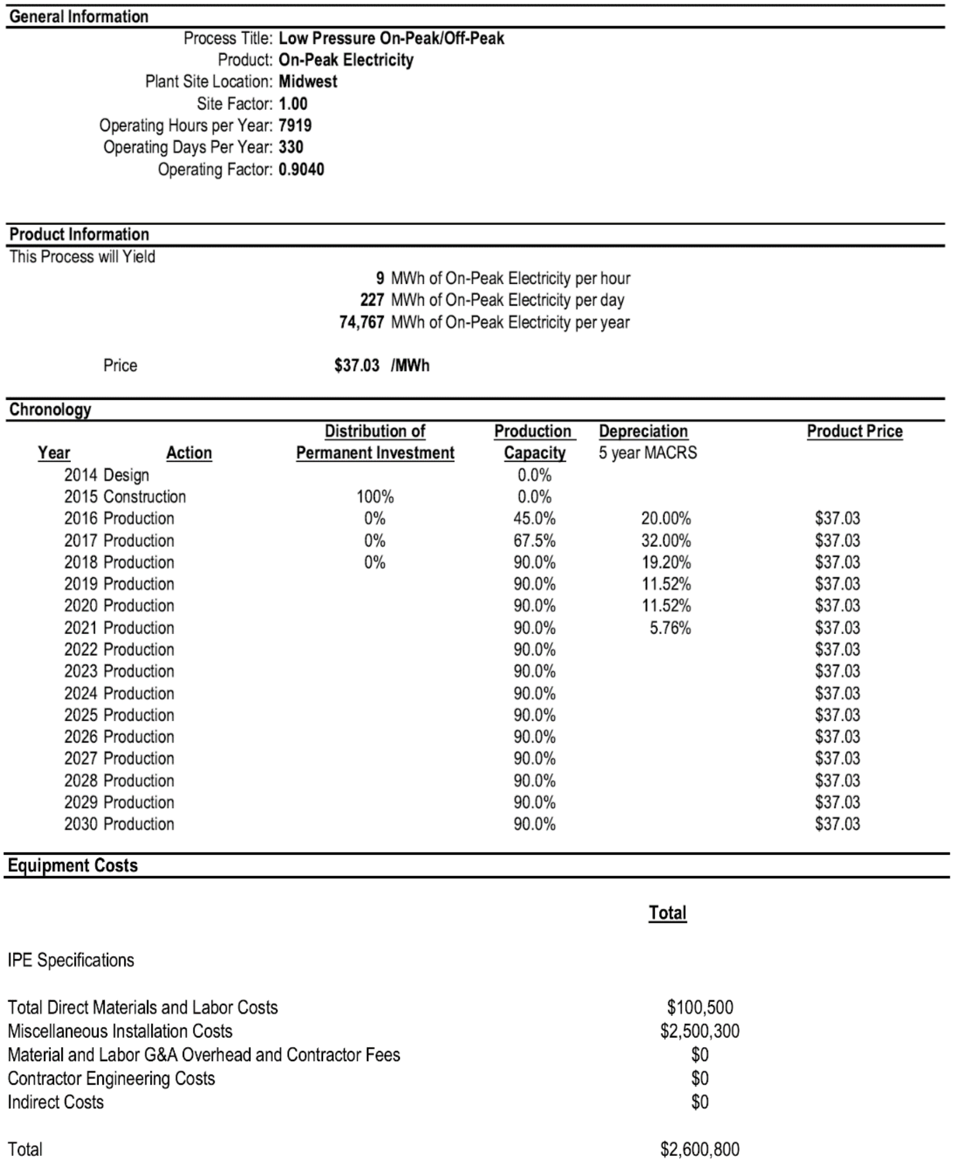
Sensitivity Analyses

Note: The Sensitivity Analyses section below takes quite a bit of memory to update each time a cell is changed; therefore, automatic calculations are turned off. After making your axis selections, press "F9" to recalculate the IRR values. (These two lines may be deleted before printing.)

	Vary Initial Value by +/-
x-axis	50%
y-axis	50%

							Variable Costs					
		$1,295,908	$1,555,089	$1,814,271	$2,073,453	$2,332,634	***$2,591,816***	$2,850,997	$3,110,179	$3,369,360	$3,628,542	$3,887,724
Product Price	$18.52	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$22.22	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$25.92	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$29.62	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$33.33	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$37.03	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$40.73	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$44.44	-7.82%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$48.14	0.27%	-7.09%	-20.83%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$51.84	6.03%	0.68%	-6.42%	-18.92%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
	$55.55	10.76%	6.32%	1.08%	-5.78%	-17.29%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR

On peak/Off-peak (Low Pressure Storage)



General Information

Process Title: **Low Pressure On-Peak/Off-Peak**
Product: **On-Peak Electricity**
Plant Site Location: **Midwest**
Site Factor: **1.00**
Operating Hours per Year: **7919**
Operating Days Per Year: **330**
Operating Factor: **0.9040**

Product Information

This Process will Yield

9	MWh of On-Peak Electricity per hour
227	MWh of On-Peak Electricity per day
74,767	MWh of On-Peak Electricity per year

Price **$37.03 /MWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2014	Design		0.0%		
2015	Construction	100%	0.0%		
2016	Production	0%	45.0%	20.00%	$37.03
2017	Production	0%	67.5%	32.00%	$37.03
2018	Production	0%	90.0%	19.20%	$37.03
2019	Production		90.0%	11.52%	$37.03
2020	Production		90.0%	11.52%	$37.03
2021	Production		90.0%	5.76%	$37.03
2022	Production		90.0%		$37.03
2023	Production		90.0%		$37.03
2024	Production		90.0%		$37.03
2025	Production		90.0%		$37.03
2026	Production		90.0%		$37.03
2027	Production		90.0%		$37.03
2028	Production		90.0%		$37.03
2029	Production		90.0%		$37.03
2030	Production		90.0%		$37.03

Equipment Costs

	Total
IPE Specifications	
Total Direct Materials and Labor Costs	$100,500
Miscellaneous Installation Costs	$2,500,300
Material and Labor G&A Overhead and Contractor Fees	$0
Contractor Engineering Costs	$0
Indirect Costs	$0
Total	$2,600,800

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:
1	Carbon Dioxide	lb	1454.2447 lb per MWh of On-Peak Electricity	$0.000E+00 per lb

Total Weighted Average: $0.000E+00 per MWh of On-Peak Electricity

Byproducts

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price
1	Oxygen	lb	528.69504 lb per MWh of On-Peak Electricity	$0.045 per lb

Total Weighted Average: $23.791 per MWh of On-Peak Electricity

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost
1	High Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
2	Low Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
3	Process Water	gal	0 gal per MWh of On-Peak Electricit	$0.000E+00 per gal
4	Cooling Water	lb	2164.83 lb per MWh of On-Peak Electricity	$1.200E-05 per lb
5	Electricity	MWh	1.83 MWh per MWh of On-Peak Electri	$28.140 per MWh
6	Fired Heater Fuel	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb

Total Weighted Average: $51.522 per MWh of On-Peak Electricity

Variable Costs

General Expenses:

Selling / Transfer Expenses:	**3.00% of Sales**
Direct Research:	**4.80% of Sales**
Allocated Research:	**0.50% of Sales**
Administrative Expense:	**2.00% of Sales**
Management Incentive Compensation:	**1.25% of Sales**

Working Capital

Accounts Receivable	⇨	**30**	**Days**
Cash Reserves (excluding Raw Materials)	⇨	**30**	**Days**
Accounts Payable	⇨	**30**	**Days**
On-Peak Electricity Inventory	⇨	**4**	**Days**
Raw Materials	⇨	**2**	**Days**

Total Permanent Investment

Cost of Site Preparations:	**5.00%**	**of Total Bare Module Costs**
Cost of Service Facilities:	**5.00%**	**of Total Bare Module Costs**
Allocated Costs for utility plants and related facilities:	**$0**	
Cost of Contingencies and Contractor Fees:	**18.00%**	**of Direct Permanent Investment**
Cost of Land:	**2.00%**	**of Total Depreciable Capital**
Cost of Royalties:	**$0**	
Cost of Plant Start-Up:	**10.00%**	**of Total Depreciable Capital**

Fixed Costs

Operations

Operators per Shift:	**1**	**(assuming 5 shifts)**
Direct Wages and Benefits:	**$40**	**/operator hour**
Direct Salaries and Benefits:	**15%**	**of Direct Wages and Benefits**
Operating Supplies and Services:	**6%**	**of Direct Wages and Benefits**
Technical Assistance to Manufacturing:	**$60,000.00**	**per year, for each Operator per Shift**
Control Laboratory:	**$65,000.00**	**per year, for each Operator per Shift**

Maintenance

Wages and Benefits:	**4.50%**	**of Total Depreciable Capital**
Salaries and Benefits:	**25%**	**of Maintenance Wages and Benefits**
Materials and Services:	**100%**	**of Maintenance Wages and Benefits**
Maintenance Overhead:	**5%**	**of Maintenance Wages and Benefits**

Operating Overhead

General Plant Overhead:	**7.10%**	**of Maintenance and Operations Wages and Benefits**
Mechanical Department Services:	**2.40%**	**of Maintenance and Operations Wages and Benefits**
Employee Relations Department:	**5.90%**	**of Maintenance and Operations Wages and Benefits**
Business Services:	**7.40%**	**of Maintenance and Operations Wages and Benefits**

Property Taxes and Insurance

Property Taxes and Insurance:	**2%**	**of Total Depreciable Capital**

Straight Line Depreciation

Direct Plant:	8.00%	**of Total Depreciable Capital, less 1.18 times the Allocated Costs for Utility Plants and Related Facilities**
Allocated Plant:	6.00%	**of 1.18 times the Allocated Costs for Utility Plants and Related Facilities**

Other Annual Expenses

Rental Fees (Office and Laboratory Space):	**$0**
Licensing Fees:	**$0**
Miscellaneous:	**$0**

Depletion Allowance

Annual Depletion Allowance:	**$0**

Variable Cost Summary

Variable Costs at 100% Capacity:

General Expenses			
Selling / Transfer Expenses:		$	83,059
Direct Research:		$	132,894
Allocated Research:		$	13,843
Administrative Expense:		$	55,372
Management Incentive Compensation:		$	34,608
Total General Expenses		$	319,776
Raw Materials	$0.000000 per MWh of On-Peak Electr		$0
Byproducts	$23.791277 per MWh of On-Peak Electr		($1,778,801)
Utilities	$51.522173 per MWh of On-Peak Electr		$3,852,156
Total Variable Costs		**$**	**2,393,130**

Fixed Cost Summary

Operations		
Direct Wages and Benefits	$	416,000
Direct Salaries and Benefits	$	62,400
Operating Supplies and Services	$	24,960
Technical Assistance to Manufacturing	$	300,000
Control Laboratory	$	325,000
Total Operations	**$**	**1,128,360**
Maintenance		
Wages and Benefits	$	151,913
Salaries and Benefits	$	37,978
Materials and Services	$	151,913
Maintenance Overhead	$	7,596
Total Maintenance	**$**	**349,399**
Operating Overhead		
General Plant Overhead:	$	47,449
Mechanical Department Services:	$	16,039
Employee Relations Department:	$	39,429
Business Services:	$	49,454
Total Operating Overhead	**$**	**152,370**
Property Taxes and Insurance		
Property Taxes and Insurance:	$	67,517
Other Annual Expenses		
Rental Fees (Office and Laboratory Space):	$	-
Licensing Fees:	$	-
Miscellaneous:	$	-
Total Other Annual Expenses	**$**	**-**
Total Fixed Costs	**$**	**1,697,646**

Investment Summary

Installed Equipment Costs:		
Total Direct Materials and Labor Costs	$ 100,500	
Miscellaneous Installation Costs	$ 2,500,300	
Material and Labor G&A Overhead and Contractor Fees	$ -	
Contractor Engineering Costs	$ -	
Indirect Costs	$ -	
Total:		**$ 2,600,800**
Direct Permanent Investment		
Cost of Site Preparations:	$ 130,040	
Cost of Service Facilities:	$ 130,040	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		**$ 2,860,880**
Total Depreciable Capital		
Cost of Contingencies & Contractor Fees	$ 514,958	
Total Depreciable Capital		**$ 3,375,838**
Total Permanent Investment		
Cost of Land:	$ 67,517	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 337,584	
Total Permanent Investment - Unadjusted		$ 3,780,939
Site Factor		1.00
Total Permanent Investment		**$ 3,780,939**

Working Capital

	2015	2016	2017
Accounts Receivable	$ 102,401	$ 51,201	$ 51,201
Cash Reserves	$ 205,267	$ 102,633	$ 102,633
Accounts Payable	$ (142,477)	$ (71,239)	$ (71,239)
On-Peak Electricity Inventory	$ 13,653	$ 6,827	$ 6,827
Raw Materials	$ -	$ -	$ -
Total	**$ 178,844**	**$ 89,422**	**$ 89,422**
Present Value at 15%	*$ 155,517*	*$ 67,616*	*$ 58,796*

Total Capital Investment	**$ 4,062,868**

Cash Flow Summary

Year	Percentage of Design Capacity	Product Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Depletion Allowance	Taxible Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 15%
2014	0%		-	-	-	-	-	-	-	-	-	-	-	-
2015	0%		-	(3,780,900)	(178,800)	-	-	-	-	-	-	-	(3,959,800)	(3,443,300)
2016	45%	$37.03	1,245,900	-	(89,400)	(1,076,900)	(1,697,600)	(675,200)	-	(2,203,800)	595,000	(1,608,800)	(1,023,100)	(4,216,900)
2017	68%	$37.03	1,868,800	-	(89,400)	(1,615,400)	(1,697,600)	(1,080,300)	-	(2,524,500)	681,600	(1,842,900)	(852,000)	(4,777,100)
2018	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	(648,200)	-	(2,007,900)	542,100	(1,465,700)	(817,600)	(5,244,500)
2019	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	(388,900)	-	(1,748,600)	472,100	(1,276,500)	(887,600)	(5,685,800)
2020	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	(388,900)	-	(1,748,600)	472,100	(1,276,500)	(887,600)	(6,069,500)
2021	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	(194,400)	-	(1,554,200)	419,600	(1,134,500)	(940,100)	(6,423,000)
2022	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(6,747,400)
2023	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(7,029,600)
2024	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(7,274,900)
2025	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(7,488,300)
2026	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(7,673,800)
2027	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(7,835,100)
2028	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(7,975,400)
2029	90%	$37.03	2,491,800	-	-	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(992,600)	(8,097,400)
2030	90%	$37.03	2,491,800	-	357,700	(2,153,800)	(1,697,600)	-	-	(1,359,700)	367,100	(992,600)	(634,900)	(8,165,200)

Profitability Measures

The Internal Rate of Return (IRR) for this project is Negative IRR

The Net Present Value (NPV) of this project in 2014 is $ (8,165,200)

ROI Analysis (Third Production Year)

Annual Sales	**2,491,758**
Annual Costs	**(3,851,464)**
Depreciation	**(302,475)**
Income Tax	**448,789**
Net Earnings	**(1,213,392)**
Total Capital Investment	**4,138,627**
ROI	**-29.32%**

Sensitivity Analyses

Note: The Sensitivity Analyses section below takes quite a bit of memory to update each time a cell is changed; therefore, automatic calculations are turned off. After making your axis selections, press "F9" to recalculate the IRR values. (These two lines may be deleted before printing.)

	Vary Initial Value by +/-
x-axis	50%
y-axis	50%

						Variable Costs					
Product Price	$1,196,565	$1,435,878	$1,675,191	$1,914,504	$2,153,817	***$2,393,130***	$2,632,443	$2,871,756	$3,111,069	$3,350,383	$3,589,696
$18.52	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$22.22	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$25.92	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$29.62	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$33.33	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$37.03	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$40.73	-16.79%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$44.44	-4.49%	-14.15%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$48.14	2.51%	-3.35%	-11.99%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$51.84	7.83%	3.28%	-2.29%	-10.15%	-26.27%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR
$55.55	12.33%	8.44%	4.02%	-1.31%	-8.55%	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR	Negative IRR

Curtailment (High Pressure Storage)

General Information

Process Title: **High Pressure Curtailment**
Product: **On-Peak Electricity**
Plant Site Location: **Midwest**
Site Factor: **1.00**
Operating Hours per Year: **7919**
Operating Days Per Year: **330**
Operating Factor: **0.9040**

Product Information

This Process will Yield

9 MWh of On-Peak Electricity per hour
227 MWh of On-Peak Electricity per day
74,767 MWh of On-Peak Electricity per year

Price **$37.03 /MWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2014	Design		0.0%		
2015	Construction	100%	0.0%		
2016	Production	0%	45.0%	20.00%	$37.03
2017	Production	0%	67.5%	32.00%	$37.03
2018	Production	0%	90.0%	19.20%	$37.03
2019	Production		90.0%	11.52%	$37.03
2020	Production		90.0%	11.52%	$37.03
2021	Production		90.0%	5.76%	$37.03
2022	Production		90.0%		$37.03
2023	Production		90.0%		$37.03
2024	Production		90.0%		$37.03
2025	Production		90.0%		$37.03
2026	Production		90.0%		$37.03
2027	Production		90.0%		$37.03
2028	Production		90.0%		$37.03
2029	Production		90.0%		$37.03
2030	Production		90.0%		$37.03

Equipment Costs

	Total
IPE Specifications	
Total Direct Materials and Labor Costs	$100,500
Miscellaneous Installation Costs	$2,500,300
Material and Labor G&A Overhead and Contractor Fees	$0
Contractor Engineering Costs	$0
Indirect Costs	$0
Total	$2,600,800

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:
1	Carbon Dioxide	lb	1454.2447 lb per MWh of On-Peak Electricity	$0.000E+00 per lb

Total Weighted Average: $0.000E+00 per MWh of On-Peak Electricity

Byproducts

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price
1	Oxygen	lb	528.69504 lb per MWh of On-Peak Electricity	$0.045 per lb

Total Weighted Average: $23.791 per MWh of On-Peak Electricity

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost
1	High Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
2	Low Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
3	Process Water	gal	0 gal per MWh of On-Peak Electricit	$0.000E+00 per gal
4	Cooling Water	lb	8172.4598 lb per MWh of On-Peak Electricity	$1.200E-05 per lb
5	Electricity	MWh	1.868 MWh per MWh of On-Peak Electri	$0.000E+00 per MWh
6	Fired Heater Fuel	lb	16.726715 lb per MWh of On-Peak Electricity	$0.090 per lb

Total Weighted Average: $1.603 per MWh of On-Peak Electricity

Variable Costs

General Expenses:

Selling / Transfer Expenses:	**3.00% of Sales**
Direct Research:	**4.80% of Sales**
Allocated Research:	**0.50% of Sales**
Administrative Expense:	**2.00% of Sales**
Management Incentive Compensation:	**1.25% of Sales**

Working Capital

Accounts Receivable	⇨	**30**	**Days**
Cash Reserves (excluding Raw Materials)	⇨	**30**	**Days**
Accounts Payable	⇨	**30**	**Days**
On-Peak Electricity Inventory	⇨	**4**	**Days**
Raw Materials	⇨	**2**	**Days**

Total Permanent Investment

Cost of Site Preparations:	5.00%	of Total Bare Module Costs
Cost of Service Facilities:	5.00%	of Total Bare Module Costs
Allocated Costs for utility plants and related facilities:	$0	
Cost of Contingencies and Contractor Fees:	18.00%	of Direct Permanent Investment
Cost of Land:	2.00%	of Total Depreciable Capital
Cost of Royalties:	$0	
Cost of Plant Start-Up:	10.00%	of Total Depreciable Capital

Fixed Costs

Operations

Operators per Shift:	1	(assuming 5 shifts)
Direct Wages and Benefits:	$40	/operator hour
Direct Salaries and Benefits:	15%	of Direct Wages and Benefits
Operating Supplies and Services:	6%	of Direct Wages and Benefits
Technical Assistance to Manufacturing:	$60,000.00	per year, for each Operator per Shift
Control Laboratory:	$65,000.00	per year, for each Operator per Shift

Maintenance

Wages and Benefits:	4.50%	of Total Depreciable Capital
Salaries and Benefits:	25%	of Maintenance Wages and Benefits
Materials and Services:	100%	of Maintenance Wages and Benefits
Maintenance Overhead:	5%	of Maintenance Wages and Benefits

Operating Overhead

General Plant Overhead:	7.10%	of Maintenance and Operations Wages and Benefits
Mechanical Department Services:	2.40%	of Maintenance and Operations Wages and Benefits
Employee Relations Department:	5.90%	of Maintenance and Operations Wages and Benefits
Business Services:	7.40%	of Maintenance and Operations Wages and Benefits

Property Taxes and Insurance

Property Taxes and Insurance:	2%	of Total Depreciable Capital

Straight Line Depreciation

Direct Plant:	8.00%	of Total Depreciable Capital, less 1.18 times the Allocated Costs for Utility Plants and Related Facilities
Allocated Plant:	6.00%	of 1.18 times the Allocated Costs for Utility Plants and Related Facilities

Other Annual Expenses

Rental Fees (Office and Laboratory Space):	$0
Licensing Fees:	$0
Miscellaneous:	$0

Depletion Allowance

Annual Depletion Allowance:	$0

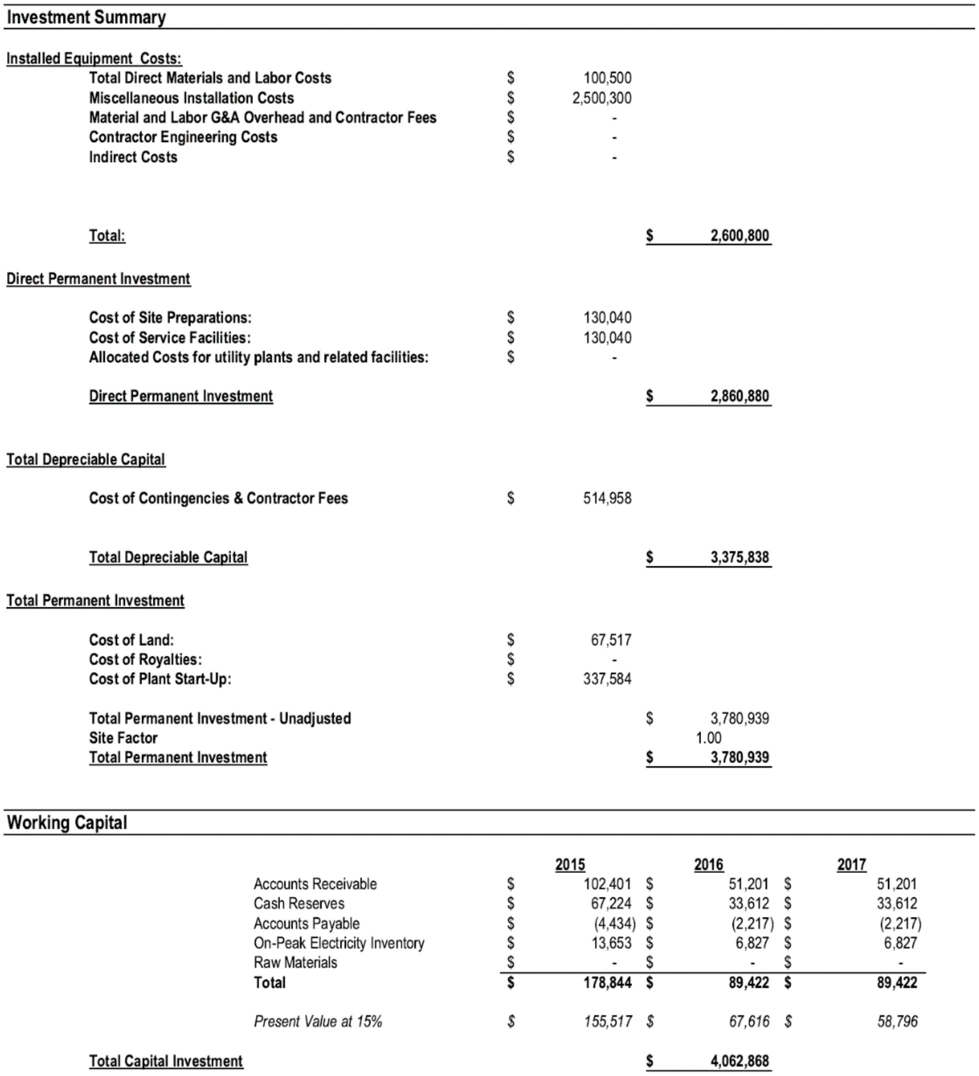
Variable Cost Summary

Variable Costs at 100% Capacity:

General Expenses			
Selling / Transfer Expenses:		$	83,059
Direct Research:		$	132,894
Allocated Research:		$	13,843
Administrative Expense:		$	55,372
Management Incentive Compensation:		$	34,608
Total General Expenses		$	319,776
Raw Materials	$0.000000 per MWh of On-Peak Electr		$0
Byproducts	$23.791277 per MWh of On-Peak Electr		($1,778,801)
Utilities	$1.603454 per MWh of On-Peak Electr		$119,885
Total Variable Costs		**$**	**(1,339,140)**

Fixed Cost Summary

Operations		
Direct Wages and Benefits	$	416,000
Direct Salaries and Benefits	$	62,400
Operating Supplies and Services	$	24,960
Technical Assistance to Manufacturing	$	300,000
Control Laboratory	$	325,000
Total Operations	**$**	**1,128,360**
Maintenance		
Wages and Benefits	$	151,913
Salaries and Benefits	$	37,978
Materials and Services	$	151,913
Maintenance Overhead	$	7,596
Total Maintenance	**$**	**349,399**
Operating Overhead		
General Plant Overhead:	$	47,449
Mechanical Department Services:	$	16,039
Employee Relations Department:	$	39,429
Business Services:	$	49,454
Total Operating Overhead	**$**	**152,370**
Property Taxes and Insurance		
Property Taxes and Insurance:	$	67,517
Other Annual Expenses		
Rental Fees (Office and Laboratory Space):	$	-
Licensing Fees:	$	-
Miscellaneous:	$	-
Total Other Annual Expenses	**$**	**-**
Total Fixed Costs	**$**	**1,697,646**



Investment Summary

Installed Equipment Costs:				
Total Direct Materials and Labor Costs	$	100,500		
Miscellaneous Installation Costs	$	2,500,300		
Material and Labor G&A Overhead and Contractor Fees	$	-		
Contractor Engineering Costs	$	-		
Indirect Costs	$	-		
Total:			**$**	**2,600,800**
Direct Permanent Investment				
Cost of Site Preparations:	$	130,040		
Cost of Service Facilities:	$	130,040		
Allocated Costs for utility plants and related facilities:	$	-		
Direct Permanent Investment			**$**	**2,860,880**
Total Depreciable Capital				
Cost of Contingencies & Contractor Fees	$	514,958		
Total Depreciable Capital			**$**	**3,375,838**
Total Permanent Investment				
Cost of Land:	$	67,517		
Cost of Royalties:	$	-		
Cost of Plant Start-Up:	$	337,584		
Total Permanent Investment - Unadjusted			$	3,780,939
Site Factor				1.00
Total Permanent Investment			**$**	**3,780,939**

Working Capital

		2015		**2016**		**2017**
Accounts Receivable	$	102,401	$	51,201	$	51,201
Cash Reserves	$	67,224	$	33,612	$	33,612
Accounts Payable	$	(4,434)	$	(2,217)	$	(2,217)
On-Peak Electricity Inventory	$	13,653	$	6,827	$	6,827
Raw Materials	$	-	$	-	$	-
Total	**$**	**178,844**	**$**	**89,422**	**$**	**89,422**
Present Value at 15%	*$*	*155,517*	*$*	*67,616*	*$*	*58,796*

Total Capital Investment	**$**	**4,062,868**

Cash Flow Summary

Year	Percentage of Design Capacity	Product Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Depletion Allowance	Taxible Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 15%
2014	0%		-	-	-	-	-	-	-	-	-	-	-	-
2015	0%		-	(3,780,900)	(178,800)	-	-	-	-	-	-	-	(3,959,800)	(3,443,300)
2016	45%	$37.03	1,245,900	-	(89,400)	602,600	(1,697,600)	(675,200)	-	(524,300)	141,600	(382,800)	203,000	(3,289,800)
2017	68%	$37.03	1,868,800	-	(89,400)	903,900	(1,697,600)	(1,080,300)	-	(5,200)	1,400	(3,800)	987,100	(2,640,800)
2018	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	(648,200)	-	1,351,200	(364,800)	986,400	1,634,500	(1,706,200)
2019	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	(388,900)	-	1,610,400	(434,800)	1,175,600	1,564,500	(928,400)
2020	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	(388,900)	-	1,610,400	(434,800)	1,175,600	1,564,500	(252,000)
2021	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	(194,400)	-	1,804,900	(487,300)	1,317,600	1,512,000	316,400
2022	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	793,500
2023	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	1,208,400
2024	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	1,569,200
2025	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	1,882,900
2026	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	2,155,700
2027	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	2,392,900
2028	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	2,599,200
2029	90%	$37.03	2,491,800	-	-	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,459,500	2,778,500
2030	90%	$37.03	2,491,800	-	357,700	1,205,200	(1,697,600)	-	-	1,999,300	(539,800)	1,459,500	1,817,200	2,972,700

Profitability Measures

The Internal Rate of Return (IRR) for this project is 28.18%

The Net Present Value (NPV) of this project in 2014 is $ 2,972,700

ROI Analysis (Third Production Year)

Annual Sales	**2,491,758**
Annual Costs	**(492,420)**
Depreciation	**(302,475)**
Income Tax	**(458,153)**
Net Earnings	**1,238,710**
Total Capital Investment	**4,138,627**
ROI	**29.93%**

Sensitivity Analyses

Note: The Sensitivity Analyses section below takes quite a bit of memory to update each time a cell is changed; therefore, automatic calculations are turned off. After making your axis selections, press "F9" to recalculate the IRR values. (These two lines may be deleted before printing.)

	Vary Initial Value by +/-
x-axis	50%
y-axis	50%

Product Price						**Variable Costs**					
	-66957014.51%	-80348417.41%	-93739820.31%	-107131223.21%	-120522626.11%	***-133914029.01%***	-147305431.91%	-160696834.82%	-174088237.72%	-187479640.62%	-200871043.52%
$18.52	-7.40%	-2.86%	0.74%	3.82%	6.54%	9.03%	11.33%	13.50%	15.56%	17.53%	19.43%
$22.22	0.96%	3.98%	6.68%	9.14%	11.42%	13.58%	15.62%	17.58%	19.47%	21.30%	23.07%
$25.92	6.81%	9.25%	11.51%	13.65%	15.68%	17.63%	19.51%	21.33%	23.10%	24.82%	26.51%
$29.62	11.60%	13.72%	15.74%	17.68%	19.55%	21.36%	23.12%	24.84%	26.52%	28.17%	29.79%
$33.33	15.80%	17.73%	19.59%	21.39%	23.15%	24.86%	26.53%	28.17%	29.79%	31.38%	32.94%
$37.03	19.63%	21.42%	23.17%	24.87%	26.54%	28.18%	29.78%	31.37%	32.93%	34.47%	35.99%
$40.73	23.19%	24.89%	26.55%	28.18%	29.78%	31.36%	32.91%	34.45%	35.96%	37.46%	38.94%
$44.44	26.56%	28.18%	29.78%	31.35%	32.90%	34.43%	35.94%	37.43%	38.91%	40.37%	41.83%
$48.14	29.78%	31.34%	32.88%	34.41%	35.91%	37.40%	38.88%	40.34%	41.78%	43.22%	44.64%
$51.84	32.87%	34.39%	35.89%	37.37%	38.84%	40.30%	41.74%	43.17%	44.59%	46.00%	47.40%
$55.55	35.86%	37.34%	38.81%	40.26%	41.70%	43.12%	44.54%	45.94%	47.34%	48.73%	50.10%

Curtailment (Low Pressure Storage)

General Information

Process Title: **Low Pressure Curtailment**
Product: **On-Peak Electricity**
Plant Site Location: **Midwest**
Site Factor: **1.00**
Operating Hours per Year: **7919**
Operating Days Per Year: **330**
Operating Factor: **0.9040**

Product Information

This Process will Yield

9 MWh of On-Peak Electricity per hour
227 MWh of On-Peak Electricity per day
74,767 MWh of On-Peak Electricity per year

Price **$37.03 /MWh**

Chronology

Year	Action	Distribution of Permanent Investment	Production Capacity	Depreciation 5 year MACRS	Product Price
2014	Design		0.0%		
2015	Construction	100%	0.0%		
2016	Production	0%	45.0%	20.00%	$37.03
2017	Production	0%	67.5%	32.00%	$37.03
2018	Production	0%	90.0%	19.20%	$37.03
2019	Production		90.0%	11.52%	$37.03
2020	Production		90.0%	11.52%	$37.03
2021	Production		90.0%	5.76%	$37.03
2022	Production		90.0%		$37.03
2023	Production		90.0%		$37.03
2024	Production		90.0%		$37.03
2025	Production		90.0%		$37.03
2026	Production		90.0%		$37.03
2027	Production		90.0%		$37.03
2028	Production		90.0%		$37.03
2029	Production		90.0%		$37.03
2030	Production		90.0%		$37.03

Equipment Costs

	Total
IPE Specifications	
Total Direct Materials and Labor Costs	$100,500
Miscellaneous Installation Costs	$2,500,300
Material and Labor G&A Overhead and Contractor Fees	$0
Contractor Engineering Costs	$0
Indirect Costs	$0
Total	$2,600,800

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:
1	Carbon Dioxide	lb	1454.2447 lb per MWh of On-Peak Electricity	$0.000E+00 per lb

Total Weighted Average: $0.000E+00 per MWh of On-Peak Electricity

Byproducts

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price
1	Oxygen	lb	528.69504 lb per MWh of On-Peak Electricity	$0.045 per lb

Total Weighted Average: $23.791 per MWh of On-Peak Electricity

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost
1	High Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
2	Low Pressure Steam	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb
3	Process Water	gal	0 gal per MWh of On-Peak Electricit	$0.000E+00 per gal
4	Cooling Water	lb	2164.83 lb per MWh of On-Peak Electricity	$1.200E-05 per lb
5	Electricity	MWh	1.8333451 MWh per MWh of On-Peak Electri	$0.000E+00 per MWh
6	Fired Heater Fuel	lb	0 lb per MWh of On-Peak Electricity	$0.000E+00 per lb

Total Weighted Average: $0.026 per MWh of On-Peak Electricity

Variable Costs

General Expenses:

Selling / Transfer Expenses:	**3.00% of Sales**
Direct Research:	**4.80% of Sales**
Allocated Research:	**0.50% of Sales**
Administrative Expense:	**2.00% of Sales**
Management Incentive Compensation:	**1.25% of Sales**

Working Capital

Accounts Receivable	⇨	**30**	**Days**
Cash Reserves (excluding Raw Materials)	⇨	**30**	**Days**
Accounts Payable	⇨	**30**	**Days**
On-Peak Electricity Inventory	⇨	**4**	**Days**
Raw Materials	⇨	**2**	**Days**

Total Permanent Investment

Cost of Site Preparations:	5.00%	of Total Bare Module Costs
Cost of Service Facilities:	5.00%	of Total Bare Module Costs
Allocated Costs for utility plants and related facilities:	$0	
Cost of Contingencies and Contractor Fees:	18.00%	of Direct Permanent Investment
Cost of Land:	2.00%	of Total Depreciable Capital
Cost of Royalties:	$0	
Cost of Plant Start-Up:	10.00%	of Total Depreciable Capital

Fixed Costs

Operations

Operators per Shift:	1	(assuming 5 shifts)
Direct Wages and Benefits:	$40	/operator hour
Direct Salaries and Benefits:	15%	of Direct Wages and Benefits
Operating Supplies and Services:	6%	of Direct Wages and Benefits
Technical Assistance to Manufacturing:	$60,000.00	per year, for each Operator per Shift
Control Laboratory:	$65,000.00	per year, for each Operator per Shift

Maintenance

Wages and Benefits:	4.50%	of Total Depreciable Capital
Salaries and Benefits:	25%	of Maintenance Wages and Benefits
Materials and Services:	100%	of Maintenance Wages and Benefits
Maintenance Overhead:	5%	of Maintenance Wages and Benefits

Operating Overhead

General Plant Overhead:	7.10%	of Maintenance and Operations Wages and Benefits
Mechanical Department Services:	2.40%	of Maintenance and Operations Wages and Benefits
Employee Relations Department:	5.90%	of Maintenance and Operations Wages and Benefits
Business Services:	7.40%	of Maintenance and Operations Wages and Benefits

Property Taxes and Insurance

Property Taxes and Insurance:	2%	of Total Depreciable Capital

Straight Line Depreciation

Direct Plant:	8.00%	of Total Depreciable Capital, less 1.18 times the Allocated Costs for Utility Plants and Related Facilities
Allocated Plant:	6.00%	of 1.18 times the Allocated Costs for Utility Plants and Related Facilities

Other Annual Expenses

Rental Fees (Office and Laboratory Space):	$0
Licensing Fees:	$0
Miscellaneous:	$0

Depletion Allowance

Annual Depletion Allowance:	$0

Variable Cost Summary

Variable Costs at 100% Capacity:

General Expenses

Selling / Transfer Expenses:		$	83,059
Direct Research:		$	132,894
Allocated Research:		$	13,843
Administrative Expense:		$	55,372
Management Incentive Compensation:		$	34,608
Total General Expenses		$	319,776
Raw Materials	$0.000000 per MWh of On-Peak Electr		$0
Byproducts	$23.791277 per MWh of On-Peak Electr		($1,778,801)
Utilities	$0.025973 per MWh of On-Peak Electr		$1,942
Total Variable Costs		**$**	**(1,457,084)**

Fixed Cost Summary

Operations

Direct Wages and Benefits	$	416,000
Direct Salaries and Benefits	$	62,400
Operating Supplies and Services	$	24,960
Technical Assistance to Manufacturing	$	300,000
Control Laboratory	$	325,000
Total Operations	**$**	**1,128,360**

Maintenance

Wages and Benefits	$	151,913
Salaries and Benefits	$	37,978
Materials and Services	$	151,913
Maintenance Overhead	$	7,596
Total Maintenance	**$**	**349,399**

Operating Overhead

General Plant Overhead:	$	47,449
Mechanical Department Services:	$	16,039
Employee Relations Department:	$	39,429
Business Services:	$	49,454
Total Operating Overhead	**$**	**152,370**

Property Taxes and Insurance

Property Taxes and Insurance:	$	67,517

Other Annual Expenses

Rental Fees (Office and Laboratory Space):	$	-
Licensing Fees:	$	-
Miscellaneous:	$	-
Total Other Annual Expenses	**$**	**-**
Total Fixed Costs	**$**	**1,697,646**

Investment Summary

Installed Equipment Costs:				
Total Direct Materials and Labor Costs	$	100,500		
Miscellaneous Installation Costs	$	2,500,300		
Material and Labor G&A Overhead and Contractor Fees	$	-		
Contractor Engineering Costs	$	-		
Indirect Costs	$	-		
Total:			**$**	**2,600,800**
Direct Permanent Investment				
Cost of Site Preparations:	$	130,040		
Cost of Service Facilities:	$	130,040		
Allocated Costs for utility plants and related facilities:	$	-		
Direct Permanent Investment			**$**	**2,860,880**
Total Depreciable Capital				
Cost of Contingencies & Contractor Fees	$	514,958		
Total Depreciable Capital			**$**	**3,375,838**
Total Permanent Investment				
Cost of Land:	$	67,517		
Cost of Royalties:	$	-		
Cost of Plant Start-Up:	$	337,584		
Total Permanent Investment - Unadjusted			$	3,780,939
Site Factor				1.00
Total Permanent Investment			**$**	**3,780,939**

Working Capital

		2015		2016		2017
Accounts Receivable	$	102,401	$	51,201	$	51,201
Cash Reserves	$	62,861	$	31,431	$	31,431
Accounts Payable	$	(72)	$	(36)	$	(36)
On-Peak Electricity Inventory	$	13,653	$	6,827	$	6,827
Raw Materials	$	-	$	-	$	-
Total	**$**	**178,844**	**$**	**89,422**	**$**	**89,422**
Present Value at 15%	*$*	*155,517*	*$*	*67,616*	*$*	*58,796*

Total Capital Investment	**$**	**4,062,868**

Cash Flow Summary

Year	Percentage of Design Capacity	Product Unit Price	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Depreciation	Depletion Allowance	Taxible Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 15%
2014	0%		-	-	-	-	-	-	-	-	-	-	-	-
2015	0%		-	(3,780,900)	(178,800)	-	-	-	-	-	-	-	(3,959,800)	(3,443,300)
2016	45%	$37.03	1,245,900	-	(89,400)	655,700	(1,697,600)	(675,200)	-	(471,200)	127,200	(344,000)	241,700	(3,260,500)
2017	68%	$37.03	1,868,800	-	(89,400)	983,500	(1,697,600)	(1,080,300)	-	74,400	(20,100)	54,300	1,045,200	(2,573,300)
2018	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	(648,200)	-	1,457,300	(393,500)	1,063,800	1,712,000	(1,594,400)
2019	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	(388,900)	-	1,716,600	(463,500)	1,253,100	1,642,000	(778,100)
2020	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	(388,900)	-	1,716,600	(463,500)	1,253,100	1,642,000	(68,200)
2021	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	(194,400)	-	1,911,000	(516,000)	1,395,100	1,589,500	529,400
2022	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	1,031,800
2023	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	1,468,700
2024	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	1,848,700
2025	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	2,179,000
2026	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	2,466,300
2027	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	2,716,100
2028	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	2,933,300
2029	90%	$37.03	2,491,800	-	-	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,537,000	3,122,200
2030	90%	$37.03	2,491,800	-	357,700	1,311,400	(1,697,600)	-	-	2,105,500	(568,500)	1,537,000	1,894,700	3,324,700

Profitability Measures

The Internal Rate of Return (IRR) for this project is 29.59%

The Net Present Value (NPV) of this project in 2014 is $ 3,324,700

ROI Analysis (Third Production Year)

Annual Sales	**2,491,758**
Annual Costs	**(386,271)**
Depreciation	**(302,475)**
Income Tax	**(486,813)**
Net Earnings	**1,316,199**
Total Capital Investment	**4,138,627**
ROI	**31.80%**

Sensitivity Analyses

Note: The Sensitivity Analyses section below takes quite a bit of memory to update each time a cell is changed; therefore, automatic calculations are turned off. After making your axis selections, press "F9" to recalculate the IRR values. (These two lines may be deleted before printing.)

	Vary Initial Value by +/-
x-axis	50%
y-axis	50%

							Variable Costs					
		-72854188.61%	-87425026.33%	-101995864.05%	-116566701.77%	-131137539.49%	***-145708377.22%***	-160279214.94%	-174850052.66%	-189420890.38%	-203991728.10%	-218562565.82%
Product Price	$18.52	-5.25%	-0.87%	2.69%	5.77%	8.53%	11.07%	13.43%	15.67%	17.81%	19.86%	21.84%
	$22.22	2.34%	5.44%	8.22%	10.76%	13.14%	15.38%	17.52%	19.57%	21.56%	23.48%	25.36%
	$25.92	7.91%	10.46%	12.84%	15.09%	17.23%	19.29%	21.27%	23.20%	25.07%	26.90%	28.69%
	$29.62	12.55%	14.80%	16.95%	19.00%	20.99%	22.91%	24.79%	26.62%	28.41%	30.16%	31.89%
	$33.33	16.66%	18.72%	20.71%	22.63%	24.51%	26.33%	28.12%	29.88%	31.60%	33.30%	34.98%
	$37.03	20.43%	22.35%	24.22%	26.05%	27.84%	29.59%	31.32%	33.01%	34.69%	36.34%	37.97%
	$40.73	23.94%	25.77%	27.56%	29.31%	31.03%	32.73%	34.40%	36.05%	37.68%	39.29%	40.88%
	$44.44	27.28%	29.03%	30.75%	32.44%	34.11%	35.76%	37.38%	38.99%	40.58%	42.16%	43.72%
	$48.14	30.47%	32.16%	33.83%	35.47%	37.09%	38.70%	40.29%	41.86%	43.42%	44.97%	46.51%
	$51.84	33.54%	35.18%	36.81%	38.41%	40.00%	41.57%	43.13%	44.67%	46.20%	47.72%	49.23%
	$55.55	36.52%	38.12%	39.70%	41.27%	42.83%	44.37%	45.90%	47.42%	48.93%	50.42%	51.91%

Appendix C

Safety Data

SAFETY DATA SHEET

Carbon Dioxide

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier : Carbon Dioxide

Chemical name : Carbon dioxide, gas

Other means of identification : Carbonic, Carbon Dioxide, Carbonic Anhydride, R744, Carbon Dioxide USP

Product type : Gas.

Product use : Synthetic/Analytical chemistry and Medical use.

Synonym : Carbonic, Carbon Dioxide, Carbonic Anhydride, R744, Carbon Dioxide USP

SDS # : 001013

Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : GASES UNDER PRESSURE - Liquefied gas
Simple asphyxiant.

GHS label elements

Hazard pictograms :

Signal word : Warning

Hazard statements : Contains gas under pressure; may explode if heated.
May displace oxygen and cause rapid suffocation.
May increase respiration and heart rate.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Always keep container in upright position.

Prevention : Use and store only outdoors or in a well ventilated place.

Response : Not applicable.

Storage : Protect from sunlight. Store in a well-ventilated place.

Disposal : Not applicable.

Hazards not otherwise classified : In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.
May cause frostbite.

Section 3. Composition/information on ingredients

Substance/mixture	: Substance
Chemical name	: Carbon dioxide, gas
Other means of identification	: Carbonic, Carbon Dioxide, Carbonic Anhydride, R744, Carbon Dioxide USP
Product code	: 001013

CAS number/other identifiers

CAS number : 124-38-9

Ingredient name	%	CAS number
Carbon Dioxide	100	124-38-9

Any concentration shown as a range is to protect confidentiality or is due to batch variation.

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment and hence require reporting in this section.

Occupational exposure limits, if available, are listed in Section 8.

Section 4. First aid measures

Description of necessary first aid measures

Eye contact	: Immediately flush eyes with plenty of water, occasionally lifting the upper and lower eyelids. Check for and remove any contact lenses. Continue to rinse for at least 10 minutes. Get medical attention if irritation occurs.
Inhalation	: Remove victim to fresh air and keep at rest in a position comfortable for breathing. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation. Get medical attention if adverse health effects persist or are severe. If unconscious, place in recovery position and get medical attention immediately. Maintain an open airway. Loosen tight clothing such as a collar, tie, belt or waistband.
Skin contact	: Flush contaminated skin with plenty of water. Remove contaminated clothing and shoes. Get medical attention if symptoms occur. Wash clothing before reuse. Clean shoes thoroughly before reuse.
Ingestion	: As this product is a gas, refer to the inhalation section.

Most important symptoms/effects, acute and delayed

Potential acute health effects

Eye contact	: No known significant effects or critical hazards.
Inhalation	: No known significant effects or critical hazards.
Skin contact	: No known significant effects or critical hazards.
Frostbite	: Try to warm up the frozen tissues and seek medical attention.
Ingestion	: As this product is a gas, refer to the inhalation section.

Over-exposure signs/symptoms

Eye contact	: No specific data.
Inhalation	: No specific data.
Skin contact	: No specific data.
Ingestion	: No specific data.

Indication of immediate medical attention and special treatment needed, if necessary

Notes to physician	: Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.
Specific treatments	: No specific treatment.

Section 4. First aid measures

Protection of first-aiders : No action shall be taken involving any personal risk or without suitable training. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

See toxicological information (Section 11)

Section 5. Fire-fighting measures

Extinguishing media

Suitable extinguishing media : Use an extinguishing agent suitable for the surrounding fire.

Unsuitable extinguishing media : None known.

Specific hazards arising from the chemical : Contains gas under pressure. In a fire or if heated, a pressure increase will occur and the container may burst or explode.

Hazardous thermal decomposition products : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Special protective actions for fire-fighters : Promptly isolate the scene by removing all persons from the vicinity of the incident if there is a fire. No action shall be taken involving any personal risk or without suitable training. Contact supplier immediately for specialist advice. Move containers from fire area if this can be done without risk. Use water spray to keep fire-exposed containers cool.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions, protective equipment and emergency procedures

For non-emergency personnel : No action shall be taken involving any personal risk or without suitable training. Evacuate surrounding areas. Keep unnecessary and unprotected personnel from entering. Avoid breathing gas. Provide adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Put on appropriate personal protective equipment.

For emergency responders : If specialized clothing is required to deal with the spillage, take note of any information in Section 8 on suitable and unsuitable materials. See also the information in "For non-emergency personnel".

Environmental precautions : Ensure emergency procedures to deal with accidental gas releases are in place to avoid contamination of the environment. Inform the relevant authorities if the product has caused environmental pollution (sewers, waterways, soil or air).

Methods and materials for containment and cleaning up

Small spill : Immediately contact emergency personnel. Stop leak if without risk.

Large spill : Immediately contact emergency personnel. Stop leak if without risk. Note: see Section 1 for emergency contact information and Section 13 for waste disposal.

Section 7. Handling and storage

Precautions for safe handling

Protective measures : Put on appropriate personal protective equipment (see Section 8). Contains gas under pressure. Avoid breathing gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
Avoid contact with eyes, skin and clothing. Empty containers retain product residue and can be hazardous.

Section 7. Handling and storage

Advice on general occupational hygiene	: Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed. Workers should wash hands and face before eating, drinking and smoking. Remove contaminated clothing and protective equipment before entering eating areas. See also Section 8 for additional information on hygiene measures.
Conditions for safe storage, including any incompatibilities	: Store in accordance with local regulations. Store in a segregated and approved area. Store away from direct sunlight in a dry, cool and well-ventilated area, away from incompatible materials (see Section 10). Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F). Keep container tightly closed and sealed until ready for use. See Section 10 for incompatible materials before handling or use.

Section 8. Exposure controls/personal protection

Control parameters

Occupational exposure limits

Ingredient name	Exposure limits
Carbon Dioxide	**ACGIH TLV (United States, 3/2017). Oxygen Depletion [Asphyxiant].** STEL: 54000 mg/m³ 15 minutes. STEL: 30000 ppm 15 minutes. TWA: 9000 mg/m³ 8 hours. TWA: 5000 ppm 8 hours. **NIOSH REL (United States, 10/2016).** STEL: 54000 mg/m³ 15 minutes. STEL: 30000 ppm 15 minutes. TWA: 9000 mg/m³ 10 hours. TWA: 5000 ppm 10 hours. **OSHA PEL (United States, 6/2016).** TWA: 9000 mg/m³ 8 hours. TWA: 5000 ppm 8 hours. **OSHA PEL 1989 (United States, 3/1989).** STEL: 54000 mg/m³ 15 minutes. STEL: 30000 ppm 15 minutes. TWA: 18000 mg/m³ 8 hours. TWA: 10000 ppm 8 hours.

Appropriate engineering controls	: Good general ventilation should be sufficient to control worker exposure to airborne contaminants.
Environmental exposure controls	: Emissions from ventilation or work process equipment should be checked to ensure they comply with the requirements of environmental protection legislation. In some cases, fume scrubbers, filters or engineering modifications to the process equipment will be necessary to reduce emissions to acceptable levels.

Individual protection measures

Hygiene measures	: Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing. Ensure that eyewash stations and safety showers are close to the workstation location.
Eye/face protection	: Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists, gases or dusts. If contact is possible, the following protection should be worn, unless the assessment indicates a higher degree of protection: safety glasses with side-shields.

Skin protection

Section 8. Exposure controls/personal protection

Hand protection : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary. Considering the parameters specified by the glove manufacturer, check during use that the gloves are still retaining their protective properties. It should be noted that the time to breakthrough for any glove material may be different for different glove manufacturers. In the case of mixtures, consisting of several substances, the protection time of the gloves cannot be accurately estimated.

Body protection : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Other skin protection : Appropriate footwear and any additional skin protection measures should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Respiratory protection : Based on the hazard and potential for exposure, select a respirator that meets the appropriate standard or certification. Respirators must be used according to a respiratory protection program to ensure proper fitting, training, and other important aspects of use. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

Section 9. Physical and chemical properties

Appearance

Physical state : Gas. [Compressed gas.]

Color : Colorless.

Odor : Odorless.

Odor threshold : Not available.

pH : Not available.

Melting point : Sublimation temperature: -79°C (-110.2 to °F)

Boiling point : Not available.

Critical temperature : 30.85°C (87.5°F)

Flash point : [Product does not sustain combustion.]

Evaporation rate : Not available.

Flammability (solid, gas) : Not available.

Lower and upper explosive (flammable) limits : Not available.

Vapor pressure : 830 (psig)

Vapor density : 1.53 (Air = 1) Liquid Density@BP: Solid density = 97.5 lb/ft3 (1562 kg/m3)

Specific Volume (ft ^{3}/lb) : 8.7719

Gas Density (lb/ft ^{3}) : 0.114

Relative density : Not applicable.

Solubility : Not available.

Solubility in water : Not available.

Partition coefficient: n-octanol/water : 0.83

Auto-ignition temperature : Not available.

Decomposition temperature : Not available.

Viscosity : Not applicable.

Flow time (ISO 2431) : Not available.

Molecular weight : 44.01 g/mole

Section 10. Stability and reactivity

Reactivity	: No specific test data related to reactivity available for this product or its ingredients.
Chemical stability	: The product is stable.
Possibility of hazardous reactions	: Under normal conditions of storage and use, hazardous reactions will not occur.
Conditions to avoid	: No specific data.
Incompatible materials	: No specific data.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Information on toxicological effects

Acute toxicity

Not available.

Irritation/Corrosion

Not available.

Sensitization

Not available.

Mutagenicity

Not available.

Carcinogenicity

Not available.

Reproductive toxicity

Not available.

Teratogenicity

Not available.

Specific target organ toxicity (single exposure)

Not available.

Specific target organ toxicity (repeated exposure)

Not available.

Aspiration hazard

Not available.

Information on the likely routes of exposure : Not available.

Potential acute health effects

Eye contact	: No known significant effects or critical hazards.
Inhalation	: No known significant effects or critical hazards.
Skin contact	: No known significant effects or critical hazards.

Section 11. Toxicological information

Ingestion : As this product is a gas, refer to the inhalation section.

Symptoms related to the physical, chemical and toxicological characteristics

Eye contact : No specific data.
Inhalation : No specific data.
Skin contact : No specific data.
Ingestion : No specific data.

Delayed and immediate effects and also chronic effects from short and long term exposure

Short term exposure

Potential immediate effects : Not available.
Potential delayed effects : Not available.

Long term exposure

Potential immediate effects : Not available.
Potential delayed effects : Not available.

Potential chronic health effects

Not available.

General : No known significant effects or critical hazards.
Carcinogenicity : No known significant effects or critical hazards.
Mutagenicity : No known significant effects or critical hazards.
Teratogenicity : No known significant effects or critical hazards.
Developmental effects : No known significant effects or critical hazards.
Fertility effects : No known significant effects or critical hazards.

Numerical measures of toxicity

Acute toxicity estimates

Not available.

Section 12. Ecological information

Toxicity

Not available.

Persistence and degradability

Not available.

Bioaccumulative potential

Product/ingredient name	$LogP_{ow}$	BCF	Potential
Carbon Dioxide	0.83	-	low

Mobility in soil

Soil/water partition coefficient (K_{OC}) : Not available.

Other adverse effects : No known significant effects or critical hazards.

Section 13. Disposal considerations

Disposal methods : The generation of waste should be avoided or minimized wherever possible. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Waste should not be disposed of untreated to the sewer unless fully compliant with the requirements of all authorities with jurisdiction. Empty Airgas-owned pressure vessels should be returned to Airgas. Waste packaging should be recycled. Incineration or landfill should only be considered when recycling is not feasible. This material and its container must be disposed of in a safe way. Empty containers or liners may retain some product residues. Do not puncture or incinerate container.

Section 14. Transport information

	DOT	**TDG**	**Mexico**	**IMDG**	**IATA**
UN number	UN1013	UN1013	UN1013	UN1013	UN1013
UN proper shipping name	CARBON DIOXIDE	CARBON DIOXIDE	CARBON DIOXIDE	CARBON DIOXIDE	CARBON DIOXIDE
Transport hazard class(es)	2.2 	2.2 	2.2 	2.2 	2.2 
Packing group	-	-	-	-	-
Environmental hazards	No.	No.	No.	No.	No.

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Additional information

DOT Classification : **Limited quantity** Yes.
Quantity limitation Passenger aircraft/rail: 75 kg. Cargo aircraft: 150 kg.

TDG Classification : Product classified as per the following sections of the Transportation of Dangerous Goods Regulations: 2.13-2.17 (Class 2).
Explosive Limit and Limited Quantity Index 0.125
Passenger Carrying Road or Rail Index 75

IATA : **Quantity limitation** Passenger and Cargo Aircraft: 75 kg. Cargo Aircraft Only: 150 kg.

Special precautions for user : **Transport within user's premises:** always transport in closed containers that are upright and secure. Ensure that persons transporting the product know what to do in the event of an accident or spillage.

Transport in bulk according to Annex II of MARPOL and the IBC Code : Not available.

Section 15. Regulatory information

U.S. Federal regulations : **TSCA 8(a) CDR Exempt/Partial exemption**: This material is listed or exempted.

Clean Air Act Section 112 (b) Hazardous Air Pollutants (HAPs) : Not listed

Section 15. Regulatory information

Clean Air Act Section 602 Class I Substances : Not listed

Clean Air Act Section 602 Class II Substances : Not listed

DEA List I Chemicals (Precursor Chemicals) : Not listed

DEA List II Chemicals (Essential Chemicals) : Not listed

SARA 302/304

Composition/information on ingredients

No products were found.

SARA 304 RQ : Not applicable.

SARA 311/312

Classification : Refer to Section 2: Hazards Identification of this SDS for classification of substance.

State regulations

Massachusetts : This material is listed.
New York : This material is not listed.
New Jersey : This material is listed.
Pennsylvania : This material is listed.

International regulations

Chemical Weapon Convention List Schedules I, II & III Chemicals

Not listed.

Montreal Protocol (Annexes A, B, C, E)

Not listed.

Stockholm Convention on Persistent Organic Pollutants

Not listed.

Rotterdam Convention on Prior Informed Consent (PIC)

Not listed.

UNECE Aarhus Protocol on POPs and Heavy Metals

Not listed.

Inventory list

Australia : This material is listed or exempted.
Canada : This material is listed or exempted.
China : This material is listed or exempted.
Europe : This material is listed or exempted.
Japan : **Japan inventory (ENCS)**: This material is listed or exempted.
Japan inventory (ISHL): This material is listed or exempted.
Malaysia : Not determined.
New Zealand : This material is listed or exempted.
Philippines : This material is listed or exempted.
Republic of Korea : This material is listed or exempted.
Taiwan : This material is listed or exempted.
Thailand : Not determined.
Turkey : This material is listed or exempted.
United States : This material is listed or exempted.
Viet Nam : Not determined.

Section 16. Other information

Hazardous Material Information System (U.S.A.)

Health	/	1
Flammability		0
Physical hazards		3

Caution: HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. Although HMIS® ratings and the associated label are not required on SDSs or products leaving a facility under 29 CFR 1910.1200, the preparer may choose to provide them. HMIS® ratings are to be used with a fully implemented HMIS® program. HMIS® is a registered trademark and service mark of the American Coatings Association, Inc.

The customer is responsible for determining the PPE code for this material. For more information on HMIS® Personal Protective Equipment (PPE) codes, consult the HMIS® Implementation Manual.

National Fire Protection Association (U.S.A.)

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Copyright ©2001, National Fire Protection Association, Quincy, MA 02269. This warning system is intended to be interpreted and applied only by properly trained individuals to identify fire, health and reactivity hazards of chemicals. The user is referred to certain limited number of chemicals with recommended classifications in NFPA 49 and NFPA 325, which would be used as a guideline only. Whether the chemicals are classified by NFPA or not, anyone using the 704 systems to classify chemicals does so at their own risk.

Procedure used to derive the classification

Classification	Justification
GASES UNDER PRESSURE - Liquefied gas	Expert judgment

History

Date of printing : 2/12/2018

Date of issue/Date of revision : 2/12/2018

Date of previous issue : 4/25/2017

Version : 0.03

Key to abbreviations : ATE = Acute Toxicity Estimate
BCF = Bioconcentration Factor
GHS = Globally Harmonized System of Classification and Labelling of Chemicals
IATA = International Air Transport Association
IBC = Intermediate Bulk Container
IMDG = International Maritime Dangerous Goods
LogPow = logarithm of the octanol/water partition coefficient
MARPOL = International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978. ("Marpol" = marine pollution)
UN = United Nations

References : Not available.

Notice to reader

Section 16. Other information

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

SAFETY DATA SHEET

Oxygen

Section 1. Identification

GHS product identifier : Oxygen

Chemical name : oxygen

Other means of identification : Molecular oxygen; Oxygen molecule; Pure oxygen; O2; UN 1072; Dioxygen; Oxygen USP, Aviator's Breathing Oxygen (ABO)

Product type : Gas.

Product use : Synthetic/Analytical chemistry.

Synonym : Molecular oxygen; Oxygen molecule; Pure oxygen; O2; UN 1072; Dioxygen; Oxygen USP, Aviator's Breathing Oxygen (ABO)

SDS # : 001043

Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : OXIDIZING GASES - Category 1
GASES UNDER PRESSURE - Compressed gas

GHS label elements

Hazard pictograms :

Signal word : Danger

Hazard statements : May cause or intensify fire; oxidizer.
Contains gas under pressure; may explode if heated.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Open valve slowly. Use only with equipment cleaned for Oxygen service.

Prevention : Keep away from clothing, incompatible materials and combustible materials. Keep reduction valves, valves and fittings free from oil and grease.

Response : In case of fire: Stop leak if safe to do so.

Storage : Protect from sunlight. Store in a well-ventilated place.

Disposal : Not applicable.

Hazards not otherwise classified : None known.

Section 3. Composition/information on ingredients

Substance/mixture : Substance

Chemical name : oxygen

Other means of identification : Molecular oxygen; Oxygen molecule; Pure oxygen; O2; UN 1072; Dioxygen; Oxygen USP, Aviator's Breathing Oxygen (ABO)

Product code : 001043

CAS number/other identifiers

CAS number : 7782-44-7

Ingredient name	%	CAS number
oxygen	100	7782-44-7

Any concentration shown as a range is to protect confidentiality or is due to batch variation.

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment and hence require reporting in this section.

Occupational exposure limits, if available, are listed in Section 8.

Section 4. First aid measures

Description of necessary first aid measures

Eye contact : Immediately flush eyes with plenty of water, occasionally lifting the upper and lower eyelids. Check for and remove any contact lenses. Continue to rinse for at least 10 minutes. Get medical attention.

Inhalation : Remove victim to fresh air and keep at rest in a position comfortable for breathing. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation. Get medical attention if adverse health effects persist or are severe. If unconscious, place in recovery position and get medical attention immediately. Maintain an open airway. Loosen tight clothing such as a collar, tie, belt or waistband.

Skin contact : Flush contaminated skin with plenty of water. Remove contaminated clothing and shoes. Get medical attention if symptoms occur. Wash clothing before reuse. Clean shoes thoroughly before reuse.

Ingestion : As this product is a gas, refer to the inhalation section.

Most important symptoms/effects, acute and delayed

Potential acute health effects

Eye contact : Contact with rapidly expanding gas may cause burns or frostbite.

Inhalation : No known significant effects or critical hazards.

Skin contact : Contact with rapidly expanding gas may cause burns or frostbite.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Ingestion : As this product is a gas, refer to the inhalation section.

Over-exposure signs/symptoms

Eye contact : No specific data.

Inhalation : No specific data.

Skin contact : No specific data.

Ingestion : No specific data.

Indication of immediate medical attention and special treatment needed, if necessary

Notes to physician : Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.

Specific treatments : No specific treatment.

Section 4. First aid measures

Protection of first-aiders	: No action shall be taken involving any personal risk or without suitable training. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

See toxicological information (Section 11)

Section 5. Fire-fighting measures

Extinguishing media

Suitable extinguishing media	: Use an extinguishing agent suitable for the surrounding fire.
Unsuitable extinguishing media	: None known.
Specific hazards arising from the chemical	: Contains gas under pressure. Oxidizing material. This material increases the risk of fire and may aid combustion. Contact with combustible material may cause fire. In a fire or if heated, a pressure increase will occur and the container may burst or explode.
Hazardous thermal decomposition products	: No specific data.
Special protective actions for fire-fighters	: Promptly isolate the scene by removing all persons from the vicinity of the incident if there is a fire. No action shall be taken involving any personal risk or without suitable training. Contact supplier immediately for specialist advice. Move containers from fire area if this can be done without risk. Use water spray to keep fire-exposed containers cool. If involved in fire, shut off flow immediately if it can be done without risk.
Special protective equipment for fire-fighters	: Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions, protective equipment and emergency procedures

For non-emergency personnel	: No action shall be taken involving any personal risk or without suitable training. Evacuate surrounding areas. Keep unnecessary and unprotected personnel from entering. Shut off all ignition sources. No flares, smoking or flames in hazard area. Avoid breathing gas. Provide adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Put on appropriate personal protective equipment.
For emergency responders	: If specialized clothing is required to deal with the spillage, take note of any information in Section 8 on suitable and unsuitable materials. See also the information in "For non-emergency personnel".
Environmental precautions	: Ensure emergency procedures to deal with accidental gas releases are in place to avoid contamination of the environment. Inform the relevant authorities if the product has caused environmental pollution (sewers, waterways, soil or air).

Methods and materials for containment and cleaning up

Small spill	: Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment.
Large spill	: Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment. Note: see Section 1 for emergency contact information and Section 13 for waste disposal.

Section 7. Handling and storage

Precautions for safe handling

Section 7. Handling and storage

Protective measures : Put on appropriate personal protective equipment (see Section 8). Contains gas under pressure. Avoid breathing gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
Avoid contact with eyes, skin and clothing. Empty containers retain product residue and can be hazardous. Keep away from clothing, incompatible materials and combustible materials. Keep reduction valves free from grease and oil.

Advice on general occupational hygiene : Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed. Workers should wash hands and face before eating, drinking and smoking. Remove contaminated clothing and protective equipment before entering eating areas. See also Section 8 for additional information on hygiene measures.

Conditions for safe storage, including any incompatibilities : Store in accordance with local regulations. Store in a segregated and approved area. Store away from direct sunlight in a dry, cool and well-ventilated area, away from incompatible materials (see Section 10). Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F). Separate from reducing agents and combustible materials. Store away from grease and oil. Keep container tightly closed and sealed until ready for use. See Section 10 for incompatible materials before handling or use.

Section 8. Exposure controls/personal protection

Control parameters

Occupational exposure limits

Ingredient name	Exposure limits
oxygen	None.

Appropriate engineering controls : Good general ventilation should be sufficient to control worker exposure to airborne contaminants.

Environmental exposure controls : Emissions from ventilation or work process equipment should be checked to ensure they comply with the requirements of environmental protection legislation. In some cases, fume scrubbers, filters or engineering modifications to the process equipment will be necessary to reduce emissions to acceptable levels.

Individual protection measures

Hygiene measures : Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing. Ensure that eyewash stations and safety showers are close to the workstation location.

Eye/face protection : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists, gases or dusts. If contact is possible, the following protection should be worn, unless the assessment indicates a higher degree of protection: safety glasses with side-shields.

Skin protection

Hand protection : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary. Considering the parameters specified by the glove manufacturer, check during use that the gloves are still retaining their protective properties. It should be noted that the time to breakthrough for any glove material may be different for different glove manufacturers. In the case of mixtures, consisting of several substances, the protection time of the gloves cannot be accurately estimated.

Section 8. Exposure controls/personal protection

Body protection : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Other skin protection : Appropriate footwear and any additional skin protection measures should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Respiratory protection : Based on the hazard and potential for exposure, select a respirator that meets the appropriate standard or certification. Respirators must be used according to a respiratory protection program to ensure proper fitting, training, and other important aspects of use. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

Section 9. Physical and chemical properties

Appearance

Physical state : Gas. [Compressed gas.]

Color : Colorless. Blue.

Odor : Odorless.

Odor threshold : Not available.

pH : Not available.

Melting point : -218.4°C (-361.1°F)

Boiling point : -183°C (-297.4°F)

Critical temperature : -118.15°C (-180.7°F)

Flash point : [Product does not sustain combustion.]

Evaporation rate : Not available.

Flammability (solid, gas) : Extremely flammable in the presence of the following materials or conditions: reducing materials, combustible materials and organic materials.

Lower and upper explosive (flammable) limits : Not available.

Vapor pressure : Not available.

Vapor density : 1.1 (Air = 1)

Specific Volume (ft ^{3}/lb) : 12.0482

Gas Density (lb/ft ^{3}) : 0.083

Relative density : Not applicable.

Solubility : Not available.

Solubility in water : Not available.

Partition coefficient: n-octanol/water : 0.65

Auto-ignition temperature : Not available.

Decomposition temperature : Not available.

Viscosity : Not applicable.

Flow time (ISO 2431) : Not available.

Molecular weight : 32 g/mole

Section 10. Stability and reactivity

Reactivity : No specific test data related to reactivity available for this product or its ingredients.

Chemical stability : The product is stable.

Possibility of hazardous reactions : Hazardous reactions or instability may occur under certain conditions of storage or use.
Conditions may include the following:
contact with combustible materials
Reactions may include the following:
risk of causing fire

Section 10. Stability and reactivity

Conditions to avoid : No specific data.

Incompatible materials : Highly reactive or incompatible with the following materials:
combustible materials
reducing materials
grease
oil

Hazardous decomposition products : Under normal conditions of storage and use, hazardous decomposition products should not be produced.

Hazardous polymerization : Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Information on toxicological effects

Acute toxicity

Not available.

Irritation/Corrosion

Not available.

Sensitization

Not available.

Mutagenicity

Not available.

Carcinogenicity

Not available.

Reproductive toxicity

Not available.

Teratogenicity

Not available.

Specific target organ toxicity (single exposure)

Not available.

Specific target organ toxicity (repeated exposure)

Not available.

Aspiration hazard

Not available.

Information on the likely routes of exposure : Not available.

Potential acute health effects

Eye contact : Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation : No known significant effects or critical hazards.
Skin contact : Contact with rapidly expanding gas may cause burns or frostbite.
Ingestion : As this product is a gas, refer to the inhalation section.

Symptoms related to the physical, chemical and toxicological characteristics

Section 11. Toxicological information

Eye contact : No specific data.

Inhalation : No specific data.

Skin contact : No specific data.

Ingestion : No specific data.

Delayed and immediate effects and also chronic effects from short and long term exposure

Short term exposure

Potential immediate effects : Not available.

Potential delayed effects : Not available.

Long term exposure

Potential immediate effects : Not available.

Potential delayed effects : Not available.

Potential chronic health effects

Not available.

General : No known significant effects or critical hazards.

Carcinogenicity : No known significant effects or critical hazards.

Mutagenicity : No known significant effects or critical hazards.

Teratogenicity : No known significant effects or critical hazards.

Developmental effects : No known significant effects or critical hazards.

Fertility effects : No known significant effects or critical hazards.

Numerical measures of toxicity

Acute toxicity estimates

Not available.

Section 12. Ecological information

Toxicity

Not available.

Persistence and degradability

Not available.

Bioaccumulative potential

Product/ingredient name	$LogP_{ow}$	BCF	Potential
oxygen	0.65	-	low

Mobility in soil

Soil/water partition coefficient (K_{OC}) : Not available.

Other adverse effects : No known significant effects or critical hazards.

Section 13. Disposal considerations

Disposal methods	: The generation of waste should be avoided or minimized wherever possible. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Waste should not be disposed of untreated to the sewer unless fully compliant with the requirements of all authorities with jurisdiction. Empty Airgas-owned pressure vessels should be returned to Airgas. Waste packaging should be recycled. Incineration or landfill should only be considered when recycling is not feasible. This material and its container must be disposed of in a safe way. Empty containers or liners may retain some product residues. Do not puncture or incinerate container.

Section 14. Transport information

	DOT	**TDG**	**Mexico**	**IMDG**	**IATA**
UN number	UN1072	UN1072	UN1072	UN1072	UN1072
UN proper shipping name	OXYGEN, COMPRESSED	OXYGEN, COMPRESSED	OXYGEN, COMPRESSED	OXYGEN, COMPRESSED	OXYGEN, COMPRESSED
Transport hazard class(es)	2.2 (5.1) 	2.2 	2.2 (5.1) 	2.2 (5.1) 	2.2 (5.1) 
Packing group	-	-	-	-	-
Environmental hazards	No.	No.	No.	No.	No.

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Additional information

DOT Classification : **Limited quantity** Yes.
Quantity limitation Passenger aircraft/rail: 75 kg. Cargo aircraft: 150 kg.
Special provisions A52

TDG Classification : Product classified as per the following sections of the Transportation of Dangerous Goods Regulations: 2.13-2.17 (Class 2), 2.23-2.25 (Class 5).
Explosive Limit and Limited Quantity Index 0.125
ERAP Index 3000
Passenger Carrying Ship Index 50
Passenger Carrying Road or Rail Index 75
Special provisions 42

IATA : **Quantity limitation** Passenger and Cargo Aircraft: 75 kg. Cargo Aircraft Only: 150 kg.

Special precautions for user : **Transport within user's premises:** always transport in closed containers that are upright and secure. Ensure that persons transporting the product know what to do in the event of an accident or spillage.

Transport in bulk according to Annex II of MARPOL and the IBC Code : Not available.

Section 15. Regulatory information

U.S. Federal regulations	: **TSCA 8(a) CDR Exempt/Partial exemption**: This material is listed or exempted.
Clean Air Act Section 112 (b) Hazardous Air Pollutants (HAPs)	: Not listed
Clean Air Act Section 602 Class I Substances	: Not listed
Clean Air Act Section 602 Class II Substances	: Not listed
DEA List I Chemicals (Precursor Chemicals)	: Not listed
DEA List II Chemicals (Essential Chemicals)	: Not listed

SARA 302/304

Composition/information on ingredients

No products were found.

SARA 304 RQ : Not applicable.

SARA 311/312

Classification : Refer to Section 2: Hazards Identification of this SDS for classification of substance.

State regulations

Massachusetts	: This material is listed.
New York	: This material is not listed.
New Jersey	: This material is listed.
Pennsylvania	: This material is listed.

International regulations

Chemical Weapon Convention List Schedules I, II & III Chemicals

Not listed.

Montreal Protocol (Annexes A, B, C, E)

Not listed.

Stockholm Convention on Persistent Organic Pollutants

Not listed.

Rotterdam Convention on Prior Informed Consent (PIC)

Not listed.

UNECE Aarhus Protocol on POPs and Heavy Metals

Not listed.

Inventory list

Australia	: This material is listed or exempted.
Canada	: This material is listed or exempted.
China	: This material is listed or exempted.
Europe	: This material is listed or exempted.
Japan	: **Japan inventory (ENCS)**: Not determined. **Japan inventory (ISHL)**: Not determined.
Malaysia	: Not determined.
New Zealand	: This material is listed or exempted.
Philippines	: This material is listed or exempted.
Republic of Korea	: This material is listed or exempted.

Section 15. Regulatory information

Taiwan : This material is listed or exempted.
Thailand : Not determined.
Turkey : Not determined.
United States : This material is listed or exempted.
Viet Nam : Not determined.

Section 16. Other information

Hazardous Material Information System (U.S.A.)

Health	/	0
Flammability		0
Physical hazards		3

Caution: HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. Although HMIS® ratings and the associated label are not required on SDSs or products leaving a facility under 29 CFR 1910.1200, the preparer may choose to provide them. HMIS® ratings are to be used with a fully implemented HMIS® program. HMIS® is a registered trademark and service mark of the American Coatings Association, Inc.

The customer is responsible for determining the PPE code for this material. For more information on HMIS® Personal Protective Equipment (PPE) codes, consult the HMIS® Implementation Manual.

National Fire Protection Association (U.S.A.)

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Copyright ©2001, National Fire Protection Association, Quincy, MA 02269. This warning system is intended to be interpreted and applied only by properly trained individuals to identify fire, health and reactivity hazards of chemicals. The user is referred to certain limited number of chemicals with recommended classifications in NFPA 49 and NFPA 325, which would be used as a guideline only. Whether the chemicals are classified by NFPA or not, anyone using the 704 systems to classify chemicals does so at their own risk.

Procedure used to derive the classification

Classification	Justification
OXIDIZING GASES - Category 1 GASES UNDER PRESSURE - Compressed gas	Expert judgment According to package

History

Date of printing : 2/3/2018
Date of issue/Date of revision : 2/3/2018
Date of previous issue : 1/27/2017
Version : 0.03

Key to abbreviations : ATE = Acute Toxicity Estimate
BCF = Bioconcentration Factor
GHS = Globally Harmonized System of Classification and Labelling of Chemicals
IATA = International Air Transport Association
IBC = Intermediate Bulk Container
IMDG = International Maritime Dangerous Goods
LogPow = logarithm of the octanol/water partition coefficient
MARPOL = International Convention for the Prevention of Pollution From Ships, 1973

Section 16. Other information

as modified by the Protocol of 1978. ("Marpol" = marine pollution)
UN = United Nations

References : Not available.

◤ **Indicates information that has changed from previously issued version.**

Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

SAFETY DATA SHEET

Carbon Monoxide

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier : Carbon Monoxide

Chemical name : carbon monoxide

Other means of identification : Carbon oxide (CO); CO; Exhaust gas; Flue gas; Carbonic oxide; Carbon oxide; Carbone (oxyde de); Carbonio (ossido di); Kohlenmonoxid; Kohlenoxyd; Koolmonoxyde; NA 9202; Oxyde de carbone; UN 1016; Wegla tlenek; Carbon monooxide

Product type : Gas.

Product use : Synthetic/Analytical chemistry.

Synonym : Carbon oxide (CO); CO; Exhaust gas; Flue gas; Carbonic oxide; Carbon oxide; Carbone (oxyde de); Carbonio (ossido di); Kohlenmonoxid; Kohlenoxyd; Koolmonoxyde; NA 9202; Oxyde de carbone; UN 1016; Wegla tlenek; Carbon monooxide

SDS # : 001014

Supplier's details :
Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture :
FLAMMABLE GASES - Category 1
GASES UNDER PRESSURE - Compressed gas
ACUTE TOXICITY (inhalation) - Category 3
TOXIC TO REPRODUCTION (Fertility) - Category 1
TOXIC TO REPRODUCTION (Unborn child) - Category 1
SPECIFIC TARGET ORGAN TOXICITY (REPEATED EXPOSURE) - Category 1

GHS label elements

Hazard pictograms :

Signal word : Danger

Hazard statements :
Extremely flammable gas.
Contains gas under pressure; may explode if heated.
Toxic if inhaled.
May damage fertility or the unborn child.
Causes damage to organs through prolonged or repeated exposure.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Approach suspected leak area with caution.

Section 2. Hazards identification

Prevention : Obtain special instructions before use. Do not handle until all safety precautions have been read and understood. Wear protective gloves. Wear eye or face protection. Wear protective clothing. Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking. Use only outdoors or in a well-ventilated area. Do not breathe gas. Do not eat, drink or smoke when using this product. Wash hands thoroughly after handling.

Response : Get medical attention if you feel unwell. IF exposed or concerned: Get medical attention. IF INHALED: Remove person to fresh air and keep comfortable for breathing. Call a POISON CENTER or physician. Leaking gas fire: Do not extinguish, unless leak can be stopped safely. Eliminate all ignition sources if safe to do so.

Storage : Store locked up. Protect from sunlight. Store in a well-ventilated place.

Disposal : Dispose of contents and container in accordance with all local, regional, national and international regulations.

Hazards not otherwise classified : In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.

Section 3. Composition/information on ingredients

Substance/mixture : Substance

Chemical name : carbon monoxide

Other means of identification : Carbon oxide (CO); CO; Exhaust gas; Flue gas; Carbonic oxide; Carbon oxide; Carbone (oxyde de); Carbonio (ossido di); Kohlenmonoxid; Kohlenoxyd; Koolmonoxyde; NA 9202; Oxyde de carbone; UN 1016; Wegla tlenek; Carbon monooxide

Product code : 001014

CAS number/other identifiers

CAS number : 630-08-0

Ingredient name	%	CAS number
carbon monoxide	100	630-08-0

Any concentration shown as a range is to protect confidentiality or is due to batch variation.

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment and hence require reporting in this section.

Occupational exposure limits, if available, are listed in Section 8.

Section 4. First aid measures

Description of necessary first aid measures

Eye contact : Immediately flush eyes with plenty of water, occasionally lifting the upper and lower eyelids. Check for and remove any contact lenses. Continue to rinse for at least 10 minutes. Get medical attention.

Inhalation : Remove victim to fresh air and keep at rest in a position comfortable for breathing. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation. Get medical attention. If necessary, call a poison center or physician. If unconscious, place in recovery position and get medical attention immediately. Maintain an open airway. Loosen tight clothing such as a collar, tie, belt or waistband.

Skin contact : Flush contaminated skin with plenty of water. Remove contaminated clothing and shoes. To avoid the risk of static discharges and gas ignition, soak contaminated clothing thoroughly with water before removing it. Continue to rinse for at least 10 minutes. Get medical attention. Wash clothing before reuse. Clean shoes thoroughly before reuse.

Ingestion : As this product is a gas, refer to the inhalation section.

Most important symptoms/effects, acute and delayed

Section 4. First aid measures

Potential acute health effects

Eye contact	Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation	Toxic if inhaled.
Skin contact	Contact with rapidly expanding gas may cause burns or frostbite.
Frostbite	Try to warm up the frozen tissues and seek medical attention.
Ingestion	As this product is a gas, refer to the inhalation section.

Over-exposure signs/symptoms

Eye contact	No specific data.
Inhalation	Adverse symptoms may include the following:, reduced fetal weight, increase in fetal deaths, skeletal malformations
Skin contact	Adverse symptoms may include the following:, reduced fetal weight, increase in fetal deaths, skeletal malformations
Ingestion	Adverse symptoms may include the following:, reduced fetal weight, increase in fetal deaths, skeletal malformations

Indication of immediate medical attention and special treatment needed, if necessary

Notes to physician	Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.
Specific treatments	No specific treatment.
Protection of first-aiders	No action shall be taken involving any personal risk or without suitable training. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation. Wash contaminated clothing thoroughly with water before removing it, or wear gloves.

See toxicological information (Section 11)

Section 5. Fire-fighting measures

Extinguishing media

Suitable extinguishing media	Use an extinguishing agent suitable for the surrounding fire.
Unsuitable extinguishing media	None known.

Specific hazards arising from the chemical	Contains gas under pressure. Extremely flammable gas. In a fire or if heated, a pressure increase will occur and the container may burst, with the risk of a subsequent explosion.
Hazardous thermal decomposition products	Decomposition products may include the following materials: carbon dioxide carbon monoxide
Special protective actions for fire-fighters	Promptly isolate the scene by removing all persons from the vicinity of the incident if there is a fire. No action shall be taken involving any personal risk or without suitable training. Contact supplier immediately for specialist advice. Move containers from fire area if this can be done without risk. Use water spray to keep fire-exposed containers cool. If involved in fire, shut off flow immediately if it can be done without risk. If this is impossible, withdraw from area and allow fire to burn. Fight fire from protected location or maximum possible distance. Eliminate all ignition sources if safe to do so.
Special protective equipment for fire-fighters	Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions, protective equipment and emergency procedures

For non-emergency personnel : Accidental releases pose a serious fire or explosion hazard. No action shall be taken involving any personal risk or without suitable training. Evacuate surrounding areas. Keep unnecessary and unprotected personnel from entering. Shut off all ignition sources. No flares, smoking or flames in hazard area. Do not breathe gas. Provide adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Put on appropriate personal protective equipment.

For emergency responders : If specialized clothing is required to deal with the spillage, take note of any information in Section 8 on suitable and unsuitable materials. See also the information in "For non-emergency personnel".

Environmental precautions : Ensure emergency procedures to deal with accidental gas releases are in place to avoid contamination of the environment. Inform the relevant authorities if the product has caused environmental pollution (sewers, waterways, soil or air).

Methods and materials for containment and cleaning up

Small spill : Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment.

Large spill : Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment. Note: see Section 1 for emergency contact information and Section 13 for waste disposal.

Section 7. Handling and storage

Precautions for safe handling

Protective measures : Put on appropriate personal protective equipment (see Section 8). Contains gas under pressure. Avoid exposure - obtain special instructions before use. Avoid exposure during pregnancy. Do not handle until all safety precautions have been read and understood. Do not get in eyes or on skin or clothing. Do not breathe gas. Use only with adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Do not enter storage areas and confined spaces unless adequately ventilated. Store and use away from heat, sparks, open flame or any other ignition source. Use explosion-proof electrical (ventilating, lighting and material handling) equipment. Use only non-sparking tools. Empty containers retain product residue and can be hazardous. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.

Advice on general occupational hygiene : Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed. Workers should wash hands and face before eating, drinking and smoking. Remove contaminated clothing and protective equipment before entering eating areas. See also Section 8 for additional information on hygiene measures.

Conditions for safe storage, including any incompatibilities : Store in accordance with local regulations. Store in a segregated and approved area. Store away from direct sunlight in a dry, cool and well-ventilated area, away from incompatible materials (see Section 10). Store locked up. Eliminate all ignition sources. Keep container tightly closed and sealed until ready for use. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Section 8. Exposure controls/personal protection

Control parameters

Occupational exposure limits

Section 8. Exposure controls/personal protection

Ingredient name	Exposure limits
carbon monoxide	**California PEL for Chemical Contaminants (*Table AC-1*) (United States).** PEL: 25 ppm 8 hours. CEIL: 200 ppm **ACGIH TLV (United States, 3/2017).** TWA: 25 ppm 8 hours. TWA: 29 mg/m³ 8 hours. **OSHA PEL 1989 (United States, 3/1989).** TWA: 35 ppm 8 hours. TWA: 40 mg/m³ 8 hours. CEIL: 200 ppm CEIL: 229 mg/m³ **NIOSH REL (United States, 10/2016).** TWA: 35 ppm 10 hours. TWA: 40 mg/m³ 10 hours. CEIL: 200 ppm CEIL: 229 mg/m³ **OSHA PEL (United States, 6/2016).** TWA: 50 ppm 8 hours. TWA: 55 mg/m³ 8 hours.

Appropriate engineering controls : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits. The engineering controls also need to keep gas, vapor or dust concentrations below any lower explosive limits. Use explosion-proof ventilation equipment.

Environmental exposure controls : Emissions from ventilation or work process equipment should be checked to ensure they comply with the requirements of environmental protection legislation. In some cases, fume scrubbers, filters or engineering modifications to the process equipment will be necessary to reduce emissions to acceptable levels.

Individual protection measures

Hygiene measures : Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing. Ensure that eyewash stations and safety showers are close to the workstation location.

Eye/face protection : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists, gases or dusts. If contact is possible, the following protection should be worn, unless the assessment indicates a higher degree of protection: safety glasses with side-shields.

Skin protection

Hand protection : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary. Considering the parameters specified by the glove manufacturer, check during use that the gloves are still retaining their protective properties. It should be noted that the time to breakthrough for any glove material may be different for different glove manufacturers. In the case of mixtures, consisting of several substances, the protection time of the gloves cannot be accurately estimated.

Body protection : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product. When there is a risk of ignition from static electricity, wear anti-static protective clothing. For the greatest protection from static discharges, clothing should include anti-static overalls, boots and gloves.

Section 10. Stability and reactivity

Conditions to avoid : Avoid all possible sources of ignition (spark or flame). Do not pressurize, cut, weld, braze, solder, drill, grind or expose containers to heat or sources of ignition.

Incompatible materials : Oxidizers

Hazardous decomposition products : Under normal conditions of storage and use, hazardous decomposition products should not be produced.

Hazardous polymerization : Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Information on toxicological effects

Acute toxicity

Product/ingredient name	Result	Species	Dose	Exposure
carbon monoxide	LC50 Inhalation Gas.	Rat	3760 ppm	1 hours

Irritation/Corrosion

Not available.

Sensitization

Not available.

Mutagenicity

Not available.

Carcinogenicity

Not available.

Reproductive toxicity

Not available.

Teratogenicity

Not available.

Specific target organ toxicity (single exposure)

Not available.

Specific target organ toxicity (repeated exposure)

Name	Category	Route of exposure	Target organs
carbon monoxide	Category 1	Not determined	Not determined

Aspiration hazard

Not available.

Information on the likely routes of exposure : Routes of entry anticipated: Inhalation.

Potential acute health effects

Eye contact : Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation : Toxic if inhaled.
Skin contact : Contact with rapidly expanding gas may cause burns or frostbite.
Ingestion : As this product is a gas, refer to the inhalation section.

Symptoms related to the physical, chemical and toxicological characteristics

Section 11. Toxicological information

Eye contact	: No specific data.
Inhalation	: Adverse symptoms may include the following:, reduced fetal weight, increase in fetal deaths, skeletal malformations
Skin contact	: Adverse symptoms may include the following:, reduced fetal weight, increase in fetal deaths, skeletal malformations
Ingestion	: Adverse symptoms may include the following:, reduced fetal weight, increase in fetal deaths, skeletal malformations

Delayed and immediate effects and also chronic effects from short and long term exposure

Short term exposure

Potential immediate effects	: Not available.
Potential delayed effects	: Not available.

Long term exposure

Potential immediate effects	: Not available.
Potential delayed effects	: Not available.

Potential chronic health effects

Not available.

General	: Causes damage to organs through prolonged or repeated exposure.
Carcinogenicity	: No known significant effects or critical hazards.
Mutagenicity	: No known significant effects or critical hazards.
Teratogenicity	: May damage the unborn child.
Developmental effects	: No known significant effects or critical hazards.
Fertility effects	: May damage fertility.

Numerical measures of toxicity

Acute toxicity estimates

Not available.

Section 12. Ecological information

Toxicity

Not available.

Persistence and degradability

Not available.

Bioaccumulative potential

Not available.

Mobility in soil

Soil/water partition coefficient (K_{OC})	: Not available.
Other adverse effects	: No known significant effects or critical hazards.

Section 13. Disposal considerations

Disposal methods : The generation of waste should be avoided or minimized wherever possible. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Waste should not be disposed of untreated to the sewer unless fully compliant with the requirements of all authorities with jurisdiction. Empty Airgas-owned pressure vessels should be returned to Airgas. Waste packaging should be recycled. Incineration or landfill should only be considered when recycling is not feasible. This material and its container must be disposed of in a safe way. Empty containers or liners may retain some product residues. Do not puncture or incinerate container.

Section 14. Transport information

	DOT	**TDG**	**Mexico**	**IMDG**	**IATA**
UN number	UN1016	UN1016	UN1016	UN1016	UN1016
UN proper shipping name	CARBON MONOXIDE, COMPRESSED	CARBON MONOXIDE, COMPRESSED	CARBON MONOXIDE, COMPRESSED	CARBON MONOXIDE, COMPRESSED	CARBON MONOXIDE, COMPRESSED
Transport hazard class(es)	2.3 (2.1) 	2.3 (2.1) 	2.3 (2.1) 	2.3 (2.1) 	2.3 (2.1) 
Packing group	-	-	-	-	-
Environmental hazards	No.	No.	No.	No.	No.

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Additional information

DOT Classification : Toxic - Inhalation hazard Zone D
Limited quantity Yes.
Quantity limitation Passenger aircraft/rail: Forbidden. Cargo aircraft: 25 kg.
Special provisions 4

TDG Classification : Product classified as per the following sections of the Transportation of Dangerous Goods Regulations: 2.13-2.17 (Class 2), 2.13-2.17 (Class 2).
Explosive Limit and Limited Quantity Index 0
ERAP Index 500
Passenger Carrying Ship Index Forbidden
Passenger Carrying Road or Rail Index Forbidden

IATA : **Quantity limitation** Passenger and Cargo Aircraft: Forbidden. Cargo Aircraft Only: Forbidden.

Special precautions for user : **Transport within user's premises:** always transport in closed containers that are upright and secure. Ensure that persons transporting the product know what to do in the event of an accident or spillage.

Transport in bulk according to Annex II of MARPOL and the IBC Code : Not available.

Section 15. Regulatory information

U.S. Federal regulations : **TSCA 8(a) CDR Exempt/Partial exemption**: Not determined

Clean Air Act Section 112 (b) Hazardous Air Pollutants (HAPs) : Not listed

Clean Air Act Section 602 Class I Substances : Not listed

Clean Air Act Section 602 Class II Substances : Not listed

DEA List I Chemicals (Precursor Chemicals) : Not listed

DEA List II Chemicals (Essential Chemicals) : Not listed

SARA 302/304

Composition/information on ingredients

No products were found.

SARA 304 RQ : Not applicable.

SARA 311/312

Classification : Refer to Section 2: Hazards Identification of this SDS for classification of substance.

State regulations

Massachusetts : This material is listed.

New York : This material is not listed.

New Jersey : This material is listed.

Pennsylvania : This material is listed.

California Prop. 65

⚠ **WARNING**: This product can expose you to Carbon monoxide, which is known to the State of California to cause birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov.

Ingredient name	No significant risk level	Maximum acceptable dosage level
Carbon monoxide	-	-

International regulations

Chemical Weapon Convention List Schedules I, II & III Chemicals

Not listed.

Montreal Protocol (Annexes A, B, C, E)

Not listed.

Stockholm Convention on Persistent Organic Pollutants

Not listed.

Rotterdam Convention on Prior Informed Consent (PIC)

Not listed.

UNECE Aarhus Protocol on POPs and Heavy Metals

Not listed.

Inventory list

Australia : This material is listed or exempted.

Canada : This material is listed or exempted.

China : This material is listed or exempted.

Section 15. Regulatory information

Europe	: This material is listed or exempted.
Japan	: **Japan inventory (ENCS)**: This material is listed or exempted. **Japan inventory (ISHL)**: Not determined.
Malaysia	: Not determined.
New Zealand	: This material is listed or exempted.
Philippines	: This material is listed or exempted.
Republic of Korea	: This material is listed or exempted.
Taiwan	: This material is listed or exempted.
Thailand	: Not determined.
Turkey	: Not determined.
United States	: This material is listed or exempted.
Viet Nam	: Not determined.

Section 16. Other information

Hazardous Material Information System (U.S.A.)

Health	*	3
Flammability		4
Physical hazards		3

Caution: HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. Although HMIS® ratings and the associated label are not required on SDSs or products leaving a facility under 29 CFR 1910.1200, the preparer may choose to provide them. HMIS® ratings are to be used with a fully implemented HMIS® program. HMIS® is a registered trademark and service mark of the American Coatings Association, Inc.

The customer is responsible for determining the PPE code for this material. For more information on HMIS® Personal Protective Equipment (PPE) codes, consult the HMIS® Implementation Manual.

National Fire Protection Association (U.S.A.)

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Copyright ©2001, National Fire Protection Association, Quincy, MA 02269. This warning system is intended to be interpreted and applied only by properly trained individuals to identify fire, health and reactivity hazards of chemicals. The user is referred to certain limited number of chemicals with recommended classifications in NFPA 49 and NFPA 325, which would be used as a guideline only. Whether the chemicals are classified by NFPA or not, anyone using the 704 systems to classify chemicals does so at their own risk.

Procedure used to derive the classification

Classification	Justification
FLAMMABLE GASES - Category 1	Expert judgment
GASES UNDER PRESSURE - Compressed gas	According to package
ACUTE TOXICITY (inhalation) - Category 3	On basis of test data
TOXIC TO REPRODUCTION (Fertility) - Category 1	Expert judgment
TOXIC TO REPRODUCTION (Unborn child) - Category 1	Expert judgment
SPECIFIC TARGET ORGAN TOXICITY (REPEATED EXPOSURE) - Category 1	Expert judgment

History

Date of printing : 11/29/2017

Section 16. Other information

Date of issue/Date of revision	: 11/29/2017
Date of previous issue	: 2/20/2017
Version	: 1

Key to abbreviations :
ATE = Acute Toxicity Estimate
BCF = Bioconcentration Factor
GHS = Globally Harmonized System of Classification and Labelling of Chemicals
IATA = International Air Transport Association
IBC = Intermediate Bulk Container
IMDG = International Maritime Dangerous Goods
LogPow = logarithm of the octanol/water partition coefficient
MARPOL = International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978. ("Marpol" = marine pollution)
UN = United Nations

References : Not available.

◤ **Indicates information that has changed from previously issued version.**

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SAFETY DATA SHEET

Nitrogen

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier : Nitrogen

Chemical name : nitrogen

Other means of identification : nitrogen (dot); nitrogen gas; Nitrogen NF, Nitrogen FG

Product type : Gas.

Product use : Synthetic/Analytical chemistry.

Synonym : nitrogen (dot); nitrogen gas; Nitrogen NF, Nitrogen FG

SDS # : 001040

Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : GASES UNDER PRESSURE - Compressed gas
SIMPLE ASPHYXIANTS

GHS label elements

Hazard pictograms :

Signal word : Warning

Hazard statements : Contains gas under pressure; may explode if heated.
May displace oxygen and cause rapid suffocation.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction.

Prevention : Not applicable.

Response : Not applicable.

Storage : Protect from sunlight. Store in a well-ventilated place.

Disposal : Not applicable.

Supplemental label elements : Keep container tightly closed. Use only with adequate ventilation. Do not enter storage areas and confined spaces unless adequately ventilated.

Hazards not otherwise classified : In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.

Section 3. Composition/information on ingredients

Substance/mixture : Substance

Chemical name : nitrogen

Other means of identification : nitrogen (dot); nitrogen gas; Nitrogen NF, Nitrogen FG

Product code : 001040

CAS number/other identifiers

CAS number : 7727-37-9

Ingredient name	%	CAS number
Nitrogen	100	7727-37-9

Any concentration shown as a range is to protect confidentiality or is due to batch variation.

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment and hence require reporting in this section.

Occupational exposure limits, if available, are listed in Section 8.

Section 4. First aid measures

Description of necessary first aid measures

Eye contact : Immediately flush eyes with plenty of water, occasionally lifting the upper and lower eyelids. Check for and remove any contact lenses. Continue to rinse for at least 10 minutes. Get medical attention if irritation occurs.

Inhalation : Remove victim to fresh air and keep at rest in a position comfortable for breathing. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation. Get medical attention if adverse health effects persist or are severe. If unconscious, place in recovery position and get medical attention immediately. Maintain an open airway. Loosen tight clothing such as a collar, tie, belt or waistband. In case of inhalation of decomposition products in a fire, symptoms may be delayed. The exposed person may need to be kept under medical surveillance for 48 hours.

Skin contact : Flush contaminated skin with plenty of water. Remove contaminated clothing and shoes. Get medical attention if symptoms occur. Wash clothing before reuse. Clean shoes thoroughly before reuse.

Ingestion : As this product is a gas, refer to the inhalation section.

Most important symptoms/effects, acute and delayed

Potential acute health effects

Eye contact : Contact with rapidly expanding gas may cause burns or frostbite.

Inhalation : At very high concentrations, can displace the normal air and cause suffocation from lack of oxygen.

Skin contact : Contact with rapidly expanding gas may cause burns or frostbite.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Ingestion : As this product is a gas, refer to the inhalation section.

Over-exposure signs/symptoms

Eye contact : No specific data.

Inhalation : No specific data.

Skin contact : No specific data.

Ingestion : No specific data.

Indication of immediate medical attention and special treatment needed, if necessary

Section 4. First aid measures

Notes to physician : In case of inhalation of decomposition products in a fire, symptoms may be delayed. The exposed person may need to be kept under medical surveillance for 48 hours.

Specific treatments : No specific treatment.

Protection of first-aiders : No action shall be taken involving any personal risk or without suitable training. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

See toxicological information (Section 11)

Section 5. Fire-fighting measures

Extinguishing media

Suitable extinguishing media : Use an extinguishing agent suitable for the surrounding fire.

Unsuitable extinguishing media : None known.

Specific hazards arising from the chemical : Contains gas under pressure. In a fire or if heated, a pressure increase will occur and the container may burst or explode.

Hazardous thermal decomposition products : Decomposition products may include the following materials:
nitrogen oxides

Special protective actions for fire-fighters : Promptly isolate the scene by removing all persons from the vicinity of the incident if there is a fire. No action shall be taken involving any personal risk or without suitable training. Contact supplier immediately for specialist advice. Move containers from fire area if this can be done without risk. Use water spray to keep fire-exposed containers cool.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions, protective equipment and emergency procedures

For non-emergency personnel : No action shall be taken involving any personal risk or without suitable training. Evacuate surrounding areas. Keep unnecessary and unprotected personnel from entering. Avoid breathing gas. Provide adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Put on appropriate personal protective equipment.

For emergency responders : If specialized clothing is required to deal with the spillage, take note of any information in Section 8 on suitable and unsuitable materials. See also the information in "For non-emergency personnel".

Environmental precautions : Ensure emergency procedures to deal with accidental gas releases are in place to avoid contamination of the environment. Inform the relevant authorities if the product has caused environmental pollution (sewers, waterways, soil or air).

Methods and materials for containment and cleaning up

Small spill : Immediately contact emergency personnel. Stop leak if without risk.

Large spill : Immediately contact emergency personnel. Stop leak if without risk. Note: see Section 1 for emergency contact information and Section 13 for waste disposal.

Section 7. Handling and storage

Precautions for safe handling

Protective measures : Put on appropriate personal protective equipment (see Section 8). Contains gas under pressure. Avoid breathing gas. Use only with adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.

Avoid contact with eyes, skin and clothing. Empty containers retain product residue and can be hazardous.

Advice on general occupational hygiene : Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed. Workers should wash hands and face before eating, drinking and smoking. Remove contaminated clothing and protective equipment before entering eating areas. See also Section 8 for additional information on hygiene measures.

Conditions for safe storage, including any incompatibilities : Store in accordance with local regulations. Store in a segregated and approved area. Store away from direct sunlight in a dry, cool and well-ventilated area, away from incompatible materials (see Section 10). Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F). Keep container tightly closed and sealed until ready for use. See Section 10 for incompatible materials before handling or use.

Section 8. Exposure controls/personal protection

Control parameters

Occupational exposure limits

Ingredient name	Exposure limits
Nitrogen	**ACGIH TLV (United States, 3/2017). Oxygen Depletion [Asphyxiant].**

Appropriate engineering controls : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits.

Environmental exposure controls : Emissions from ventilation or work process equipment should be checked to ensure they comply with the requirements of environmental protection legislation. In some cases, fume scrubbers, filters or engineering modifications to the process equipment will be necessary to reduce emissions to acceptable levels.

Individual protection measures

Hygiene measures : Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing. Ensure that eyewash stations and safety showers are close to the workstation location.

Eye/face protection : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists, gases or dusts. If contact is possible, the following protection should be worn, unless the assessment indicates a higher degree of protection: safety glasses with side-shields.

Skin protection

Hand protection : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary. Considering the parameters specified by the glove manufacturer, check during use that the gloves are still retaining their protective properties. It should be noted that the time to breakthrough for any glove material may be different for different glove manufacturers. In the case of mixtures, consisting of several substances, the protection time of the gloves cannot be accurately estimated.

Section 8. Exposure controls/personal protection

Body protection	Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
Other skin protection	Appropriate footwear and any additional skin protection measures should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
Respiratory protection	The gas can cause asphyxiation without warning by replacing the oxygen in the air. Based on the hazard and potential for exposure, select a respirator that meets the appropriate standard or certification. If operating conditions cause high gas concentrations to be produced or any recommended or statutory exposure limit is exceeded, use an air-fed respirator or self-contained breathing apparatus. Respirators must be used according to a respiratory protection program to ensure proper fitting, training, and other important aspects of use. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

Section 9. Physical and chemical properties

Appearance

Physical state	Gas. [Compressed gas.]
Color	Colorless.
Odor	Odorless.
Odor threshold	Not available.
pH	Not available.
Melting point	-210.01°C (-346°F)
Boiling point	-196°C (-320.8°F)
Critical temperature	-146.95°C (-232.5°F)
Flash point	[Product does not sustain combustion.]
Evaporation rate	Not available.
Flammability (solid, gas)	Not available.
Lower and upper explosive (flammable) limits	Not available.
Vapor pressure	Not available.
Vapor density	0.967 (Air = 1) Liquid Density@BP: 50.46 lb/ft3 (808.3 kg/m3)
Specific Volume (ft ^{3}/lb)	13.8889
Gas Density (lb/ft ^{3})	0.072
Relative density	Not applicable.
Solubility	Not available.
Solubility in water	Not available.
Partition coefficient: n-octanol/water	0.67
Auto-ignition temperature	Not available.
Decomposition temperature	Not available.
Viscosity	Not applicable.
Flow time (ISO 2431)	Not available.
Molecular weight	28.02 g/mole

Section 10. Stability and reactivity

Reactivity	: No specific test data related to reactivity available for this product or its ingredients.
Chemical stability	: The product is stable.
Possibility of hazardous reactions	: Under normal conditions of storage and use, hazardous reactions will not occur.
Conditions to avoid	: Do not allow gas to accumulate in low or confined areas.
Incompatible materials	: No specific data.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Information on toxicological effects

Acute toxicity

Not available.

Irritation/Corrosion

Not available.

Sensitization

Not available.

Mutagenicity

Not available.

Carcinogenicity

Not available.

Reproductive toxicity

Not available.

Teratogenicity

Not available.

Specific target organ toxicity (single exposure)

Not available.

Specific target organ toxicity (repeated exposure)

Not available.

Aspiration hazard

Not available.

Information on the likely routes of exposure : Not available.

Potential acute health effects

Eye contact	: Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation	: At very high concentrations, can displace the normal air and cause suffocation from lack of oxygen.

Section 11. Toxicological information

Skin contact : Contact with rapidly expanding gas may cause burns or frostbite.

Ingestion : As this product is a gas, refer to the inhalation section.

Symptoms related to the physical, chemical and toxicological characteristics

Eye contact : No specific data.

Inhalation : No specific data.

Skin contact : No specific data.

Ingestion : No specific data.

Delayed and immediate effects and also chronic effects from short and long term exposure

Short term exposure

Potential immediate effects : Not available.

Potential delayed effects : Not available.

Long term exposure

Potential immediate effects : Not available.

Potential delayed effects : Not available.

Potential chronic health effects

Not available.

General : No known significant effects or critical hazards.

Carcinogenicity : No known significant effects or critical hazards.

Mutagenicity : No known significant effects or critical hazards.

Teratogenicity : No known significant effects or critical hazards.

Developmental effects : No known significant effects or critical hazards.

Fertility effects : No known significant effects or critical hazards.

Numerical measures of toxicity

Acute toxicity estimates

Not available.

Section 12. Ecological information

Toxicity

Not available.

Persistence and degradability

Not available.

Bioaccumulative potential

Product/ingredient name	$LogP_{ow}$	BCF	Potential
Nitrogen	0.67	-	low

Mobility in soil

Soil/water partition coefficient (K_{OC}) : Not available.

Section 12. Ecological information

Other adverse effects : No known significant effects or critical hazards.

Section 13. Disposal considerations

Disposal methods : The generation of waste should be avoided or minimized wherever possible. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Waste should not be disposed of untreated to the sewer unless fully compliant with the requirements of all authorities with jurisdiction. Empty Airgas-owned pressure vessels should be returned to Airgas. Waste packaging should be recycled. Incineration or landfill should only be considered when recycling is not feasible. This material and its container must be disposed of in a safe way. Empty containers or liners may retain some product residues. Do not puncture or incinerate container.

Section 14. Transport information

	DOT	**TDG**	**Mexico**	**IMDG**	**IATA**
UN number	UN1066	UN1066	UN1066	UN1066	UN1066
UN proper shipping name	NITROGEN, COMPRESSED	NITROGEN, COMPRESSED	NITROGEN, COMPRESSED	NITROGEN, COMPRESSED	NITROGEN, COMPRESSED
Transport hazard class(es)	2.2 	2.2 	2.2 	2.2 	2.2 
Packing group	-	-	-	-	-
Environmental hazards	No.	No.	No.	No.	No.

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Additional information

DOT Classification : **Limited quantity** Yes.
Quantity limitation Passenger aircraft/rail: 75 kg. Cargo aircraft: 150 kg.

TDG Classification : Product classified as per the following sections of the Transportation of Dangerous Goods Regulations: 2.13-2.17 (Class 2).
Explosive Limit and Limited Quantity Index 0.125
Passenger Carrying Road or Rail Index 75

IATA : **Quantity limitation** Passenger and Cargo Aircraft: 75 kg. Cargo Aircraft Only: 150 kg.

Special precautions for user : **Transport within user's premises:** always transport in closed containers that are upright and secure. Ensure that persons transporting the product know what to do in the event of an accident or spillage.

Transport in bulk according to Annex II of MARPOL and the IBC Code : Not available.

Section 15. Regulatory information

U.S. Federal regulations	: **TSCA 8(a) CDR Exempt/Partial exemption**: This material is listed or exempted.
Clean Air Act Section 112 (b) Hazardous Air Pollutants (HAPs)	: Not listed
Clean Air Act Section 602 Class I Substances	: Not listed
Clean Air Act Section 602 Class II Substances	: Not listed
DEA List I Chemicals (Precursor Chemicals)	: Not listed
DEA List II Chemicals (Essential Chemicals)	: Not listed

SARA 302/304

Composition/information on ingredients

No products were found.

SARA 304 RQ : Not applicable.

SARA 311/312

Classification : Refer to Section 2: Hazards Identification of this SDS for classification of substance.

State regulations

Massachusetts	: This material is listed.
New York	: This material is not listed.
New Jersey	: This material is listed.
Pennsylvania	: This material is listed.

International regulations

Chemical Weapon Convention List Schedules I, II & III Chemicals

Not listed.

Montreal Protocol (Annexes A, B, C, E)

Not listed.

Stockholm Convention on Persistent Organic Pollutants

Not listed.

Rotterdam Convention on Prior Informed Consent (PIC)

Not listed.

UNECE Aarhus Protocol on POPs and Heavy Metals

Not listed.

Inventory list

Australia	: This material is listed or exempted.
Canada	: This material is listed or exempted.
China	: This material is listed or exempted.
Europe	: This material is listed or exempted.
Japan	: **Japan inventory (ENCS)**: Not determined. **Japan inventory (ISHL)**: Not determined.
Malaysia	: Not determined.
New Zealand	: This material is listed or exempted.
Philippines	: This material is listed or exempted.
Republic of Korea	: This material is listed or exempted.

Section 15. Regulatory information

Taiwan : This material is listed or exempted.
Thailand : Not determined.
Turkey : Not determined.
United States : This material is listed or exempted.
Viet Nam : Not determined.

Section 16. Other information

Hazardous Material Information System (U.S.A.)

Health	/	0
Flammability		0
Physical hazards		3

Caution: HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. Although HMIS® ratings and the associated label are not required on SDSs or products leaving a facility under 29 CFR 1910.1200, the preparer may choose to provide them. HMIS® ratings are to be used with a fully implemented HMIS® program. HMIS® is a registered trademark and service mark of the American Coatings Association, Inc.

The customer is responsible for determining the PPE code for this material. For more information on HMIS® Personal Protective Equipment (PPE) codes, consult the HMIS® Implementation Manual.

National Fire Protection Association (U.S.A.)

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Copyright ©2001, National Fire Protection Association, Quincy, MA 02269. This warning system is intended to be interpreted and applied only by properly trained individuals to identify fire, health and reactivity hazards of chemicals. The user is referred to certain limited number of chemicals with recommended classifications in NFPA 49 and NFPA 325, which would be used as a guideline only. Whether the chemicals are classified by NFPA or not, anyone using the 704 systems to classify chemicals does so at their own risk.

Procedure used to derive the classification

Classification	Justification
GASES UNDER PRESSURE - Compressed gas SIMPLE ASPHYXIANTS	Expert judgment Expert judgment

History

Date of printing : 4/30/2019
Date of issue/Date of revision : 4/30/2019
Date of previous issue : 4/30/2019
Version : 1.03

Key to abbreviations :
ATE = Acute Toxicity Estimate
BCF = Bioconcentration Factor
GHS = Globally Harmonized System of Classification and Labelling of Chemicals
IATA = International Air Transport Association
IBC = Intermediate Bulk Container
IMDG = International Maritime Dangerous Goods
LogPow = logarithm of the octanol/water partition coefficient
MARPOL = International Convention for the Prevention of Pollution From Ships, 1973

Section 16. Other information

as modified by the Protocol of 1978. ("Marpol" = marine pollution)
UN = United Nations

References : Not available.

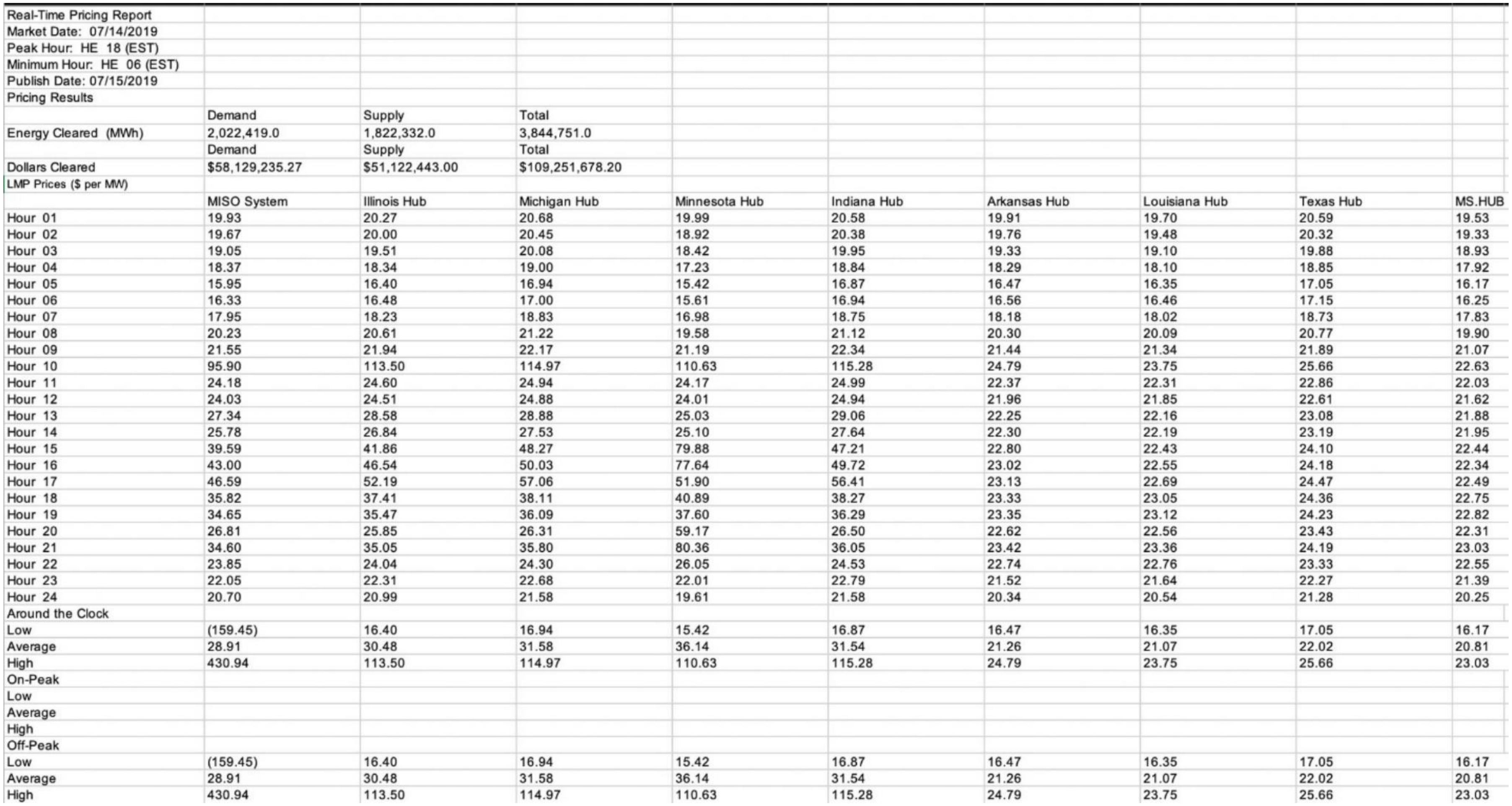
Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

Appendix D

Sample Electricity Pricing Data

The table reproduced below is a set of sample data from the real-time pricing of the Midwest electrical grid. Average on-peak and off-peak electricity prices were determined by averaging data from several representative months with the available data.



Real-Time Pricing Report									
Market Date: 07/14/2019									
Peak Hour: HE 18 (EST)									
Minimum Hour: HE 06 (EST)									
Publish Date: 07/15/2019									
Pricing Results									
	Demand	Supply	Total						
Energy Cleared (MWh)	2,022,419.0	1,822,332.0	3,844,751.0						
	Demand	Supply	Total						
Dollars Cleared	$58,129,235.27	$51,122,443.00	$109,251,678.20						
LMP Prices ($ per MW)									
	MISO System	Illinois Hub	Michigan Hub	Minnesota Hub	Indiana Hub	Arkansas Hub	Louisiana Hub	Texas Hub	MS.HUB
Hour 01	19.93	20.27	20.68	19.99	20.58	19.91	19.70	20.59	19.53
Hour 02	19.67	20.00	20.45	18.92	20.38	19.76	19.48	20.32	19.33
Hour 03	19.05	19.51	20.08	18.42	19.95	19.33	19.10	19.88	18.93
Hour 04	18.37	18.34	19.00	17.23	18.84	18.29	18.10	18.85	17.92
Hour 05	15.95	16.40	16.94	15.42	16.87	16.47	16.35	17.05	16.17
Hour 06	16.33	16.48	17.00	15.61	16.94	16.56	16.46	17.15	16.25
Hour 07	17.95	18.23	18.83	16.98	18.75	18.18	18.02	18.73	17.83
Hour 08	20.23	20.61	21.22	19.58	21.12	20.30	20.09	20.77	19.90
Hour 09	21.55	21.94	22.17	21.19	22.34	21.44	21.34	21.89	21.07
Hour 10	95.90	113.50	114.97	110.63	115.28	24.79	23.75	25.66	22.63
Hour 11	24.18	24.60	24.94	24.17	24.99	22.37	22.31	22.86	22.03
Hour 12	24.03	24.51	24.88	24.01	24.94	21.96	21.85	22.61	21.62
Hour 13	27.34	28.58	28.88	25.03	29.06	22.25	22.16	23.08	21.88
Hour 14	25.78	26.84	27.53	25.10	27.64	22.30	22.19	23.19	21.95
Hour 15	39.59	41.86	48.27	79.88	47.21	22.80	22.43	24.10	22.44
Hour 16	43.00	46.54	50.03	77.64	49.72	23.02	22.55	24.18	22.34
Hour 17	46.59	52.19	57.06	51.90	56.41	23.13	22.69	24.47	22.49
Hour 18	35.82	37.41	38.11	40.89	38.27	23.33	23.05	24.36	22.75
Hour 19	34.65	35.47	36.09	37.60	36.29	23.35	23.12	24.23	22.82
Hour 20	26.81	25.85	26.31	59.17	26.50	22.62	22.56	23.43	22.31
Hour 21	34.60	35.05	35.80	80.36	36.05	23.42	23.36	24.19	23.03
Hour 22	23.85	24.04	24.30	26.05	24.53	22.74	22.76	23.33	22.55
Hour 23	22.05	22.31	22.68	22.01	22.79	21.52	21.64	22.27	21.39
Hour 24	20.70	20.99	21.58	19.61	21.58	20.34	20.54	21.28	20.25
Around the Clock									
Low	(159.45)	16.40	16.94	15.42	16.87	16.47	16.35	17.05	16.17
Average	28.91	30.48	31.58	36.14	31.54	21.26	21.07	22.02	20.81
High	430.94	113.50	114.97	110.63	115.28	24.79	23.75	25.66	23.03
On-Peak									
Low									
Average									
High									
Off-Peak									
Low	(159.45)	16.40	16.94	15.42	16.87	16.47	16.35	17.05	16.17
Average	28.91	30.48	31.58	36.14	31.54	21.26	21.07	22.02	20.81
High	430.94	113.50	114.97	110.63	115.28	24.79	23.75	25.66	23.03