DEVELOPING A FRAMEWORK FOR METHANOL SUPPLY CHAIN OPTIMIZATION INCORPORATING RENEWABLE PRODUCTION TECHNOLOGIES: A CASE STUDY OF TEXAS

A Thesis

by

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ABSTRACT

Solving the environmental and societal problems associated with rising greenhouse gas (GHS) emissions and climate change are crucial challenges our global society is currently facing in order to secure a sustainable future. A potential solution to this global issue is the conversion of carbon free thermal and kinetic energy from the sun and wind into a manageable energy such as electricity. However, the intermittent natural of solar and wind energies greatly hinders the practical application of renewable technologies into electricity generation. Hence, the conversion of renewable energy into an energy carriers, specifically methanol, is investigated in this research.

A Mixed Integral Linear Programming (MILP) model was developed as a framework for renewable energy generated methanol to meet the electricity demands of Texas. Renewable energy potentials of solar (kWh/m^2/day) and wind (m/s) and associated capacity factors were considered per county of Texas. The model calculates all the costs associated with building and operating the selected renewable power plants, electrolyzer systems, methanol production plants, Carbon Capture Unit (CCU) for Carbon Dioxide (CO_2) capture and compression, and transportation costs of water, Carbon Dioxide (CO_2), and product. The total cost was minimized to identify the most optimal locations of plant construction for renewable energy generated methanol.

Based on the results of this supply chain optimization model, the Levelized Cost of Energy (LCOE) for the production of renewable energy generated methanol to meet the demands of the top five energy consuming counties of Texas is estimated to be

$29.58/GJ to $30.92/GJ without the sale of Oxygen (O_2) gas and $25.09/GJ to $26.28/GJ with the sale of Oxygen. The sale of Oxygen is only considered at a 50% discount price of current selling price to consider the price elasticity of the market. Wind power plants was selected over solar power plants for methanol production which showed that wind energy was more cost competitive than solar energy. A rudimentary case study was conducted to calculate the LCOE of solar energy powered methanol production which is roughly $38/GJ to meet the 44 % of total energy consumption of Texas. Further work can be done on the supply chain network to compare the cost competitiveness of methanol production as energy carriers to that of hydrogen production.

DEDICATION

First of all, I would like to thank my committee chair, Professor Pistikopoulos for essentially motivating me to pursue a career in the field of Energy. He has been a great inspiration at a personal and profession level during my time at Texas A&M University and will continue to be so for the many years to come. I would like to also thank my committee members, Professor El-Halwagi and Professor Mannan for their guidance and support throughout the course of this research.

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Contributors

This work was supervised by a thesis committee consisting of Professor Stratos Pistikopoulos, Mahmoud El-Halwagi and M. Sam Mannan of the Artie McFerrin Department of Chemical Engineering and the Texas A&M Energy Institute.

All work for the thesis was completed by the student, under the advisement of Professor Stratos Pistikopoulos, Doha Demirhan, and William Tso of the Artie McFerrin Department of Chemical Engineering.

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1. INTRODUCTION

1.1 Problem Statement

Global warming and climate change has become an inevitable problem of today and the future. Emission of greenhouse gases (GHG) into the atmosphere has been identified as the leading cause of global warming. However, our current energy systems are heavily depended on fossil fuel sources, which are identified as the dominant GHG emitter. In addition, the global energy consumption and demand will continue to rise based on predicted increase in population. To address the issues associated with climate change, there is a high demand for innovative approaches to generate clean and non-Carbon Dioxide (CO_2) emitting forms of energy in mass industrial scale. As of now, renewable energies such as solar and wind energy sources are being extensively studied for potential alternatives to the conventional energy sources such as petroleum, coal, and natural gas as a clean and sustainable solution.

Solar and wind energies have several advantages over conventional energy sources. With the current technologies available in the market, renewable energies can be directly converted to transmittable energy through a process that is non-CO_2 emitting, can be produced anywhere compared to the disproportionately located petroleum reserves, and most importantly are abundant and do not deplete over time. However, even though renewable energies have become more economically feasible over the years owing to the decrease of production cost and improvement of conversion efficiencies, there is a significant constraint to how fast renewable energies can replace fossil energy sources due to its intermittent natural of supply based on hourly, seasonally, and geographically variation. Meaning the most productive and efficient hours to produce renewable energy do not always align with the hours of demand from energy consumers and at peak producing hours, there is a surplus of renewable energy generated electricity that cannot be consumed in the market.

In addition, the construction of solar and wind energy power plants are generally placed in remote and far from the grid locations where high renewable energy potentials are present. In which case, safe and efficient storage and transportation of the generated energy can act as another cost constraint.

One possible solution to the intermittency problem of renewable energy is the use of energy carriers such as hydrogen, ammonia, or methanol for later use at distant locations. Hydrogen are generated through the electrolysis of water using solar and wind energy generated electricity and further compressed or liquefied as hydrogen or synthesized to hydrogen carrying chemicals such as methanol and ammonia. The produced chemicals can act as energy carriers for convenient storage and safe transportation to locations of demand. In addition, carbon recycling is proposed and utilized for the production of renewable methanol as renewable energy generated hydrogen was coupled with CO_2 gas captured from point sources or ultimately the atmosphere. The following figure depicts the carbon cycle within the “methanol economy”, an economy where methanol replaces fossil sources as fuel for transportation, heating, electricity generation, and as a precursor of commodity chemicals. Such idea of a “methanol economy” was first proposed and advocated by Nobel Prize winner George A. Olah in 1990s and is further explained in section 2.3.

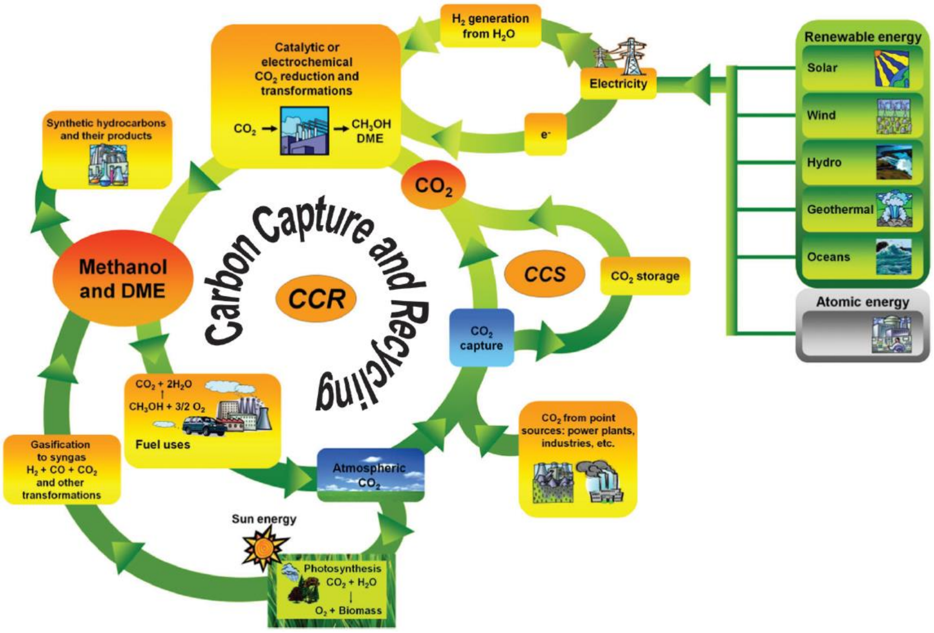


Figure 1. Anthropogenic carbon cycle within the Methanol Economy. (Reprinted from [1])

1.2 Objective

In this research, a systematic analysis of the various tradeoffs and competing options to build and operate a renewable energy generated methanol process using catalytic Carbon Dioxide (CO_2) hydrogenation was conducted by constructing and evaluating a Mixed Integral Linear Programming (MILP) supply chain model. Methanol was chosen as a potential energy carrier due to the versatile applications as direct fuel for electricity, transportation, heating, and common feedstock for synthetic hydrocarbons.[2] Most importantly, for the purpose of this research, methanol was chosen over other potential energy carries due to the little modification necessary to implement as turbine fuel to the existing power plants for electricity generate.[3]

The MILP supply chain network model evaluated the most optimal locations in Texas to build and operate a solar or wind power plant facility for methanol production. The electricity generated from renewable energy will produce hydrogen from water using Proton Exchange Membrane (PEM) electrolyzer technology. The produced hydrogen was further synthesized to methanol that acts as an energy carrier with the addition of CO_2 gas. The produced methanol was transported to meet the demands of the top five electricity consuming counties of Texas.

The capital and operating costs of constructing and maintaining a renewable energy power plant, methanol production plant, and carbon capture unit were considered in the model. In addition, the purchase and transportation cost of feedstock, water and CO_2 gas, and transportation cost of final product to demand site were taken into considered in the model to calculate an estimated Levelized Cost of Energy (LCOE).

2. LITERATURE REVIEW

2.1 Renewable Energy: Advantages and Limitations

Preventing the progress of climate change and resolving the energy crisis are few of the main challenges our global society is facing. Developing a clean and emission-free energy system is a major breakthrough in this regard. Solar and wind energies have been extensively studied as a clean and sustainable replacement of the current fossil fuel-based energy system. The following sections will cover the advantages and limitations of solar and wind energies as an alternative energy source of the current energy system.

2.1.1 Solar Energy

Solar energy is considered one of most sustainable sources of energy and a leading solution to the current energy crisis due to its ubiquitous property and CO_2 emission free nature.[4] Most importantly, the sun is the basis of energy on Earth and offers an unlimited source of energy. About 885 million terawatt-hours reach the surface of the Earth in a year, which is equivalent to 6,200 times the commercial energy consumed globally in 2008 and 4,200 times the predicted global energy demand by 2035 based on International Energy Agency's predictions in 2011.[5] The volume of solar energy compared to global energy demand is depicted in the below figure.

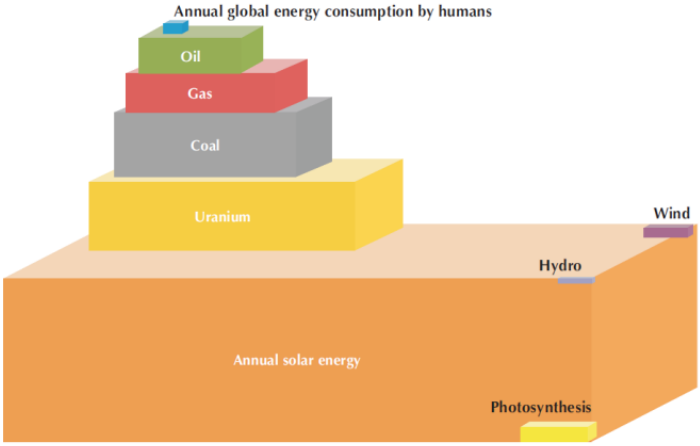


Figure 2. Available energy resources respect to annual solar energy availability. (Reprinted from [5])

However, the technical conversion of solar energy to a mendable form of energy such as electricity is heavily dependent on the regional, seasonal, and daily variation of solar energy. Such intermittent natural of solar energy is one of the main challenges of predicting the Levelized Cost of Energy (LCOE) of a solar power plant. An example of the annual variation of solar energy can be seen in the below figure.

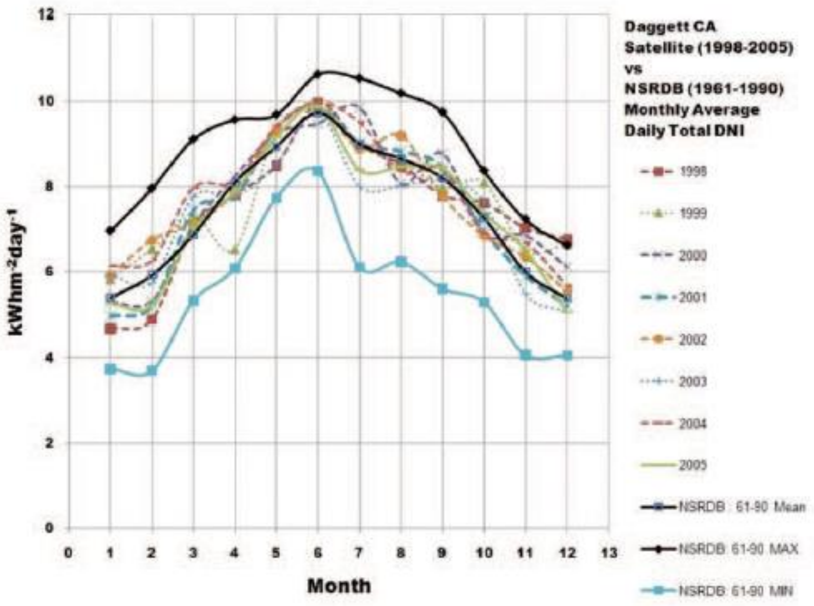
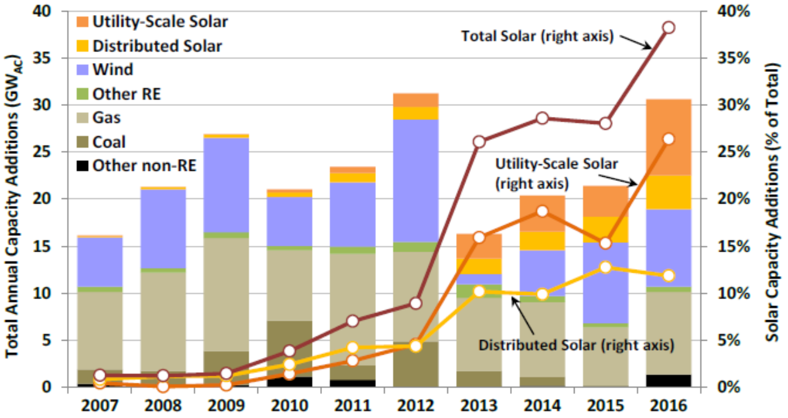


Figure 3. Annual variation of monthly average daily total (kWh/m^2/day) from 1961 through 2005 at Daggett, California. (Reprinted from [6])

In addition to the intermittent natural of solar energy, the technical cost associated with the efficient and economical production of solar energy has been a main constrain of solar energy. Despite such challenges, solar energy have been experiencing extreme growth in the last few year driven by the declining cost of solar modules and federal and state government incentives. Solar power was the largest source of addition in the United States electricity generating capacity of 2016 as can be seen in the below graph, where solar energy accounts for 38% of all new capacity added to the grid in 2016 (from a source published in 2017).



Sources: ABB, AWEA, GTM/SEIA Solar Market Insight Reports, Berkeley Lab

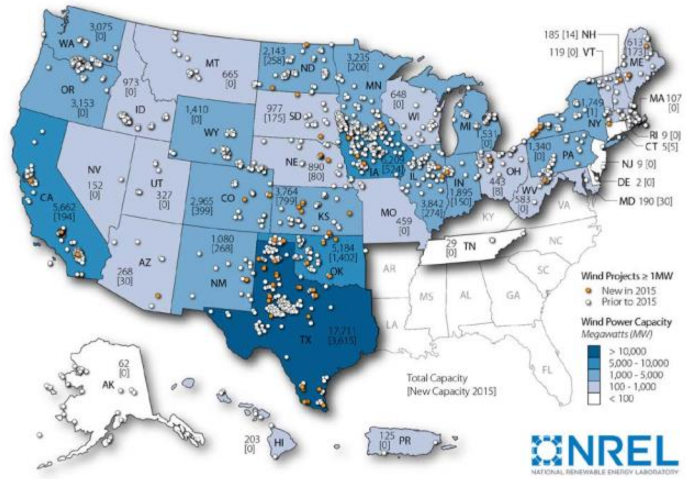
Figure 4. United States electricity generating capacity additions in 2016. (Reprinted from [7])

By the end of 2016, utility-scale solar power capacity accounted for 121.4 gigawatt across the United States of which 83.3 gigawatt were from first year producing solar power plants in 2016.[7]

2.1.2 Wind Energy

Just like solar energy, wind energy is a clean and sustainable source of energy. Wind power systems have been used by mankind for centuries from old windmills for water pumping or grain grinding in Holland to the current day electricity generating wind turbines.[8] Electricity is generated by the lift imposed on the blades of wind turbines created by the wind's kinetic energy. As of 2016, wind turbine generated electricity occupies nearly 6% of the total United States utility-scale electricity generation. This is equivalent to 226 billion kilowatt-hours of electricity generated from wind turbines, which is a significant increase from 6 billion kilowatt-hours in 2000.[9] Such dramatic increase in market share of wind turbine generated electricity is by part due to the subsidies provided by government policies. However, even with the decrease of subsidies in recent years, the cost of electricity generated from wind turbines are continuing to decrease and are staying competitive with technological advancement.

The following map of the United States shows all the wind power plants in operation as of 2015. Texas is the leading state of wind energy production and consumption.



Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2015.

Figure 5. Profile of wind power plants in operation in the United States, 2015. (Reprinted from [5])

Wind energy is a clean and CO_2 emission free energy. However, just like solar energy, wind fluctuates geographically, seasonally, and daily which requires an effective energy storage and transportation method to harvest wind energy. In addition, one of the most publicized drawback of wind energy is noise pollution which hinders the operation of wind power plants near residential regions.

2.2 Energy Carriers

Energy carriers of interest in this research are hydrogen carriers such as methanol or ammonia, which can securely store hydrogen as a stable chemical formula compared to compressed hydrogen gas or liquefied hydrogen. The properties of hydrogen and methanol as energy carriers are investigated in this section. Conventional and renewable technologies to produce such energy carriers are also investigated.

2.2.1 Hydrogen

Hydrogen is a very promising energy carrier or fuel that is clean and free of carbon dioxide emission. Although hydrogen is not naturally available as a readily usable substance, hydrogen is abundant and can be extracted from a variety of materials and compounds found anywhere across the planet. The following subsections cover the properties of hydrogen, advantages and limitations of hydrogen as an energy carrier, and conventional and renewable hydrogen production methods.

2.2.1.1 Properties of Hydrogen as an Energy Carrier

Hydrogen is the most abundant and simple substance of the universe. It is also colorless, odorless and tasteless and its molecular structure is very small and light structure unlike conventional petroleum-based fuels. One property of hydrogen that stands out is the high energy per mass content of 143 MJ/kg, which is up to three times larger than liquid hydrocarbon based fuels.[10] On the other hand, hydrogen is very low in volume density as a gaseous state and liquefaction of hydrogen is a highly energy intensive process. The energy density of liquid hydrogen is 9.9 MJ/L, which is roughly a third the energy density of iso-octane.[11] Hydrogen is also not available in naturally separated material and is usually bonded with other materials such as carbon and oxygen.

The use of fossil fuels in large scales has caused various sorts of problems today including pollutant emissions of harmful materials, and greenhouse gasses. Fossil fuels are also limited and disproportionately distributed at certain regions. Hydrogen on the other hand, has a very long-term viability and could be produced in variety of methods anywhere around the world. Hydrogen can be fed to a wide range of consumers such as turbines, internal combustion engines and fuel cells as well as kitchen ovens and heaters. Most importantly, the consumption of hydrogen comes with minimum harmful emissions and the byproduct is only water regardless of the method of utilization. In addition, hydrogen can be added to other fuels in order to form energy enriched mixtures and be used as alternative fuel for engines designed to run on other fuel forms due to its uniquely wide flammability range of 4~75% when conventional gasoline has a flammability range of 1~7.6%.[10] Such property opens up a wide range of possibilities for hydrogen as fuel for combustion engines and turbines where wide flammability range also indicates that engine power can be more easily controllable.[12]

Conversely, the wide flammability range of hydrogen is also accountable for one the biggest concerns regarding hydrogen safety, exclusivity of hydrogen gas. Despite the fact that inhalation of hydrogen fire is effectively harmless to the human body, the low electro-conductivity rating of hydrogen, which means fluid can easily generate a spark when in motion, is a concerning factor in regards to storage and transportation. Additionally, the low density and energy content of hydrogen gas is the biggest constraint of implementing hydrogen as an energy carrier. Even though liquid hydrogen is much higher in energy content than gas hydrogen, the compression to liquid phase requires the temperatures to be below -250 ℃, which results in the production cost of liquid hydrogen to be 4 to 5 times more than gas hydrogen production.[13] Gas hydrogen stored in compressed tank also requires gas to be kept in high pressures in the range of 350 to 700 bars. Such limitations makes production, storage, and transportation of gas or liquid hydrogen problematic and energy intensive.[1] Lastly, the infrastructures to produce, transport, and distribute hydrogen are not possible with modifications of the current energy system and requires a construction of new infrastructures for implementing hydrogen as an energy carrier.

2.2.1.2 Hydrogen Production: Conventional and Renewable Technologies

Most popular form of hydrogen production is from breaking hydrogen and carbon bonds of fossil fuels such as biomass, coal, gasoline, oil, methanol, and methane. Stream-methane reforming (SRM) has the largest share in global hydrogen production, almost 48%, and is currently known to be the most economical method. The use of coal and oil for hydrogen production are second and third place respectively with a global hydrogen production share of 30% and 18%. Hydrogen production by water electrolysis has the smallest share of 4% due to high production costs from low conversion efficiency and electrical power expenses.[10] Various hydrogen production methods and applications are illustrated in the below figure.

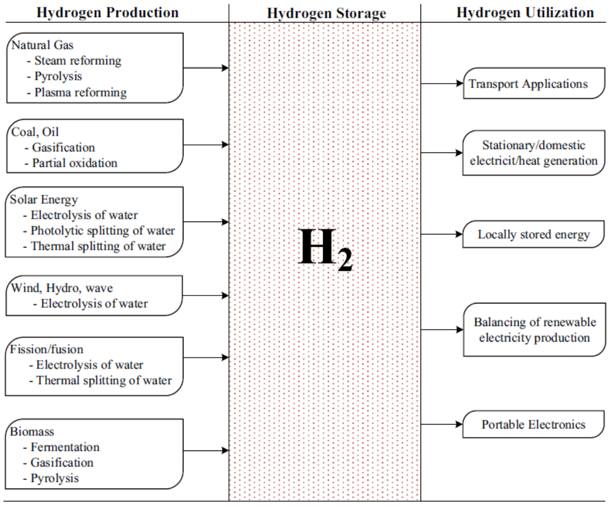


Figure 6. Hydrogen production methods, through storage to various end users. (Reprinted from [4])

The chemical reactions and steps of synthetic gas generation from fossil fuel is described in the following section 2.2.2.3. In the interest of this research, hydrogen production by electrolysis of water molecule using renewable energy is explored in this section. The electrolysis of water can be expressed with the following half reactions at the electrodes when direct current (DC) passes through a body of water.[4]

Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ $E_a^0 = 1.23\ V$

Cathode: $2H^+ + 2e^- \rightarrow H_2$ $E_c^0 = 0\ V$

The overall chemical reaction of water electrolysis process is as following.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

The minimum energy required for water electrolysis process is 39.4 kWh per kg of hydrogen produced when full efficiency is met. However, typical electrolyzer consumes up to 50 kWh per kg of hydrogen produced which is roughly 79% efficiency.[10] Many efforts are made to enhance the efficiency of water electrolysis and higher efficiencies were observed at extreme pressure and temperature conditions. However, at these extreme conditions, investment costs are higher in order to build more complex and sophisticated electrolyzers that can withstand such conditions. In addition to higher investment cost, increase in corrosion, operation and maintenance costs, and reduction of life span are also observed at these conditions that yield high efficiency.

Despite such disadvantages of water electrolysis, there are some unique qualities worth noting for hydrogen production. Electrolysis of water for hydrogen production can be conducted anywhere in the world as the only requirements for production are water and electricity. In addition, the production rate and capacity can be tuned for a certain demand of any location. Most notably, water electrolysis driven by wind, solar, geothermal systems, ocean wave or other renewable sources generated electricity can achieve a CO_2 emission free energy generating system. Energy generating system of water electrolysis using renewable source generated electricity are 8 times faster than those of water electrolysis using oil-based fuels.[14] Whereas the net energy profiles of both methods are very similar for the course of the lifespan.

2.2.2 Methanol

The versatile use of methanol as a chemical intermediate and direct fuel has increased methanol manufacture and consumption from 32 million tons per year in 2004 to 68.9 million tons per year in 2017.[15] This increasing trend is expected to continue as to reach roughly 95 million tons per year by 2020 as can be seen in the below figure.

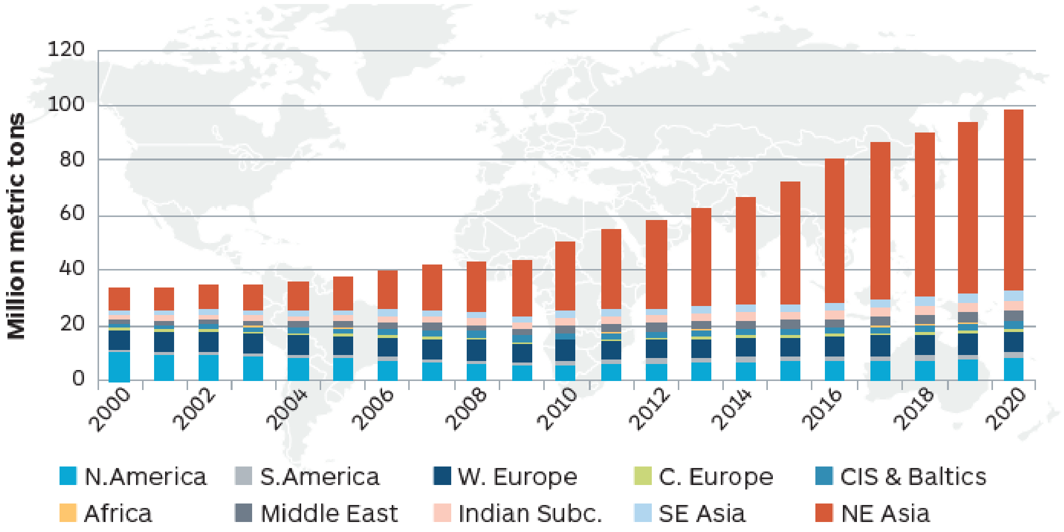


Figure 7. World methanol demand by region. (Reprinted from [16])

Such increase in consumption is fueled by the expanding demand for chemicals in China, where “NE Asia” represents China in the above figure. China has emerged as a global consumer and producer of methanol in the last 15 years. In 2000, China represented merely 12 percent of the global methanol demand whereas North America and Western Europe represented 33 and 22 percent of the global demand respectively. As of 2017, IHS predicts that Northeast Asia (China), will account for nearly 70 percent of the global demand by 2021.[17]

2.2.2.1 Properties of Methanol as an Energy Carrier

Methanol, also known as methyl alcohol or wood alcohol, is a colorless, water-soluble liquid with a relatively mild alcoholic odor. Methanol is a clean-burning fuel with an octane number of 108.7, which is higher than unleaded gasoline of 95.[18] However, the volumetric energy density of methanol is 18 MJ/L, which is only half of that of gasoline.[19,11]

Methanol is flammable and toxic like most chemicals and should be used with care. However, compared to gasoline, a common transportation fuel, the chemical and physical properties of methanol significantly reduces the risk of fire and explosion. The lower volatility and low radiant heat output properties of methanol make it difficult to be set on fire and to spread to surrounding materials. In addition, methanol burns with little or no smoke which decreases the risk of injuries associated with smoke inhalation and evacuation. Overall, methanol is considered a safe form of fuel when compared to gasoline as methanol fire is less likely to happen and is less damaging when it does occur compared to gasoline fueled fire.[2]

The most common use of methanol is as a chemical feedstock for various chemical products. Such include formaldehyde, methyl tert-butyl ether (MTBE), acetic acid, and more as shown in the below figure.

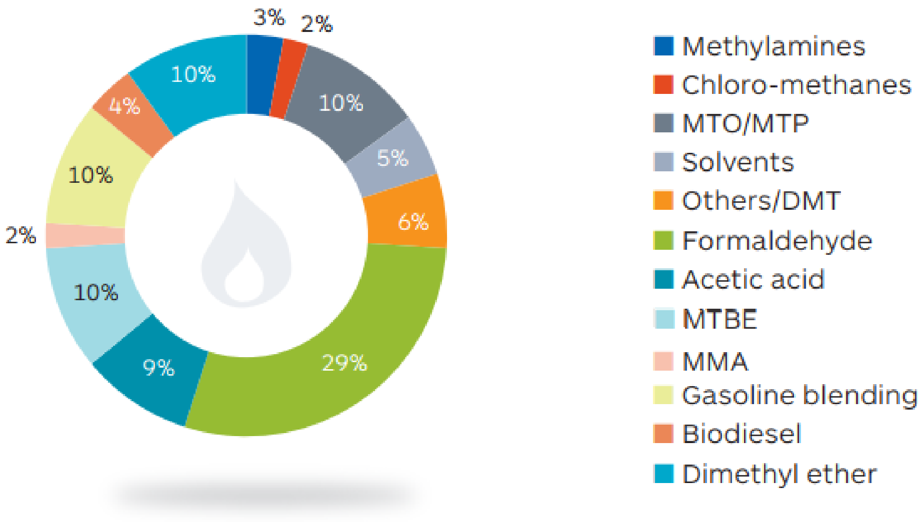


Figure 8. World methanol demand by end users in 2015. (Reprinted from [16])

These chemicals are further processed into common chemicals used on a daily basis such as paints, resins, silicones, adhesives, antifreeze, and plastics.[20]

As previously mentioned, global demand for methanol has increased significantly due to the increase in methanol demand seen primarily in China. Such demand in China is due to the significant growth the country has experienced in the past decade, which has increased demand for traditional methanol derivatives such as formaldehyde and acetic acid. These derivatives are key components to manufacturing chemicals widely used in construction, wood products, high-strength engineering resins, and insecticide applications. However the biggest factor of increase in methanol demand is actually due to the emergence of a relatively newer end user such as for production of light olefins and for energy applications.[19] Light olefins such as ethylene and propylene produced from methanol-to-olefins (MTO) processes are further processed to become primary components of plastics. Methanol is used in the energy sector as a fuel product for direct blending into gasoline, to produce biodiesel, and dimethyl ether (DME). The use of methanol for direct blending to gasoline has seen an average annual growth rate of 25 percent from 2000 to 2015 in China. The use of DME as a direct fuel source for road vehicles as an alternative to diesel or use as blended fuel into liquefied petroleum gas (LPG) for home cooking and heating applications has grown from practically nothing in 2000 to becoming a major end user of methanol by 2015. The increase demand for methanol consumption as fuel products in China over the years can be seen in the below figure.

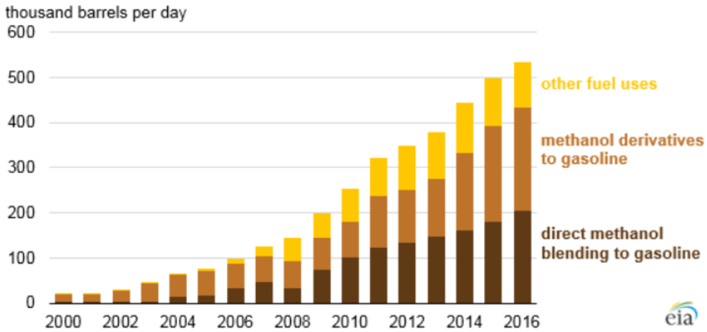


Figure 9. China methanol consumption in fuel products. (Reprinted from [19])

As of 2017, approximately 45 percent of the global methanol demand is in the energy sector and is expected to grow in the future.[21]

It is important to note that despite the end users of methanol being CO_2 emitters, methanol and its derivatives are clean burning and more efficient than conventional fossil sources. Innovative methods are currently being explored and few are practiced to recycle and utilize methanol as a carbon neutral energy source.[22] Such concepts of carbon recycle and methanol economy are covered in section 2.3.

2.2.2.3 Methanol Production: Conventional and Renewable Technologies

As of today, methanol is mostly produced by synthetic gas (syn-gas), a mixture of hydrogen, carbon monoxide (CO), and some carbon dioxide (CO_2) over a heterogeneous catalyst under controlled temperature and pressure conditions. The following chemical equations represent the methanol production using syn-gas.[1]

$$CO + 2H_2 \rightleftharpoons CH_3OH \qquad \Delta H_{298K} = -21.7 \text{ kcal/mol}$$

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \qquad \Delta H_{298K} = -11.9 \text{ kcal/mol}$$

$$CO_2 + H_2 \rightleftharpoons CO + H_2O \qquad \Delta H_{298K} = 9.8 \text{ kcal/mol}$$

The first two reactions that actually yields methanol are exothermic and results in decrease of volume as the reaction takes place. As a result, based on Le Chatelier's principle, methanol generation is favored at high pressure and low temperatures. The third reaction is the endothermic reverse water-gas shift reaction. All the above reactions are reversible and are subjective to the thermodynamic equilibrium limitations based on operating conditions and feedstock composition. The stoichiometric number, *S*, is used to characterize the composition of syn-gas.

$$S = \frac{(\text{moles } H_2 - \text{moles } CO_2)}{(\text{moles } CO + \text{moles } CO_2)}$$

A stoichiometric value equal to or slightly above 2 is preferred for methanol generation were a stoichiometric value above 2 indicates an excess of hydrogen and a value below 2 indicates a deficiency of hydrogen for ideal methanol generation. The syn-gas used as feedstock for methanol generation can be obtained from reforming or partial oxidation of any carbonaceous material including natural gas, petroleum, heavy oil, and coal. Syn-gas obtained from reforming of feedstock with high Hydrogen to Carbon ratio such as propane, butane, or naphthas, yields a stoichiometric value of approximately 2; whereas syn-gas obtained from stream reforming of methane yields a stoichiometric value of 2.8 to 3.0.

Despite the non-ideal stoichiometric value obtained from natural gas generated syn-gas, natural gas is the most widely used feedstock to produce methanol due to fewer impurities, such as sulfur and halogenated compounds, generated. Large amounts of impurities in product would require further separation from the desired product and such impurities can poison and shorten the lifespan of the catalysts. There are two common methods to generated syn-gas from natural gas, steam reforming and partial oxidation of methane. Steam reforming of methane to syn-gas is a highly endothermic process as can be seen from the following equations.[1]

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H_{298K} = 49.1 \ \text{kcal/mol}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H_{298K} = -9.8 \ \text{kcal/mol}$$

Where the syn-gas generation process is operated at high temperatures of 800 to 1,000 ℃, under pressure of 20 to 30 atm, and typically over nickel based catalyst.[23] To process this endothermic reaction, the feedstock (conventionally natural gas) is partially burned to provide heat to the system. Additional CO_2 will be added to the resulting syn-gas to correct the stoichiometric value from 3.0 to 2.0.

Partial oxidation of methane is a reaction of methane with insufficient oxygen and is another typical method to generate syn-gas. The following chemical reactions represent the syn-gas generation using partial oxidation of methane.[1]

$$CH_4 + \frac{1}{2}O_2 \leftrightarrow CO + 2H_2 \qquad \Delta H_{298K} = -8.5 \ \text{kcal/mol}$$

$$CO_2 + \frac{1}{2}O_2 \leftrightarrow CO_2 \qquad \Delta H_{298K} = -67.6 \ \text{kcal/mol}$$

$$H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O \qquad \Delta H_{298K} = -57.7 \ \text{kcal/mol}$$

The syn-gas generation process is operated at high temperatures of 800 to 1,500 ℃. This exothermic process does yield an ideal stoichiometric value of 2 initially but can further oxidize to form undesirable CO_2 and water, which contributes to safety concerns and S values lower than 2.

The technology to mass produce methanol at an industrial scale using syn-gas has improved significantly over the past century since it was first introduced by BASF in Germany in the 1920s. Most modern-day methanol plants use natural gas based syn-gas as feedstock over $CuO/ZnO/Al_2O_3$ catalyzer and has high selectivity yields of greater than 99%, which operates at high energy efficiencies of above 70%. Almost all conventional methanol production is carried out as gas phase at pressure range of 50 to 100 atm and temperature range of 200 to 300 ℃.[1] However, it is still an highly energy intensive process where cost of syn-gas generation accounts for half the total investment cost of a conventional methanol production.[24] In addition, throughout the entire cycle of conventional methanol production about 0.6 to 1.5 tons of CO_2 are emitted for each ton of methanol produced.[25] The following figure shows the flowchart of methanol generation from fossil fuel resources.

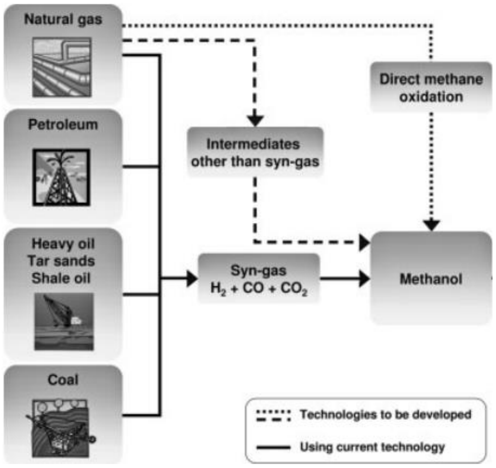


Figure 10. Methanol from fossil fuel resources. (Reprinted from [2])

In the interest of this research, electricity generated from renewable energy was used to synthesis methanol through catalytic CO_2 hydrogenation. There are two possible paths for catalytic CO_2 hydrogenation production of methanol; one-step or two-step processes. The one-step process is the direct hydrogenation of CO_2 to methanol whereas in the two-step process CO_2 is first converted to CO through reverse water gas shift reaction and then hydrogenated to methanol. Both one-step and two step-processes can be seen in the following figure.

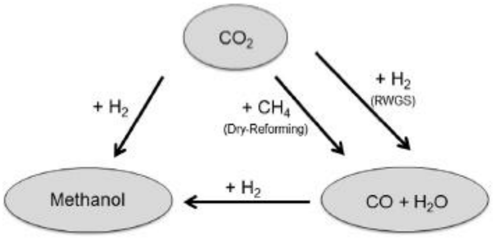


Figure 11. Methanol production from CO_2 hydrogenation. (Reprinted from [26])

2.3 Prospects of the "Methanol Economy" [2]

Methanol and its derivatives such as dimethyl ether (DME) are convenient energy storage medium as a result of its stable chemical properties. They are a readily viable feedstock for engines and fuel cells, and are precursors of larger synthetic hydrocarbons and their various chemical products. Compared to hydrogen which has significant limitations to implement in the current energy system, methanol is suggested as a practical alternative for short-term implementation that only requires few adjustments of the current energy system. The idea to use methanol as an alternative to the automobile fuel has been circulating since the 1970s. In 1973, Thomas Reed, a researcher at the Massachusetts Institute of Technology (MIT) published a paper that stated the improved performance of a vehicle in enhanced mileage and reduction of pollution while running on 10% methanol and 90% gasoline fuel compared to a vehicle running on 100% gasoline. Throughout the years that followed, similar results of higher performance and lower overall air pollutants emissions were observed and published for methanol blended gasoline and methanol fuel run vehicles. Despite such positive results over the years, methanol fuel could not break through as a widespread automobile fuel due to the resistance from the oil industry and economic aspects of oil prices. Most importantly the biggest hindrance for use of methanol over fossil fuel was that syn-gas based methanol does not alleviate the burden of carbon emissions.

A possible solution to the CO_2 footprint from methanol production was discussed in the previous section where new methods are being explored to production methanol without the generation of syn-gas. Another possible solution suggested by researchers over the years is the chemical recycling of CO_2. Instead of burning the feedstock to generate syn-gas, the necessary CO_2 component will be sequestrated from current industrial plants and necessary hydrogen will be generated from water electrolysis using electricity generated by renewable energy sources. Overtime the goal is to extract the CO_2 directly from the atmosphere using technologies such as advanced membrane separation or selective absorption methods. Ultimately, chemical recycling of CO_2 and hydrogen generation using renewable energy generated electricity can be a long-term solution to the diminishing fossil fuel resources and rising CO_2 emission. In such aspects, methanol can act as a bridge between fossil fuel and renewable energy for the future.

The “methanol economy” is a world where methanol and its derivatives replace fossil fuel as an energy carrier, a fuel for transportation and heating, and as a precursor of synthetic hydrocarbons. Further, advancements of CO_2 sequestration from the atmosphere and hydrogen generation through electrolysis can yield a carbon free methanol production that will be independent from fossil fuel resources.

3. SUPPLY CHAIN NETWORK DESCRIPTION: A CASE STUDY OF TEXAS

3.1 Background

Global warming and climate change has become an inevitable problem of today and the future. Renewable energies such as solar and wind energy sources are being extensively studied for potential alternatives to the current energy sources as a clean and sustainable solution. However, the stranded and intermittent natural of renewable energies acts as enormous barriers for renewable energies to take a larger presence in the energy market. As a possible solution, the production of energy carriers, specifically methanol, was investigated in this study to meet the energy demands across Texas. Renewable energy generated methanol was produced at renewable energy potential rich locations and delivered to demand locations as an alternative to conventional fossil fuel in this study.

3.2 Problem Formulation for Methanol Supply Chain

The following diagram shows the material flow of the renewable energy generated methanol production.

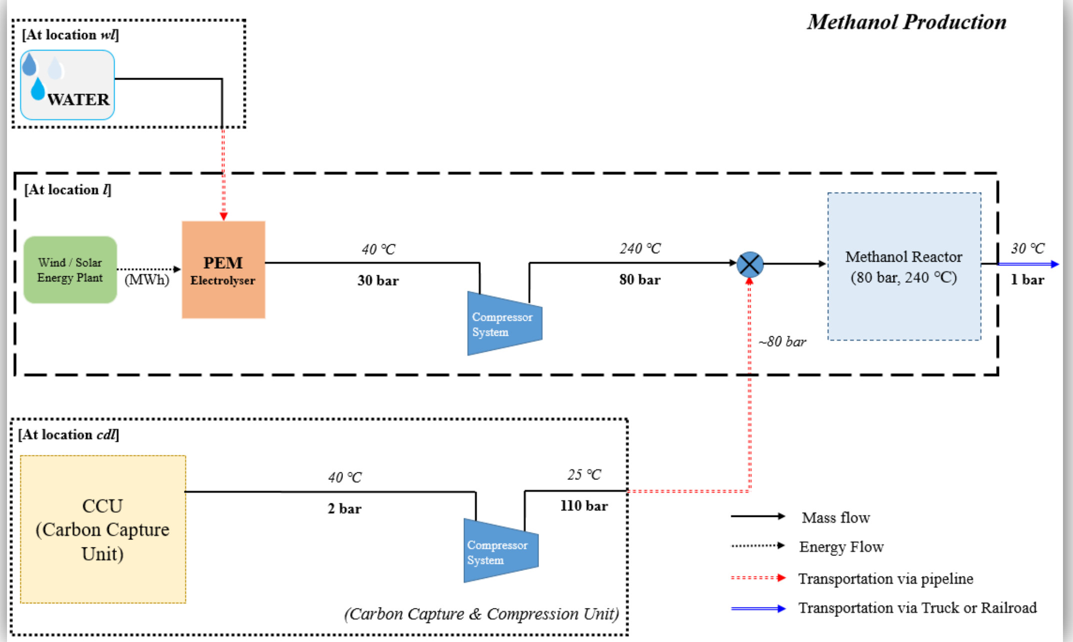


Figure 12. Flow diagram of methanol production.

The following factors are known and implemented in the methanol supply chain network model.

- Sources (renewable energy, water, carbon dioxide): types, locations, energy potentials, available quantity.
- Costs and technology specifications: renewable power plant, electrolyze system, methanol production plant, carbon capture unit
- Costs of transportation: water, carbon dioxide, product
- Demand target: 44% of Texas demand (5 counties)

Additionally, the equivalent operating hours of methanol plant is assumed to be 8,000 hours per year, which is a typical value for such type of chemical plants.[25] The objective of this study is to formulate a renewable energy generated methanol supply chain network by identifying the optimal facility locations that yields the lowest total cost. A Mixed Integer Linear Programing (MILP) was built with the listed known above for this study.

3.3 Material Balance for Methanol Production

The material balance for methanol production can be seen in the below table. For this model, ten different capacities of methanol production were considered; smallest production capacity being 32 ton/day (t1) and largest production capacity being 5,014 ton/day (t10). The t10 capacity of 5,014 ton/day was considered as the maximum size as the world's current largest methanol production plant capacity is 5,000 ton/day.[27]

Table 1. Material balance of methanol production used in this model for capacities t1 to t5.

Methanol Plant Capacities (T)			t1	t2	t3	t4	t5
Solar Power Plant	Capacity	MW_{DC}	60	170	284	568	1,132
	Energy Produced (CF = 0.24)	MWh_{DC}	14.3	40.7	68.2	136.4	271.7
Wind Power Plant	Capacity	MW_{DC}	35	99	166	333	663
	Energy Produced (CF = 0.41)	MWh_{DC}	14.3	40.7	68.2	136	272
Electrolyzer System	No. of PEM (Proton Onsite M-200)	n	13	37	62	124	247
	Energy Consumption, $ER_{r,t}$	MWh_{DC}	14.3	40.7	68.2	136.4	271.7
	Water Consumption, $FW_{p,t}$	kg/hr	2,656	7,558	12,665	25,331	50,457
	H_2 flow out, $HO_{p,t}$	kg/hr	257	733	1,228	2,455	4,891
	O_2 flow out, $OO_{p,t}$	kg/hr	2,043	5,814	9,743	19,486	38,814
CCU Plant	Flue gas in	kg/hr	10,494	29,828	50,022	100,039	199,250
	wt% of CO_2 in flue gas	wt-%	20	20	20	20	20
	90% CO_2 flow out, $FC_{p,t}$	kg/hr	2,099	5,966	10,004	20,008	39,850
Methanol Production Plant	H_2 flow in, $HO_{p,t}$	kg/hr	257	733	1,228	2,455	4,891
	90% CO_2 flow in, $FC_{p,t}$	kg/hr	2,099	5,966	10,004	20,008	39,850
	Gas Mixture into Reactor	kg/hr	2,356	6,698	11,232	22,463	44,741
	Methanol Production, $PR_{p,t}$	kg/hr	1,320	3,753	6,294	12,588	25,072
		ton/day	32	90	151	302	602
		ton/yr	10,560	30,024	50,352	100,703	200,573

Table 2. Material balance of methanol production used in this model for capacities t6 to t10.

Methanol Plant Capacities (T)			**t6**	**t7**	**t8**	**t9**	**t10**
Solar Power Plant	Capacity	MW_{DC}	1,884	2,823	4,175	6,265	9,410
	Energy Produced (CF = 0.24)	MWh_{DC}	452	678	1,002	1,504	2,258
Wind Power Plant	Capacity	MW_{DC}	1,103	1,653	2,444	3,668	5,508
	Energy Produced (CF = 0.41)	MWh_{DC}	452	678	1,002	1,504	2,258
Electrolyzer System	No. of PEM (Proton Onsite M-200)	n	411	616	911	1367	2053
	Energy Consumption, $ER_{r,t}$	MWh_{DC}	452	678	1002	1504	2258
	Water Consumption, $FW_{p,t}$	kg/hr	83,959	125,837	186,100	279,252	419,389
	H_2 flow out, $HO_{p,t}$	kg/hr	8,138	12,197	18,038	27,067	40,649
	O_2 flow out, $OO_{p,t}$	kg/hr	64,586	96,800	143,157	214,814	322,613
CCU Plant	Flue gas in	kg/hr	332,083	498,125	737,225	1,105,837	1,660,416
	wt% of CO_2 in flue gas	wt-%	20	20	20	20	20
	90% CO_2 flow out, $FC_{p,t}$	kg/hr	66,417	99,625	147,445	221,167	332,083
Methanol Production Plant	H_2 flow in, $HO_{p,t}$	kg/hr	8,138	12,197	18,038	27,067	40,649
	90% CO_2 flow in, $FC_{p,t}$	kg/hr	66,417	99,625	147,445	221,167	332,083
	Gas Mixture into Reactor	kg/hr	59,775	89,662	132,700	199,051	298,875
	Methanol Production, $PR_{p,t}$	kg/hr	41,786	62,679	92,765	139,148	208,931
		ton/day	1,003	1,504	2,226	3,340	5,014
		ton/yr	334,289	501,432	742,120	1,113,184	1,671,448

3.4 Supply Chain Optimization Model: Parameters, Variables & Constrains

A mixed integer linear programming (MILP) was used to conduct this methanol supply chain optimization study in Texas. Water and electricity generated from renewable energy of choice (solar or wind) were used to produce hydrogen through electrolysis and further synthesized to methanol, which are more convenient chemical form to store and transport long distances. The binary variable $y_{r,p,l,t}$ was used to express the selection of renewable energy to produce an energy carrier of a specific capacity at a candidate location. The binary variable is defined as the following.

$$y_{r,p,t,l} = \begin{cases} 1 \quad if\ renewable\ plant\ r\ is\ built\ to\ produce\ product\ p\ of\ capacity\ t\ at\ location\ l \\ \qquad 0 \quad if\ no\ plant\ is\ built\ at\ locaiton\ l \end{cases}$$

The following expression restricts the construction of at most 1 facility at each candidate location.

$$\sum_{(r,p,t)} y_{r,p,t,l} \leq 1 \qquad\qquad \forall l \in L^F$$

In addition, the following constrains imposed restriction on the maximum number of overall facilities potentially built in the supply chain network, maximum and minimum number of facilities of a specific capacity potentially selected, and restriction on only the selection of one renewable energy source per location in the supply chain network.

$$\sum_{(r,p,t,l)} y_{r,p,t,l} \leq N$$

$$\sum_{(r,p,l)} y_{r,p,t,l} \leq N_t^{max} \qquad \forall t \in T$$

$$\sum_{(r,p,l)} y_{r,p,t,l} \geq N_t^{min} \qquad \forall t \in T$$

$$\sum_{(p,t)} y_{r,p,t,l} \leq 1 \qquad \forall l \in L^F$$

3.4.1 Candidate Locations

The centroids of each counties in Texas were considered as a candidate location to build a facility that can produce renewable energy generated methanol. Texas has a total of 254 counties and the longitude and latitude coordinates of each county centroids were obtained from the Texas government database. The Federal Information Processing Standards (FIPS) number of 5 digits were used to identify each candidate location in this model. Each candidate location consist of a solar or wind renewable power plant, electrolyzers, and a production plant. Required resources (water and CO_2) were transported from source locations to the candidate locations.

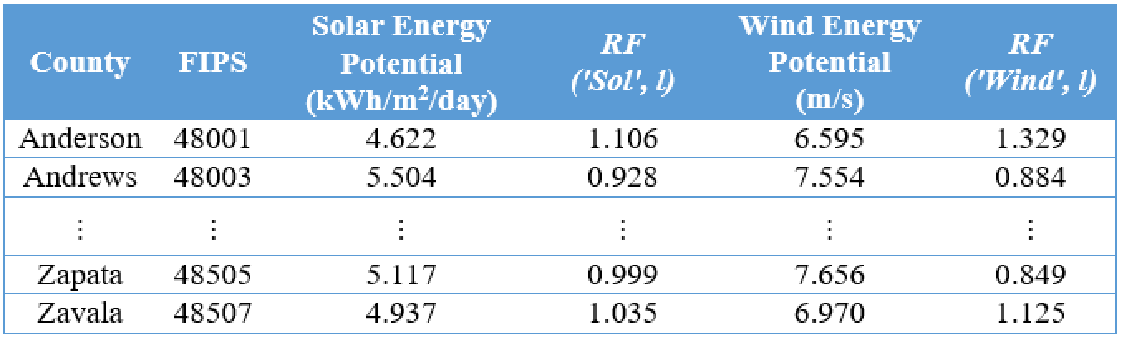
Candidate locations of this study considers a population density factor (PD_l), which restricts the selection of candidate locations that are densely populated. A detailed description of how the population density factor was calculated and incorporated into the model can be found in Section 3.4.2.3. The centroid of all counties can be visually seen as black dots and the demand locations are shown in red star in the below figure.

Figure 13. Total (254) candidate locations considered in this model.

3.4.2 Renewable Resources

Solar and wind energy sources were considered to meet the electricity requirements of the electrolyzers for water hydrolysis. Renewable energy availability per county of Texas were quantified based on data obtained from National Renewable Energy Laboratory (NREL) database.[28] The annual average of solar energy potential (kWh/m^2/day) and wind energy potential (m/s) were obtained per county of Texas. For the purpose of this study, renewable energy potential values were converted to renewable scaling factor ($RF_{r,l}$) to incorporate the cost increase or decreased based on the low or the high magnitude of renewable energy potential at a location. The assumptions and calculation methods made to generated the renewable energy scaling factor ($RF_{r,l}$) is covered in the following sub-sections of this section for solar and wind energy. The annual solar and wind energy potential with corresponding renewable energy scaling factor ($RF_{r,l}$) for Texas counties can be seen in the below table. A full list of the following data can be found in the Appendix.

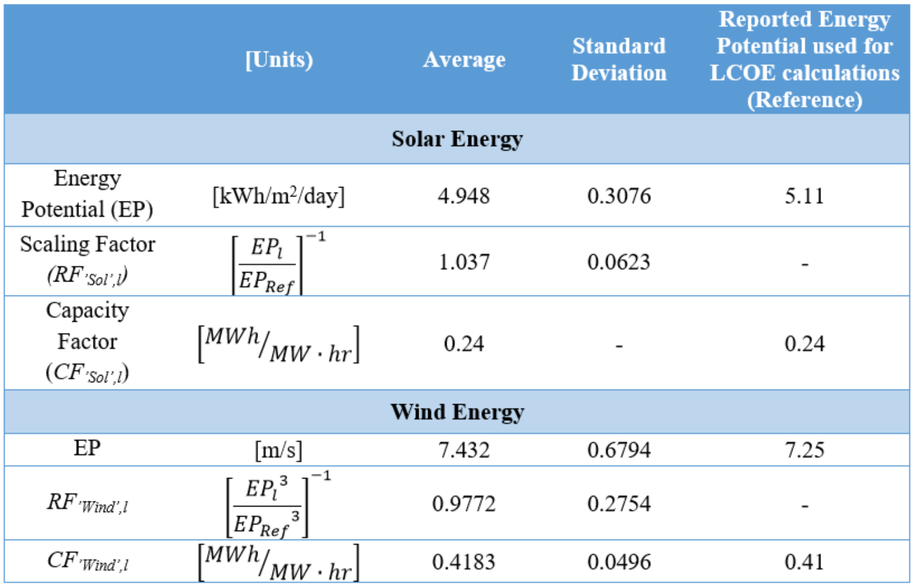
Table 3. Annual solar and wind energy potential with corresponding renewable energy scaling factor ($RF_{r,,l}$) across Texas per county.



County	FIPS	Solar Energy Potential (kWh/m^2/day)	*RF ('Sol', l)*	Wind Energy Potential (m/s)	*RF ('Wind', l)*
Anderson	48001	4.622	1.106	6.595	1.329
Andrews	48003	5.504	0.928	7.554	0.884
⋮	⋮	⋮	⋮	⋮	⋮
Zapata	48505	5.117	0.999	7.656	0.849
Zavala	48507	4.937	1.035	6.970	1.125

The above renewable energy scaling factor ($RF_{r,l}$) was generated strictly for the purpose of this research and the general statistics for the data can be seen in the below table.

Table 4. Average, standard deviation, and reference energy potential value used for renewable energy scaling factor ($RF_{r,,l}$) calculation.



	[Units)	Average	Standard Deviation	Reported Energy Potential used for LCOE calculations (Reference)
Solar Energy				
Energy Potential (EP)	[kWh/m^2/day]	4.948	0.3076	5.11
Scaling Factor ($RF_{'Sol',l}$)	$\left[\frac{EP_l}{EP_{Ref}}\right]^{-1}$	1.037	0.0623	-
Capacity Factor ($CF_{'Sol',l}$)	$\left[{}^{MWh}/_{MW \cdot hr}\right]$	0.24	-	0.24
Wind Energy				
EP	[m/s]	7.432	0.6794	7.25
$RF_{'Wind',l}$	$\left[\frac{{EP_l}^3}{{EP_{Ref}}^3}\right]^{-1}$	0.9772	0.2754	-
$CF_{'Wind',l}$	$\left[{}^{MWh}/_{MW \cdot hr}\right]$	0.4183	0.0496	0.41

Further methods and interpretation of the energy potentials to generate the renewable energy scaling factor is discussed in the following sections for solar and wind energy.

3.4.2.1 Solar Energy Potential Interpretation

Only photovoltaic (PV) power plants were considered for solar energy in this model and hence global horizontal irradiance (GHI) values were used over direct normal irradiance (DNI) values. More specifically, for the solar PV power plant of this model, 1-axis tracking type with crystalline silicon (c-Si) module was used over other types of solar power plant such as solar thermal power (CSP) plant. PV power plants were chosen over CSP plants because CSP plants have not been able to keep up with the significant price decline of PV modules over the past decade and the several newer CSP projects that has started operation in the last few years have been underperforming relative to long-term expectations.[7] In addition, tracking was chosen over fixed-tilt as current operating PV plants report greater energy production of tracking type, which typically outweighed the slightly higher up-front cost compared to fixed-tilt type.[7]

The average annual solar potential (kWh/m^2/day) were generated using the SUNY Satellite Solar Radiation model and averaged over a surface cell of 0.1 degrees in latitude and longitude (about 10 km in size).[28] The hourly radiance images from geostationary weather satellites and daily snow cover data, and monthly averages of atmospheric water vapor, trace gases, and the quantity of aerosols in the atmosphere were used to calculate the hourly total insolation falling on a horizontal surface. The global horizontal irradiance (GHI) was then calculated considering the water vapor, trace gas, and aerosols in the atmosphere and data was averaged from the hourly model output over 11 years (1998~2009) to obtain an average annual solar potential.[6]

The average annual solar potential obtained from the NREL database was normalized respect to the average GHI of 5.11 kWh/m^2/day [7] and inverted to generate the solar energy scaling factor ($RF_{r,l}$), which reflects the decrease of capital cost at regions with higher energy potential. In addition to the geographical variation of solar energy, seasonal and daily variation was taken into consideration when selecting the optimal location for a renewable power plant. The capacity factor ($CF_{r,l}$) of a renewable plant is the total production of electricity (MWh) divided by the capacity (MW) of the power plant multiplied by the hours of operation.[7] An empirical capacity factor value of 24%

was used for this model for all counties of Texas for 1-axis tracking PV module as can be seen from the below graph.[7]

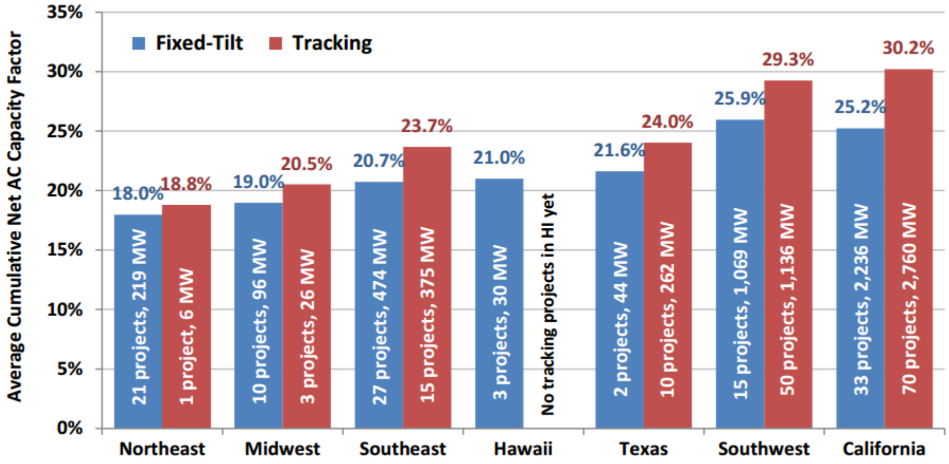


Figure 14. Cumulative Capacity Factor by region for Fixed-Tilt and Tracking PV solar panels. (Reprinted from [7])

3.4.2.2 Wind Energy Potential Interpretation

Wind turbines generators convert kinetic energy of the wind into electricity. The following equations can be used to describe how the kinetic energy in the wind is converted to electricity by the movement of the wind blades.

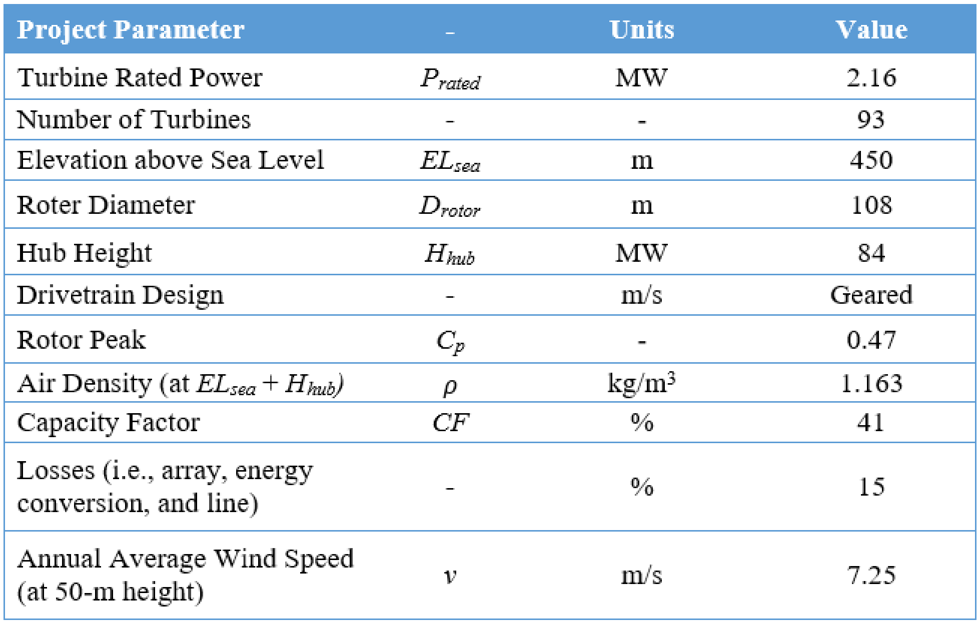
$$P_{theoretical} = C_p \cdot P_{wind} = C_p \cdot \frac{\rho}{2} \cdot \frac{\pi D^2}{4} \cdot v^3$$

$$P_{actual} = P_{theoretical} \cdot CF \cdot (1 - losses)$$

Where the following project parameters were used to calculate the leveled cost of energy (LCOE) for the land-based wind power plant reference case published in “2016 Cost of

Wind Energy Review" by NREL.[29] The overview of LCOE used for wind power plants are covered in Section 3.5.1.2.

Table 5. Project parameters of reference wind power plant. (Reprinted from [29])



Project Parameter	-	Units	Value
Turbine Rated Power	P_{rated}	MW	2.16
Number of Turbines	-	-	93
Elevation above Sea Level	EL_{sea}	m	450
Roter Diameter	D_{rotor}	m	108
Hub Height	H_{hub}	MW	84
Drivetrain Design	-	m/s	Geared
Rotor Peak	C_p	-	0.47
Air Density (at $EL_{sea} + H_{hub}$)	ρ	kg/m³	1.163
Capacity Factor	CF	%	41
Losses (i.e., array, energy conversion, and line)	-	%	15
Annual Average Wind Speed (at 50-m height)	v	m/s	7.25

All the above parameters were assumed identical for the wind power plants built in this model except for the variation in capacity factor and annual average wind speed per candidate location. The Wind Toolkit created by NREL provides wind resource data across the United States.[30] The annual average wind speed at a height of 100 m above the ground were provided in the Wind Toolkit and used for this model.[31] The wind data was calculated based on the collection of data of five minute time series of the year 2012.[31]

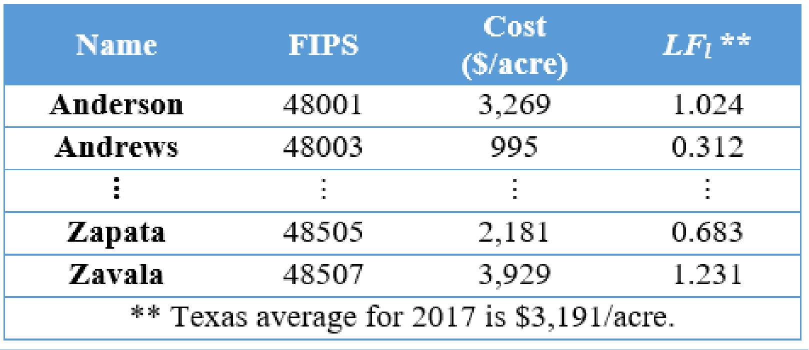
The power output by wind energy varies proportional to the cubic power of the wind speed. Such a non-linear relationship was incorporated into calculating the renewable scaling factor of wind energy as shown below. The average wind speed of 7.25 m/s was used as a reference wind speed.

$$RF_{'Wind',l} = \left[\frac{(v_l)^3}{\left(v_{reference}\right)^3}\right]^{-1}$$

3.4.2.3 Land Availability (Land Price scaling factor & Population Density factor)

Another factor to consider when deciding where to build a renewable power plant is the required land usage, availability, and acquisition or leasing costs. A method of quantifying land availability for solar and wind energy has been studied and reported in a technical report by NREL[32] but is only available as per state values for solar energy. As a result, actual land availability will not be considered for this model at the point of submission but the following considerations were made to implement land availability: land price scaling factor (LF_l) and population density factor (PD_l). The cost variation among rural land prices across Texas was taken into consideration by including a land price scaling factor calculated using actual selling price per acre reported in 2017 obtained from the Real Estate Center database of Texas A&M University. The database divides the state into 33 regions and the annual average selling price per acre is reported.[33] The land cost was further normalized with the overall average of Texas of that year. The 2017 selling price per acre were used for all counties except for El Paso, which had a 10 folds increase in reported land prices from 2016 to 2017. As a result, the average land price per acre over the course of 10 years were used for El Paso. The actual land price per acres in 2017 and the land price scaling factor can be found in the following table. A full list of the following data can be found in the Appendix.

Table 6. Land price of Texas counties and land price scaling factor (LF_l).



Name	FIPS	Cost ($/acre)	LF_l **
Anderson	48001	3,269	1.024
Andrews	48003	995	0.312
⋮	⋮	⋮	⋮
Zapata	48505	2,181	0.683
Zavala	48507	3,929	1.231
** Texas average for 2017 is $3,191/acre.			

Furthermore, a population density factor (PD_l) is implemented in this model that restricts the selection of candidate locations with high population density. This is to account for the fact that counties with high population densities are counties with high urbanization where land availability is most likely scare for a large renewable energy generated chemical facility and land prices are higher than the weighted average. The population density was calculated based on reported population from 2016 and reported land area per county (km^2). For the current model, any county with a population density above 200 people per square kilometers were excluded from being selected as a candidate facility location. The value, 200 people per square kilometers, was arbitrary selected for the purpose of this study and a total of 13 counties were excluded from this constraint, including all five demand locations of this study. A visual representation of the population density respect to the electricity consumption per county can be seen in the below graph.

The electricity consumption per year (MWh) values were also derived from total electricity consumption of Texas in 2016 and population per county reported in 2016. More detailed description on how the electricity consumption per year per county was calculated are covered in Section 3.4.7.

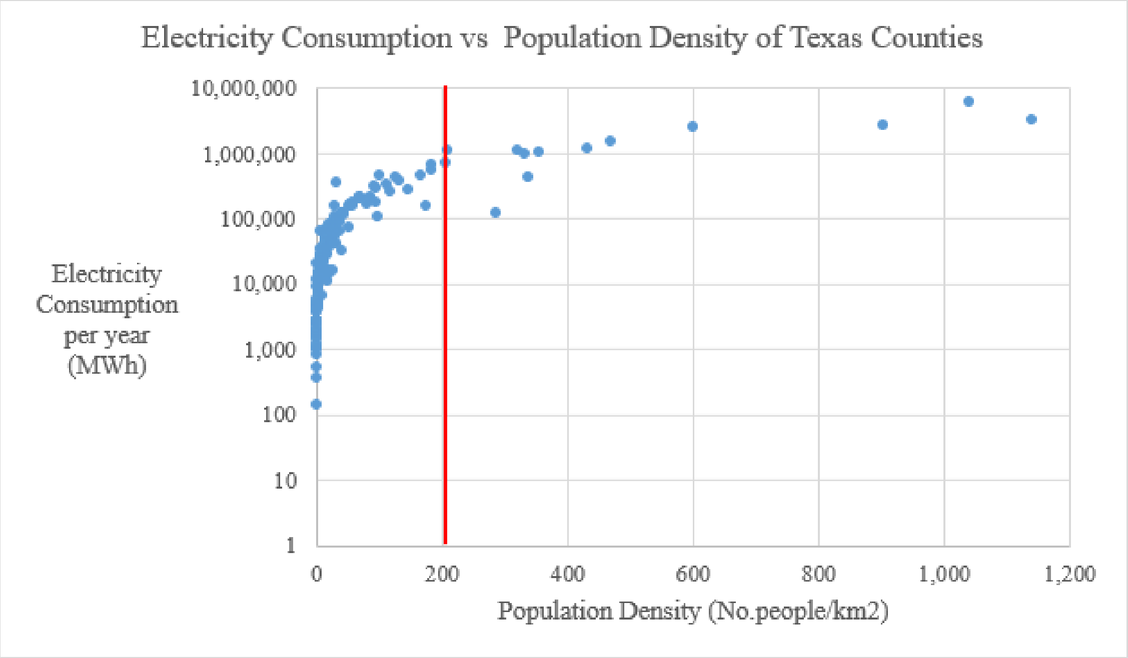


Figure 15. Electricity consumption versus population density of Texas counties.

3.4.3 Water resources

Water is the main resource to produce renewable energy generated energy carriers and is required for the production of all three products in this model. Water data was obtained from the “Withdrawal and Consumption of Water by Thermoelectric Power Plants in the United States, 2010” report from United States Geological Survey (USGS).[34] The annual withdrawal per thermoelectric power plant in the United States were provided in this report. The longitude and latitude coordinates of each source were obtained through web search to calculate the distance between the water point source and candidate location at the centroid of each county to consider for water transportation cost. Water is transported to the candidate location via pipeline. The map of all water sources included in this model can be seen in the below figure.

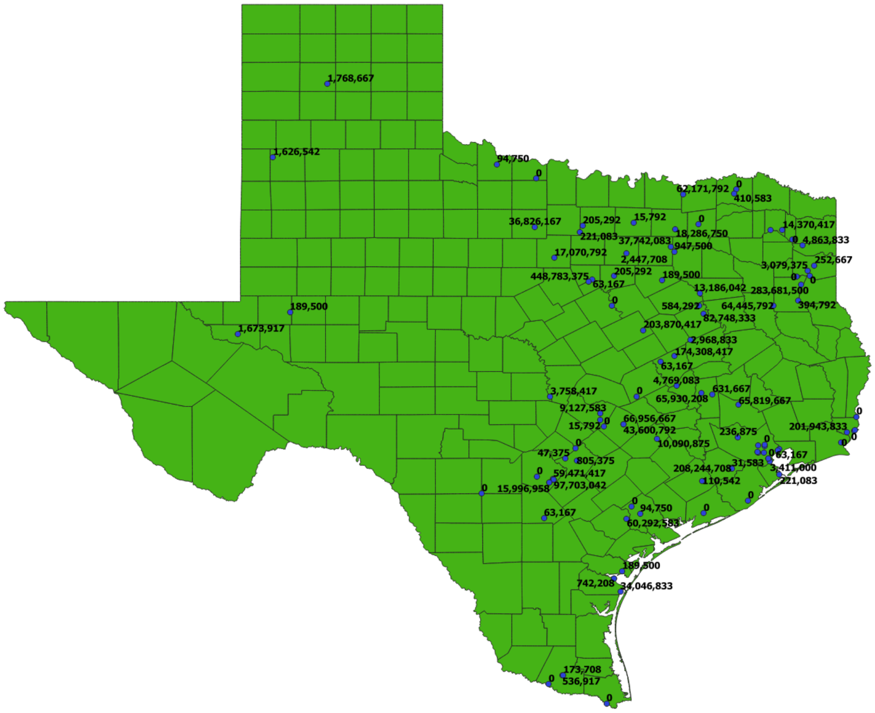


Figure 16. Water source location and availability (kg/hr) incorporated in this model.

The model has the following constraints for the water requirement.

$$\sum_{(r,p,t)} y_{r,p,t,l} \cdot FW_{p,t} = WR_l \qquad \forall l \in L^F$$

$$\sum_{(l)} w_{wl,l} \leq WA_{wl} \qquad \forall wl \in L^W$$

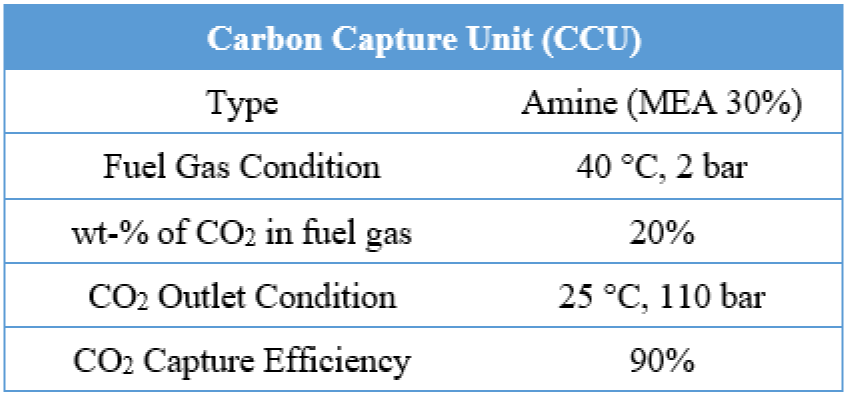
$$WR_l = \sum_{(wl)} w_{wl,l} \qquad \forall l \in L^F$$

The water requirement at candidate location (WR_l) is specified in the first equation above based on the water required to produce a product of a specific capacity ($FW_{p,t}$). The second equation states that the water flow from source location to candidate location cannot be greater than the total available water at water source location and finally the third equation states that the sum of all water flows must fulfill the required water demand at candidate location. In addition, water source has to be met within a maximum distance of 200 miles from the candidate facility location.

3.4.4 Feedstock (CO_2) resources for Methanol production

The production of methanol was considered in this model which uses Carbon dioxide (CO_2) as a feedstock. CO_2 gas has to be captured, compressed, and transported to the production plant at candidate location for methanol synthesis. For this model, currently operating power plants across Texas were considered as CO_2 point sources. The CO_2 emission per point source were calculated using the EIA published total CO_2 emission from electricity generation in Texas[35] and assumed each power plant emitted a fraction of this total CO_2 emission based on electricity production capacity.[36] The model will consider the investment and operating cost of a Carbon Capture Unit (CCU) at the point of source. The specification of CCU unit used for this model can be seen in the below table.

Table 7. Carbon Capture Unit (CCU) specifications used for this model.



Carbon Capture Unit (CCU)	
Type	Amine (MEA 30%)
Fuel Gas Condition	40 °C, 2 bar
wt-% of CO_2 in fuel gas	20%
CO_2 Outlet Condition	25 °C, 110 bar
CO_2 Capture Efficiency	90%

The longitude and latitude coordinates of CO_2 emitting power plants across Texas were used to calculate the distance between the CO_2 point source and candidate location at the centroid of each county. The transportation cost of CO_2 source accounts for the construction and operating costs of CO_2 pipeline. The geographical locations of all CO_2 sources used in this model can be seen in the below figure.

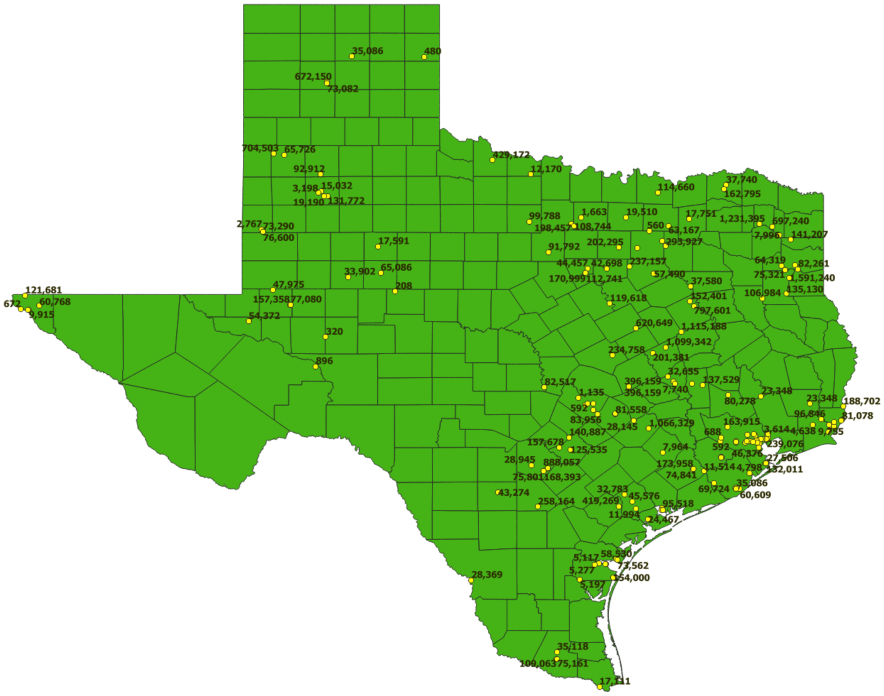


Figure 17. CO_2 source location and availability (kg/hr) incorporated in this model.

This model has identical constraints for CO_2 requirement as for the water requirement as explained in section 3.4.3 with the following equations.

$$\sum_{(r,p,t),p\in P^{MeOH}} y_{r,p,t,l} \cdot FC_{p,t} = CR_l \qquad \forall l \in L^F$$

$$\sum_{(l)} cd_{cl,l} \leq CA_{cl} \qquad \forall cl \in L^C$$

$$CR_l = \sum_{(cl)} cd_{cl,l} \qquad \forall l \in L^F$$

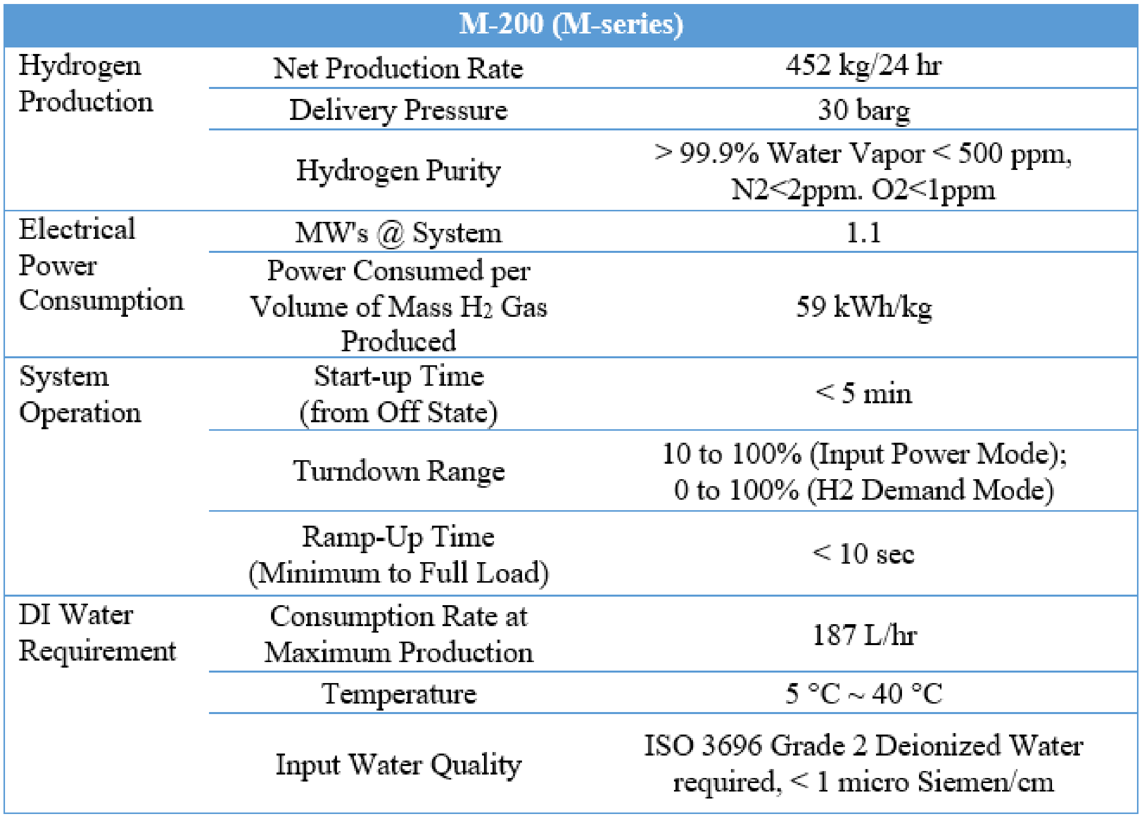
In addition, much like the maximum water transportation distance restriction, CO_2 requirement has to be met within 200 miles of candidate facility location.

3.4.5 Electrolyzer

For this study the model uses the utility scale Proton Exchange Membrane (PEM) electrolyzer from Proton OnSite, Inc. (M-series model) over other types of electrolyzers in the present-day market. There are three electrolysis technologies in the market that might play significant roles in the future energy storage application as identified by Schmidt et al.[37]; Alkaline, Proton Exchange Membrane (PEM), and Solid Oxide electrolysis cells. Currently, the most mature and widely used technology for large-scale industrial applications is Alkaline Electrolysis Cells (AEC) technology. AEC is readily available and is relatively low in capital cost due to the use of inexpensive metal and mature tack components. However, the low current density and operating pressure negatively impact the system size and hydrogen production cost. In addition, AEC cannot operate in dynamic operations, in which case can negatively affect the system efficiency and produced gas purity.[37] Due to such disadvantages, AEC was not selected for this model as this technology was considered unfit for hydrogen production using intermittent renewable sources. Second, Solid Oxide Electrolysis Cells (SOEC) is the least developed and not yet widely commercialized among the three technologies. However, there are potential advantages of SOEC for energy storage application in the future due to its' high electrical efficiency, low material cost, and ability to operate in reverse mode as fuel cell or in co-electrolysis mode to produce syngas from water stream.[37]

Proton Exchange Membrane (PEM) is most widely used for small-scale applications and preforms stronger in cell efficiency and product quality compared to AEC. PEM's biggest advantage is its' ability to function at flexible operations and is considered the most suitable technology for large-scale intermittent operation in the future out of the three technologies.[37] However, the high capital cost due to the use of expensive catalyst and materials and high water purity requirements are some drawbacks to PEM technology. Currently available large-scale PEM electrolyzer was used for this study. The specifications of M-series model (Proton OnSite, Inc.) was obtained from Proton OnSite's website[38] and can be seen in the below table.

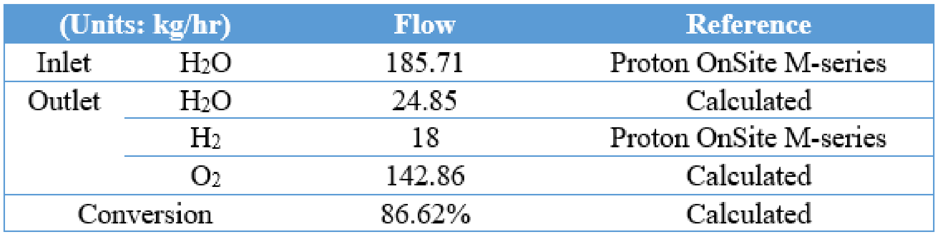
Table 8. Technical specifications of M-200 from Proton OnSite Inc. (Reprinted from [38])



M-200 (M-series)		
Hydrogen Production	Net Production Rate	452 kg/24 hr
	Delivery Pressure	30 barg
	Hydrogen Purity	> 99.9% Water Vapor < 500 ppm, N2<2ppm. O2<1ppm
Electrical Power Consumption	MW's @ System	1.1
	Power Consumed per Volume of Mass H_2 Gas Produced	59 kWh/kg
System Operation	Start-up Time (from Off State)	< 5 min
	Turndown Range	10 to 100% (Input Power Mode); 0 to 100% (H2 Demand Mode)
	Ramp-Up Time (Minimum to Full Load)	< 10 sec
DI Water Requirement	Consumption Rate at Maximum Production	187 L/hr
	Temperature	5 °C ~ 40 °C
	Input Water Quality	ISO 3696 Grade 2 Deionized Water required, < 1 micro Siemen/cm

Based on the technical specifications of the M-series, the following mass balance around the electrolyzer system was calculated based on the reaction stoichiometry for a 1.1 MW electrolyzer. The hydrogen production stoichiometry is 1 mole of water molecule is converted to 1 mole of hydrogen (H_2) and half a mole of oxygen (O_2).

Table 9. Mass balance across electrolyzer (Proton OnSite's PEM M-series model). (Reprinted from [38])



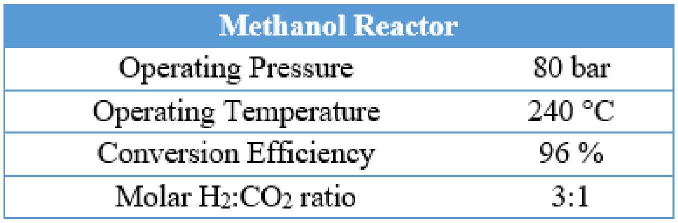
(Units: kg/hr)		Flow	Reference
Inlet	H_2O	185.71	Proton OnSite M-series
Outlet	H_2O	24.85	Calculated
	H_2	18	Proton OnSite M-series
	O_2	142.86	Calculated
Conversion		86.62%	Calculated

The above mass balance for a unit of electrolyzer was incorporated in the model as water requirement ($FW_{p,t}$), Hydrogen output ($HO_{p,t}$), and Oxygen output ($OO_{p,t}$).

3.4.6 Methanol Production Plant

Methanol is synthesis from hydrogen produced from the electrolyzer and captured CO_2 gas across a catalytic reactor. The following specifications were used for the methanol synthesis system for this model.

Table 10. Methanol reactor specifications used for model. (Reprinted from [25])



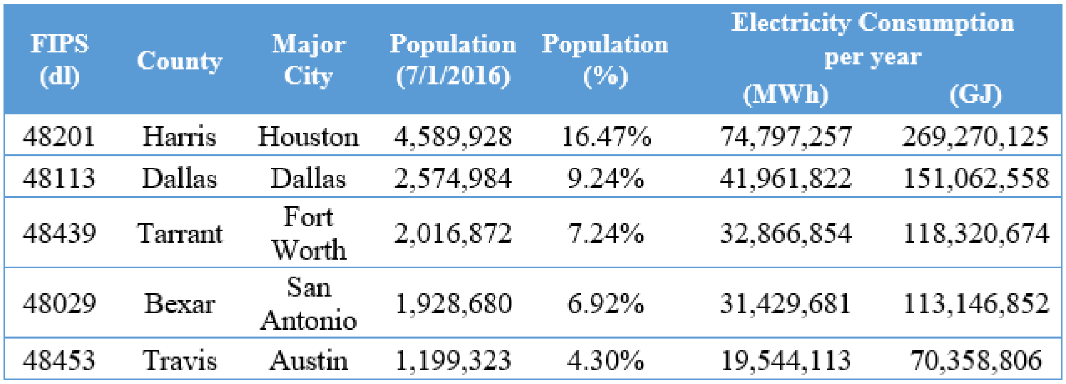
Methanol Reactor	
Operating Pressure	80 bar
Operating Temperature	240 °C
Conversion Efficiency	96 %
Molar H_2:CO_2 ratio	3:1

In addition to the reactor, the produced hydrogen from electrolyzer has to be pressurized and captured CO_2 has to be depressurized to roughly 80 bar prior to the gas mixture entering the methanol reactor system. The levelized cost function will account for these components of methanol production system.

3.4.7 Demand locations

For this study, methanol was produced with renewable production technologies to meet the demands of the top five electricity consuming counties of Texas. The electricity demand per county was calculated using the overall electricity consumption of Texas in 2016 as reported on the Energy Information Administration (EIA) site[39] and the reported population per county in 2016. The top five electricity consuming counties of Texas based on population considered for this model is as following.

Table 11. Demand locations and electricity demand of the top five energy consuming counties of Texas.



FIPS (dl)	County	Major City	Population (7/1/2016)	Population (%)	Electricity Consumption per year (MWh)	Electricity Consumption per year (GJ)
48201	Harris	Houston	4,589,928	16.47%	74,797,257	269,270,125
48113	Dallas	Dallas	2,574,984	9.24%	41,961,822	151,062,558
48439	Tarrant	Fort Worth	2,016,872	7.24%	32,866,854	118,320,674
48029	Bexar	San Antonio	1,928,680	6.92%	31,429,681	113,146,852
48453	Travis	Austin	1,199,323	4.30%	19,544,113	70,358,806

The following constrains were used to define the minimum requirement of production per demand location.

$$\sum_{(r,t)} y_{r,p,t,l} \cdot PR_{p,t} = \sum_{(dl,m)} z_{p,l,dl,m} \qquad \forall l \in L^F, p \in P$$

$$\sum_{(l,m)} z_{p,l,dl,m} \geq DR_{p,dl} \qquad p \in P, dl \in L^{DL}$$

The demand requirement ($DR_{p,dl}$) for methanol was calculated for methanol product assuming that the renewably produced methanol will replace natural gas fuel used for electricity generation at conventional power plants. Unlike other energy carriers that require a conversion (or decomposition) technology to be transformed back to energy again, methanol can directly act as a replacement of natural gas fuel at conventional power plants after minor adjustments to generate electricity.[3] The demand requirement ($DR_{p,dl}$) for methanol (kg/hr) was calculated based on the lower heating value of 21.113 MJ/kg to meet the electricity demands of the five counties of Texas.

3.5 Capital and Operating &Maintenance Costs

At a candidate facility location, the total capital costs associated with building an energy carrier plant from renewable technologies require the sum of capital cost associated with building a renewable power plant for electricity generation, purchasing a system of electrolyzers for hydrogen production, building a production plant to synthesis energy carriers, and building a carbon capture unit for methanol production.

$$
\begin{aligned}
Cost_l^{Inv\ or\ O\&M} = {} & Cost(Renewable\ Power\ Plant)_l \\
& + Cost(Electrolyzer)_l \\
& + Cost(Production\ Plant)_l \\
& + Cost(Carbon\ Capture\ Unit\ for\ CH_3OH)_l
\end{aligned}
$$

Levelized cost functions were incorporated into the model, which are expressed as total cost in US dollars (2017) per produced quantity. The maintenance and operating costs of most systems were not readily available on literatures reviews and Operating & Maintenance (O&M) cost factor of 1.04%[25] of the total capital cost per year was used to calculate such values unless explicitly mentioned otherwise under each description. A summary of all the levelized cost used in this model can be seen in the below tables.

Table 12. Levelized Capital and O&M Cost for Methanol production used in model for capacity t1 to t5.

Capital Cost (2017 USD)		Units	t1	t2	t3	t4	t5
Solar Power Plant	$RC_{r,t}$	\$/MW	\$1,082,073	\$985,093	\$985,093	\$985,093	\$985,093
	LR_r	\$/MW	\$30,000				
Wind Power Plant	$RC_{r,t}$	\$/MW	\$1,590,000				
Electrolyzer System	-	\$	\$15,884,976	\$38,646,144	\$59,933,224	\$108,029,691	\$194,056,016
	EC_t	\$/MW	\$1,110,837	\$949,537	\$878,786	\$792,007	\$714,229
Methanol Production Plant	-	\$	\$2,368,204	\$4,670,265	\$6,535,350	\$10,254,734	\$16,048,218
	$PC_{p,t}$	\$/(kg/hr)	\$1,794	\$1,244	\$1,038	\$815	\$640
CCU Plant	-	\$	\$3,343,569	\$6,593,108	\$9,226,618	\$14,477,592	\$22,656,640
	CC_t	\$/(kg/hr)	\$1,593	\$1,105	\$922	\$724	\$569
O&M Cost (2017 USD)		**Units**	**t1**	**t2**	**t3**	**t4**	**t5**
Solar Power Plant	ROM_r	\$/kW/yr	\$18.50/kW/yr				
Wind Power Plant	ROM_r	\$/kW/yr	\$43.60/kW/yr				
	LR_r	\$/kW/yr	\$8.10/kW/yr				
Electrolyzer System	-	\$/yr	\$165,204	\$401,920	\$623,306	\$1,123,509	\$2,018,183
	EOM_t	\$/MW/yr	\$11,553	\$9,875	\$9,139	\$8,237	\$7,428
Methanol Production Plant	-	\$/yr	\$24,629	\$48,571	\$67,968	\$106,649	\$166,901
	$POM_{p,t}$	\$/(kg/hr)/yr	\$18.66	\$12.94	\$10.80	\$8.47	\$6.66
CCU Plant	-	\$/yr	\$493,265	\$972,658	\$1,361,170	\$2,135,828	\$3,342,453
	$COM_{p,t}$	\$/(kg/hr)/yr	\$235.01	\$163.05	\$136.06	\$106.75	\$83.88

Table 13. Levelized Capital and O&M Cost for Methanol production used in model for capacity t6 to t10.

Capital Cost (2017 USD)		Units	t6	t7	t8	t9	t10
Solar Power Plant	$RC_{r,t}$	\$/MW	\$985,093/MW				
	LR_r	\$/MW	\$30,000/MW				
Wind Power Plant	$RC_{r,t}$	\$/MW	\$1,590,000/MW				
Electrolyzer System	-	\$	\$349,184,199	\$629,404,842	\$1,134,013,781	\$2,043,620,127	\$3,683,627,170
	EC_t	\$/MW	\$643,895	\$580,311	\$523,045	\$471,412	\$424,861
Methanol Production Plant	-	\$	\$25,178,731	\$39,509,664	\$61,995,078	\$97,278,955	\$152,647,043
	$PC_{p,t}$	\$/(kg/hr)	\$502	\$394	\$309	\$243	\$190
CCU Plant	-	\$	\$35,552,078	\$55,787,191	\$87,539,486	\$137,364,177	\$215,547,497
	CC_t	\$/(kg/hr)	\$446	\$350	\$275	\$215	\$169
O&M Cost (2017 USD)		**Units**	**t6**	**t7**	**t8**	**t9**	**t10**
Solar Power Plant	ROM_r	\$/kW/yr	\$18.50/kW/yr				
Wind Power Plant	ROM_r	\$/kW/yr	\$43.60/kW/yr				
	LR_r	\$/kW/yr	\$8.10/kW/yr				
Electrolyzer System	-	\$/yr	\$3,631,516	\$3,631,516	\$3,631,516	\$3,631,516	\$3,631,516
	EOM_t	\$/MW/yr	\$6,697	\$6,035	\$5,440	\$4,903	\$4,419
Methanol Production Plant	-	\$/yr	\$261,859	\$261,859	\$261,859	\$261,859	\$261,859
	$POM_{p,t}$	\$/(kg/hr)/yr	\$5.22	\$4.10	\$3.21	\$2.52	\$1.98
CCU Plant	-	\$/yr	\$5,244,872	\$8,230,086	\$12,914,389	\$20,264,848	\$31,798,955
	$COM_{p,t}$	\$/(kg/hr)/yr	\$65.81	\$51.63	\$40.51	\$31.78	\$24.94

3.5.1 Renewable Power Plant Cost

The costs to construct and operate solar or wind power plants in Texas were estimated for this study. Levelized Cost Of Energy (LCOE) values reported on NREL published papers “U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017”[40] and “2016 Cost of Wind Energy Review”[29] were modified and incorporated into the model. The LCOE values are multiplied by the power plant nameplate capacity, which is defined as the electricity required of the electrolyzer ($ER_{p,t}$) divided by the capacity factor ($CF_{r,l}$) to simulate a steady production and not to vary widely due to seasonal fluctuations. Renewable energy scaling factor ($RF_{r,l}$) is also considered as explained in Section 3.4.2. The following equations calculate the renewable power plant construction and operation costs for this model.

$$Cost(Renewable\ Power\ Plant)_l^{Inv}$$

$$= \sum_{(r,p,t),r\in r^{Sol}} y_{r,p,t,l} \cdot (ER_{p,t}/CF_{r,l}) \cdot (RC_{r,t} \cdot RF_{r,l} + LR_r \cdot LF_l)$$

$$+ \sum_{(r,p,t),r\in r^{Wind}} y_{r,p,t,l} \cdot (ER_{p,t}/CF_{r,l}) \cdot (RC_{r,t} \cdot RF_{r,l})$$

$$Cost(Renewable\ Power\ Plnt)_l^{OM}$$

$$= \sum_{(r,p,t),r\in r^{Sol}} y_{r,p,t,l} \cdot (ER_{p,t}/CF_{r,l}) \cdot (ROM_r \cdot 10^3)$$

$$+ \sum_{(r,p,t),r\in r^{Wind}} y_{r,p,t,l} \cdot (ER_{p,t}/CF_{r,l}) \cdot (ROM_r + LR_r \cdot LF_l) \cdot 10^3$$

The cost functions have two separate equations to account for solar or wind energy and only one section is calculated at all scenarios since each candidate location can only select one renewable source and only one facility can be built at a candidate location. This is because the LCOE values for solar and wind energy accounts for land cost differently. The LCOE for solar energy accounts for land cost as land acquisition fee and considers it a capital cost, whereas the LCOE for wind energy accounts for land cost as land lease fee and is part of the operating and maintenance cost. The cost equations of renewable energy plans are further discussed in the following sub-sections.

3.5.1.1 Solar Power Plant Cost

The cost breakdown for utility scale solar power plants applied for this model can be seen in the below figure.

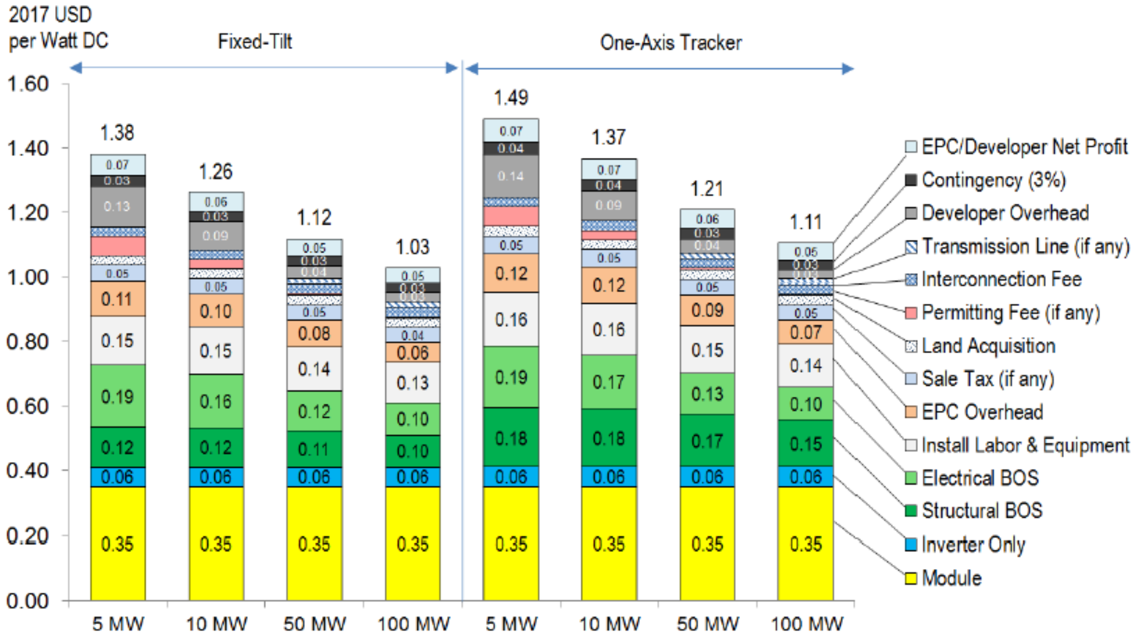


Figure 18. Capital cost breakdown for utility scale solar (PV) power plant (Units: 2017 USD/W_{dc}). (Reprinted from [40])

Based on the reported cost breakdown, few categories were not considered for the purpose of this study such as inverter cost, transmission line cost, interconnection fee, and sales tax as all the generated electricity will be used to produce energy carriers as direct current watt (W_{DC}) and will not be supply to the grid as alternating current watt (W_{AC}). As a result, the following levelized cost for solar power plant investment cost ($RC_{r,t}$) and land cost (LR_r) were used for this model.

Table 14. Modified LCOE for solar power plant.

(Units: 2017$/Wdc)	-	5 MW	10 MW	50 MW	≥ 100 MW
∑ EPC Cost		$1.07	$1.02	$0.93	$0.85
∑ Developer Cost		$0.33	$0.25	$0.17	$0.15
Land Acquisition fee	LR_r	*$0.03*	*$0.03*	*$0.03*	*$0.03*
All Else		*$0.30*	*$0.22*	*$0.14*	*$0.12*
∑ Renewable Investment Cost (EPC Cost + Developer Cost excluding Land Acquisition fee)	$RC_{r,t}$	$1.37	$1.25	$1.07	$0.97
∑ O&M Cost	$ROM_{r,t}$	$18.50/kW/yr			

In addition, the following graph was generated with the above LCOE values to interpolate the LCOE for the capacities of the solar plant used in this model. Any solar power plant capacity greater than 100 MW used the LCOE of 100 MW as a lower limit of capital cost.

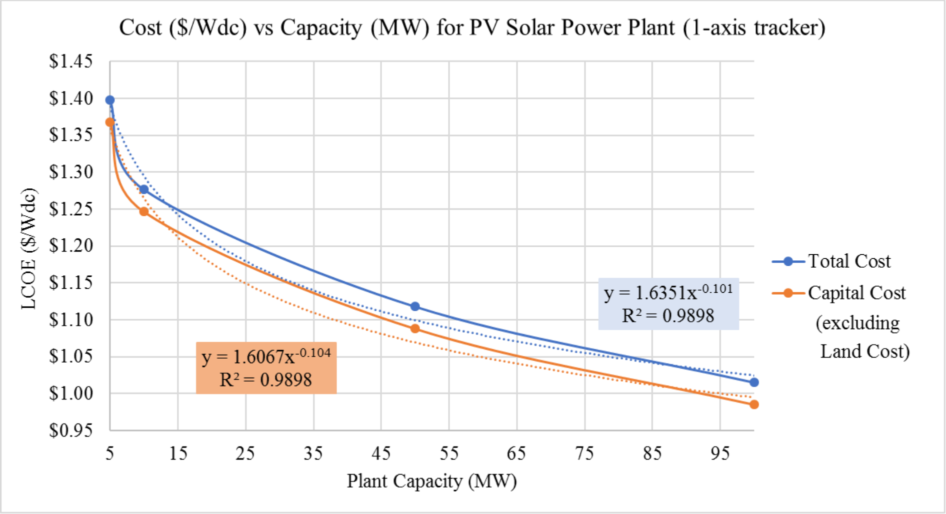


Figure 19. LCOE vs Capacity (range 5 to 100 MW) of PV Solar Power Plant (1-axis tracker).

Lastly, operating and maintenance cost of $18.50/kW/yr was used for this model.

3.5.1.2 Wind Power Plant Cost

The cost breakdown for the reference 200-MW wind power plant with specifications mentioned in Section 3.4.2.2 can be seen in the below figure.

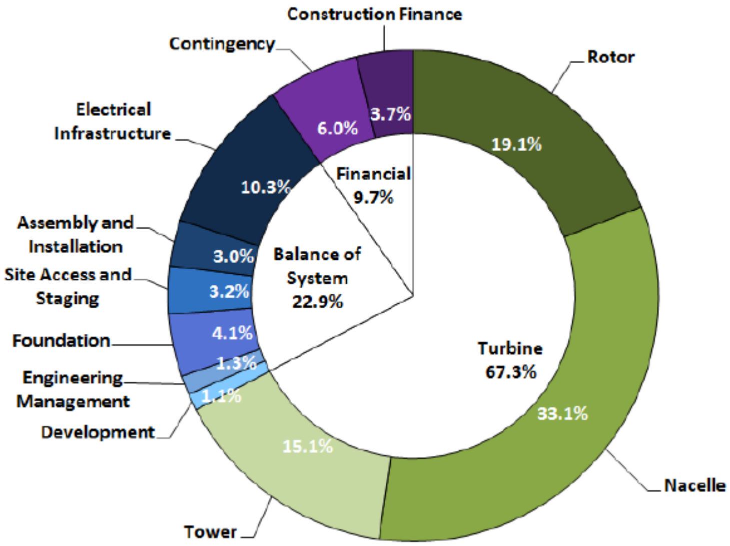
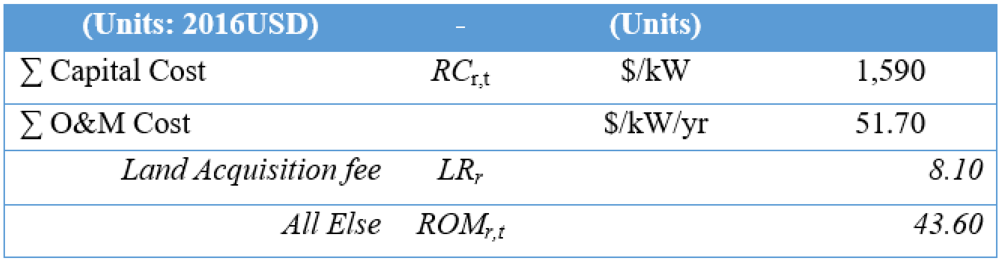


Figure 20. Capital cost breakdown for land-based reference wind power plant. (Reprinted from [29])

The following LCOE reported in “2016 Cost of Wind Energy Review”[29] was used for this model.

Table 15. LCOE for wind power plant. (Reprinted from [29])



(Units: 2016USD)	-	(Units)	
$\sum$ Capital Cost	$RC_{r,t}$	\$/kW	1,590
$\sum$ O&M Cost		\$/kW/yr	51.70
Land Acquisition fee	LR_r		*8.10*
All Else	$ROM_{r,t}$		*43.60*

The reported LCOE value is based on a fixed capacity factor of 41% with an annual average wind speed of 7.25 m/s.[29] However, we have counties with capacity factors as high of 0.561 and as low as 0.283 with a mean value of 0.418 and standard deviation of 0.050 across Texas.

3.5.2 Electrolyzer System Cost

The cost of Proton Exchange Membrane (PEM) electrolyzers from Proton OnSite, Inc. (M-series model) was considered in this model. However, the current market price of PEM electrolyzer is not readily available through open search engines. The following cost function was generated based on cost estimations made by Bellotti et al. in 2015[25] and was used to calculate the electrolyzer cost in 2017 United States Dollars.

$$Cost_{€,2015} = 1.5 \cdot 10^6 \cdot P^{0.85} \qquad (P = \text{Installed Power (MW)})$$

The above cost estimation equation was cross checked with a reported quote in 2014 (2,750,000 USD, 2014 for 0.9 ton H_2/day, Proton Onsite, PEM[41]) and was verified to have an acceptable different of 17.7%.

Based on the above cost estimation, levelized electrolyzer capital cost ($EC_{p,t}$, \$/MW) and levelized electrolyzer operation and maintenance cost ($EOM_{p,t}$, \$/MW/yr) were calculated and incorporated into the model as cost functions shown below.

$$Cost(Electrolyzer)_l^{Inv} = \sum_{(r,p,t)} y_{r,p,t,l} \cdot ER_{p,t} \cdot EC_{p,t}$$

$$Cost(Electrolyzer)_l^{OM} = \sum_{(r,p,t)} y_{r,p,t,l} \cdot ER_{p,t} \cdot EOM_{p,t}$$

3.5.3 Methanol Production Plant Cost

The following cost equation was used to calculate the capital cost of methanol production plant with a plant capacity of 54 ton/hr (gas mixture entering the reactor).[25]

$$Cost_{€,2013}^{Inv} = 14.2 \cdot 10^6 \cdot \left(\frac{M_{in}}{54{,}000}\right)^{0.65} \quad (M_{in} = \text{Gas mixture entering reactor})$$

The above cost function accounts for the cost of methanol reactor and the cost of compressors located at the inlet of the reactor to meet the reactor operating pressure of 80 bar.[42] More specification of methanol production system can be found in Section 3.4.6. The cost of methanol production plant was adjusted to USD 2017, levelized and incorporated into the model.

$$Cost(Methanol\ Production\ Plant)_l^{Inv} = \sum_{(r,p,t)} y_{r,p,t,l} \cdot PC_{p,t} \cdot PR_{p,t}$$

$$Cost(Methanol\ Production\ Plant)_l^{OM} = \sum_{(r,p,t)} y_{r,p,t,l} \cdot POM_{p,t} \cdot PR_{p,t}$$

3.5.4 Carbon Capture Unit (CCU) Cost for Methanol

A reference carbon capture project with a plant capacity of 2,808 ton/hr of fuel gas flow into the separator was used to generate the following cost functions.[43]

$$Cost_{€,2007}^{Inv} = 146.55 \cdot 10^6 \cdot \left(\frac{M_{in}}{2.808 \cdot 10^6}\right)^{0.65}$$

$$Cost_{€,2007}^{OM} = \frac{21.62 \cdot 10^6}{yr} \cdot \left(\frac{M_{in}}{2.808 \cdot 10^6}\right)^{0.65}$$

M_{in} is the mass flowrate of the fuel gas entering the absorber system. The CCU specification considered for this model can be Section 3.4.4. The above cost function is expressed as Euro of 2007 which was adjusted to USD of 2017, levelized and incorporated into the model as shown in the below equations.

$$Cost(CCU)_l^{Inv} = \sum_{(r,p,t),p \in P^{MeOH}} y_{r,p,t,l} \cdot CC_{p,t} \cdot FC_{p,t}$$

$$Cost(CCU)_l^{OM} = \sum_{(r,p,t),p \in P^{MeOH}} y_{r,p,t,l} \cdot COM_{p,t} \cdot FC_{p,t}$$

3.6 Transportation Cost

The supply chain network model of methanol considers the transportation cost between three set of point locations: water source locations to candidate locations, CO_2

source locations to candidate locations, and candidate locations to demand locations. The distances between each point locations are calculated in GAMS using the latitude-longitude coordinates and the haversine formula which is shown below.

$$distance = 2 \cdot r \cdot \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1) \cdot \cos(\varphi_2) \cdot \sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right)$$

Where, r is the radius of the earth (3,961 miles)

φ_1, φ_2 is the latitude of point 1 and latitude of point 2 (in radians)

λ_1, λ_2 is the longitude of point 1 and longitude of point 2 (in radians)

Haversine formula is used to calculate the distance between two points along a spherical surface area (Earth). The latitude-longitude coordinates were inputted into GAMS code as parameters and the distance between two points were calculated.

Only transportation via pipeline was considered for water and CO_2 transportation as large volumes of liquid and compressed gas are required to meet production demand. Truck and railroad were considered as modes of transportation for product delivery to demand locations.

3.6.1 Water Transportation

Water is the main source of feedstock for renewable energy generated methanol and the cost of water purchase and transportation via pipeline is as following.

$$\sum_{(wl,l)} w_{wl,l} \cdot 8000 \cdot \left(Cost_{wl}^{WP} + Cost_{wl,l}^{WT}\right)$$

A water price of \$2.50/ft^3 was used for this model as indicated on the Fort Worth government site for industrial use.[44] The transportation cost (US\$/kg) from water source location to candidate location is calculated with the following equation.[45]

$$Cost_{wl,l}^{WT} = DFC^{W} + DVC^{W} \cdot DI_{wl,l} \cdot DM$$

The following values of DFC, DVC, and DM were used to determine the water transportation cost.

Table 16. DFC, DVC, and DM values for water transportation via pipeline. (Reprinted from [45])

	DFC	DVC	DM	$Cost_{wl}^{WP}$
Water - Pipeline	\$0.003/kg	\$5e-6/kg-mi	1.1	\$2.50/ft^3

3.6.2 Feedstock (CO_2) Transportation

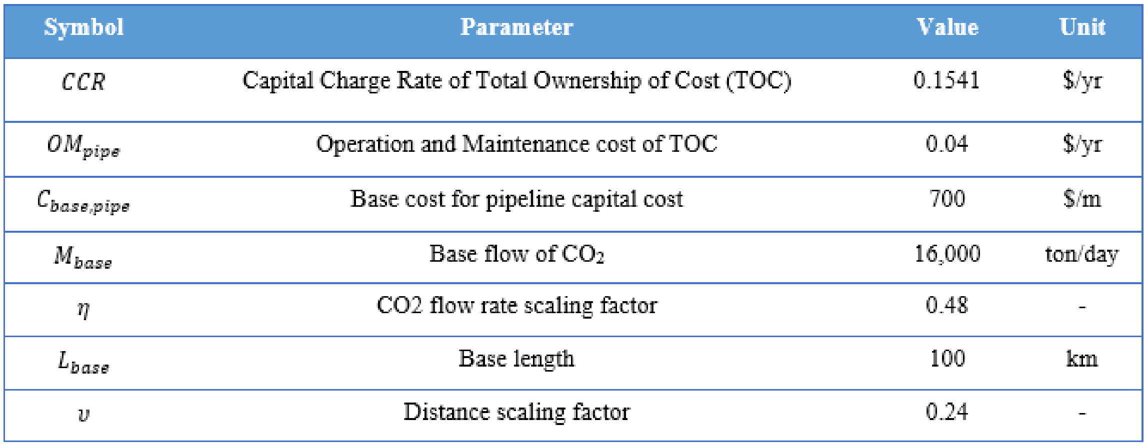
Carbon dioxide (CO_2) is another main source of feedstock for methanol production and the cost of pipeline transportation for CO_2 is calculated as following.

$$\sum_{(cl,l)} cd_{cl,l} \cdot 8000 \cdot Cost_{cl}^{CP} + Cost_{cl,l}^{CT}$$

Where, $Cost_{cl,l}^{CT}$ is the annual capital charge rate of total ownership of CO_2 pipeline and can be calculated with the following equation.[46]

$$Cost_{cl,l}^{CT} = (CCR + OM_{pipe}) \cdot \left\{ C_{base,pipe} \left(\frac{M_{transport,cl,l}}{M_{base}} \right)^{\eta} \right\} \cdot \left\{ L_{pipe,cl,l} \cdot 10^{3} \cdot \left(\frac{L_{pipe,cl,l}}{L_{base}} \right)^{\upsilon} \right\}$$

Table 17. Transpiration values for CO_2 transportation via pipeline. (Reprinted from [46])



Symbol	Parameter	Value	Unit
CCR	Capital Charge Rate of Total Ownership of Cost (TOC)	0.1541	\$/yr
OM_{pipe}	Operation and Maintenance cost of TOC	0.04	\$/yr
$C_{base,pipe}$	Base cost for pipeline capital cost	700	\$/m
M_{base}	Base flow of CO_2	16,000	ton/day
η	CO2 flow rate scaling factor	0.48	-
L_{base}	Base length	100	km
υ	Distance scaling factor	0.24	-

Hence, the following cost function can be used for this model.

$$Cost_{cl,l}^{CT} = (0.1541 + 0.04) \cdot \left\{700 \cdot \left(\frac{cd_{cl,l} \cdot 10^{-3} \cdot 24}{16,000}\right)^{0.48}\right\}$$
$$\cdot \left\{(DI_{cl,l} \cdot 1.60934) \cdot 10^{3} \cdot \left(\frac{DI_{cl,l} \cdot 1.60934}{100}\right)^{0.24}\right\}$$

However, the above transportation equation would make this Mixed Integer Linear Problem (MILP) a Mixed Integer Non-Linear Problem (MINLP) due to the power of the CO_2 flow variable ($cd_{cl,l}$). To resolve this problem, the following levelized carbon transportation cost graphs were generated for each CO_2 flow (for each production capacities).

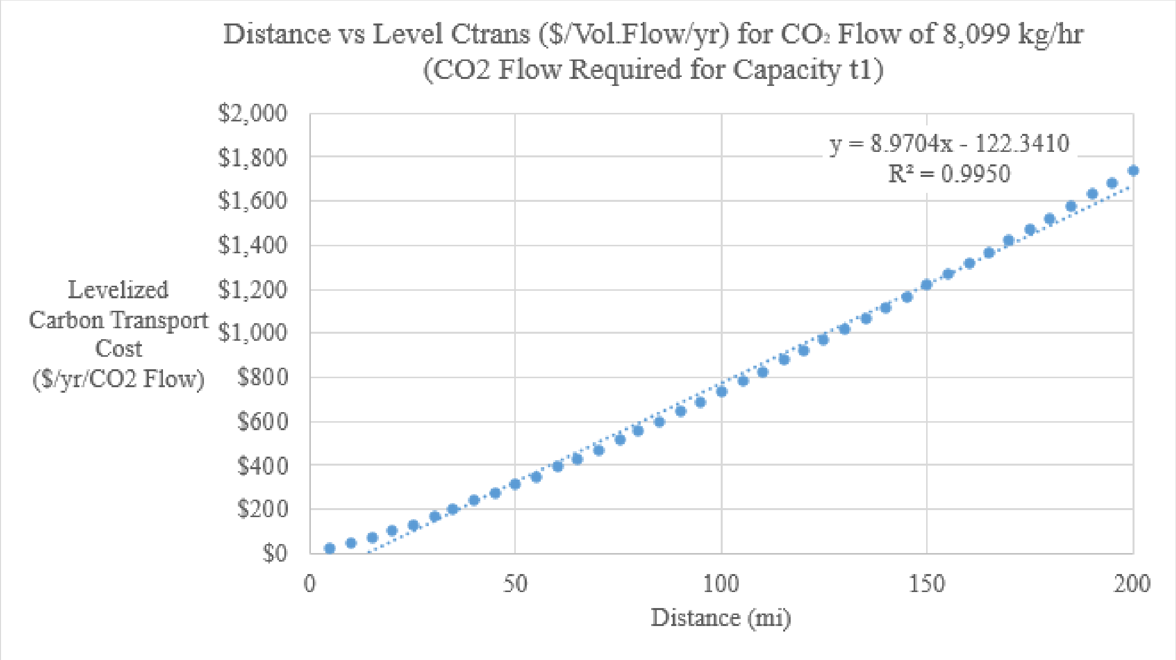


Figure 21. Levelized pipeline transportation cost of CO_2 flow for 8,099 kg/hr (capacity t1) respect to change of distance (distance range of 0 to 200 miles).

3.6.3 Product Transportation

Unlike water and CO$_2$ transportation, two different types of transportation mode (truck and railroad) were available for product transportation in this model. Railroad transportation was only available in the model when a railroad track crosses through the county of interest. The locations of railroad stations are different from the candidate locations as the later location is a hypothetical location at the centroid of each county. For the distance between candidate locations to demand locations via railroad, actual railroad station location (coordinates) were used for this model. The following map of Texas shows all the counties with railroad stations.

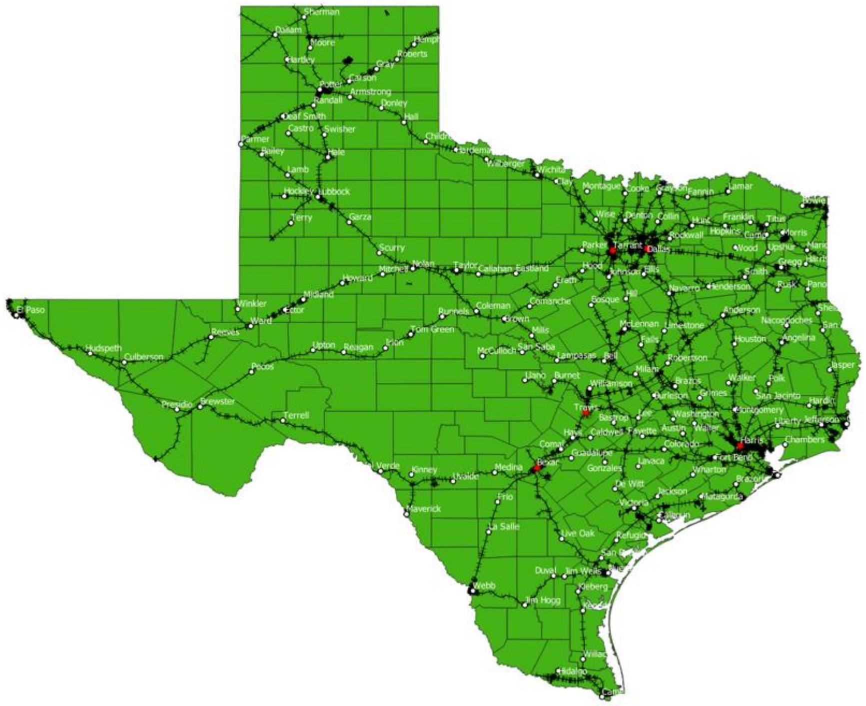


Figure 22. Railroad station locations are shown as white dots and demand locations are shown as red stars.

The following equations are used to calculate for the transportation cost of liquid methanol.

$$Ptrans(\$/yr) = \frac{SCC + TCC}{AF_{i,yr}} + (SOC + TOC) \cdot 365$$

$$\begin{aligned} \text{Where,} \quad & \boldsymbol{S}torage\ \boldsymbol{C}apital\ \boldsymbol{C}ost \\ & \boldsymbol{T}ransportation\ \boldsymbol{C}apital\ \boldsymbol{C}ost \\ & \boldsymbol{S}torage\ \boldsymbol{O}perating\ \boldsymbol{C}ost \\ & \boldsymbol{T}ransportation\ \boldsymbol{O}perating\ \boldsymbol{C}ost \end{aligned}$$

The capital and operating costs associated with storage are neglected for methanol transportation as it is a well understood and widely available liquid product in the current market. These costs are more relevant for energy carriers such as hydrogen where the storage costs can make up a larger fraction of the overall cost profile due to high construction costs and lack of current infrastructures. Hence, only the following transportation costs are considered for methanol product transportation cost.

$$\boldsymbol{T}ransportation\ \boldsymbol{C}apital\ \boldsymbol{C}ost = NTU \times TMC_{p,m}$$

$$\boldsymbol{T}ransportation\ \boldsymbol{O}perating\ \boldsymbol{C}ost = FC + LC + MC + GC$$

$$\begin{aligned} \text{Where,} \quad & \boldsymbol{F}uel\ \boldsymbol{C}ost \\ & \boldsymbol{L}abor\ \boldsymbol{C}ost \\ & \boldsymbol{M}aintenance\ \boldsymbol{C}ost \\ & \boldsymbol{G}eneral\ \boldsymbol{C}ost \end{aligned}$$

The detailed equations and variables used for each component in the above product transportation can be found in the Appendix.

3.7 Oxygen Sales

The following equation is used in the model to account for the sale of Oxygen.

$$Sales_l^{O_2} = \sum_{(r,p,t)} SP_{O_2} \cdot z_{O_2,l} \cdot 8000$$

Where $z_{O_2,l}$ is the oxygen produced at a candidate location and can be expressed as following.

$$z_{O_2,l} = \sum_{(r,p,t)} y_{r,p,t,l} \cdot Ox_{p,t}$$

The current market price of oxygen per kg was used (\$0.11794/kgO_2) in this model. The sale of highly pure oxygen can off balance the costs associated with producing renewably generated methanol. However, considering the elasticity nature of the market, the current market price of oxygen cannot be considered at face value as the construction of mass utility scale plants will create surplus of oxygen in the market. As a result, each cases will report the LCOE (\$/GJ) without the sales of oxygen gas and with the sales of oxygen gas for a discount rate of 50%, which will reduce the sale of oxygen proportionally.

3.8 Objective Function

The total cost of constructing a renewable energy generated methanol can be expressed as the following objective function.

$$MIN \quad Total\ Cost = \sum_{l \in L^F} \frac{Cost_l^{Inv}}{AF_{i,yr}} + Cost_l^{OM} - Sales_l^{O_2}$$

$$+ \begin{bmatrix} \sum_{(cl,l)} cd_{cl,l} \cdot 8000 \cdot Cost_{cl}^{CP} + Cost_{cl,l}^{CT} \\ + \sum_{(wl,l)} w_{wl,l} \cdot 8000 \cdot \left(Cost_{wl}^{WP} + Cost_{wl,l}^{WT}\right) \\ + \frac{TCC}{AF_{i,yr}} + TOC \cdot 365 \end{bmatrix}$$

Where $Cost_l^{Inv}$ accounts for total capital cost of renewable plant, electryolzer, methanol production plant and carbon capture unit (for methanol). All such equipment operation and maintenance costs are accounted for as $Cost_l^{OM}$. The total sum of investment costs are converted to equivalent annual cost (EAC) using the following equations to express as 2017 USD per year.

$$EAC(\$/yr) = \frac{Net\ Present\ Value\ (2017\ USD)}{AF_{i,yr}}$$

$$AF_{i,yr} = \frac{1 - \frac{1}{(1+i)^{yr}}}{i}$$

The annuity factor ($AF_{i,yr}$) depends on the interest rate and plant lifespan. For this study, an interest rate of 5% and plant lifespan of 25 years were used.

The total cost is levelized respect to the total energy production as can be seen from the below equation.

$$Annual\ Levelized\ Total\ Cost\left(\frac{\$}{GJ}\right) = \frac{Total\ Cost(\$)}{TEC\ (GJ)\ per\ year}$$

The total electricity consumption (TEC) for the five demand counties is 722,159,015 GJ/yr.

4. SUPPLY CHAIN NETWORK OPTIMIZATION RESULTS AND SCENARIOS

4.1 Base Case

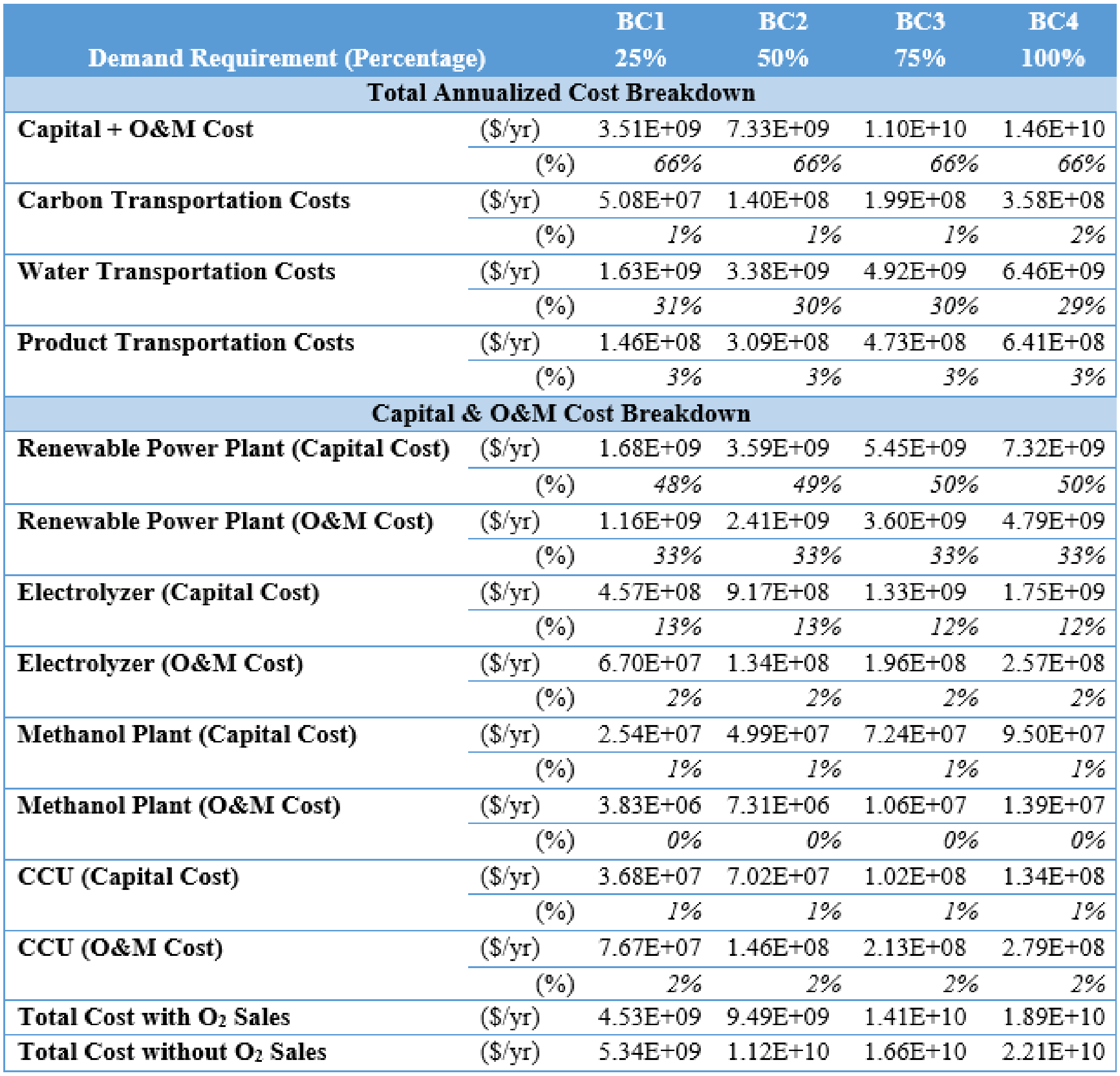
The supply chain network of methanol was built to meet the electricity demands of the top five energy consuming counties of Texas, which is equivalent to 44% of the total energy consumption of Texas in 2016. The base case will be conducted with the following assumption of the total demand requirement.

Table 18. Base Cases and percentage of demand requirement at demand location.

Base Case	% Demand Requirement
1	25%
2	50%
3	75%
4	100%

The following results were obtained from the minimization of this MILP model with the variation of energy demand.

Table 19. Cost Breakdown ($/yr) for Base Case.



		BC1	BC2	BC3	BC4
Demand Requirement (Percentage)		**25%**	**50%**	**75%**	**100%**
Total Annualized Cost Breakdown					
Capital + O&M Cost	($/yr)	3.51E+09	7.33E+09	1.10E+10	1.46E+10
	(%)	*66%*	*66%*	*66%*	*66%*
Carbon Transportation Costs	($/yr)	5.08E+07	1.40E+08	1.99E+08	3.58E+08
	(%)	*1%*	*1%*	*1%*	*2%*
Water Transportation Costs	($/yr)	1.63E+09	3.38E+09	4.92E+09	6.46E+09
	(%)	*31%*	*30%*	*30%*	*29%*
Product Transportation Costs	($/yr)	1.46E+08	3.09E+08	4.73E+08	6.41E+08
	(%)	*3%*	*3%*	*3%*	*3%*
Capital & O&M Cost Breakdown					
Renewable Power Plant (Capital Cost)	($/yr)	1.68E+09	3.59E+09	5.45E+09	7.32E+09
	(%)	*48%*	*49%*	*50%*	*50%*
Renewable Power Plant (O&M Cost)	($/yr)	1.16E+09	2.41E+09	3.60E+09	4.79E+09
	(%)	*33%*	*33%*	*33%*	*33%*
Electrolyzer (Capital Cost)	($/yr)	4.57E+08	9.17E+08	1.33E+09	1.75E+09
	(%)	*13%*	*13%*	*12%*	*12%*
Electrolyzer (O&M Cost)	($/yr)	6.70E+07	1.34E+08	1.96E+08	2.57E+08
	(%)	*2%*	*2%*	*2%*	*2%*
Methanol Plant (Capital Cost)	($/yr)	2.54E+07	4.99E+07	7.24E+07	9.50E+07
	(%)	*1%*	*1%*	*1%*	*1%*
Methanol Plant (O&M Cost)	($/yr)	3.83E+06	7.31E+06	1.06E+07	1.39E+07
	(%)	*0%*	*0%*	*0%*	*0%*
CCU (Capital Cost)	($/yr)	3.68E+07	7.02E+07	1.02E+08	1.34E+08
	(%)	*1%*	*1%*	*1%*	*1%*
CCU (O&M Cost)	($/yr)	7.67E+07	1.46E+08	2.13E+08	2.79E+08
	(%)	*2%*	*2%*	*2%*	*2%*
Total Cost with O_2 Sales	($/yr)	4.53E+09	9.49E+09	1.41E+10	1.89E+10
Total Cost without O_2 Sales	($/yr)	5.34E+09	1.12E+10	1.66E+10	2.21E+10

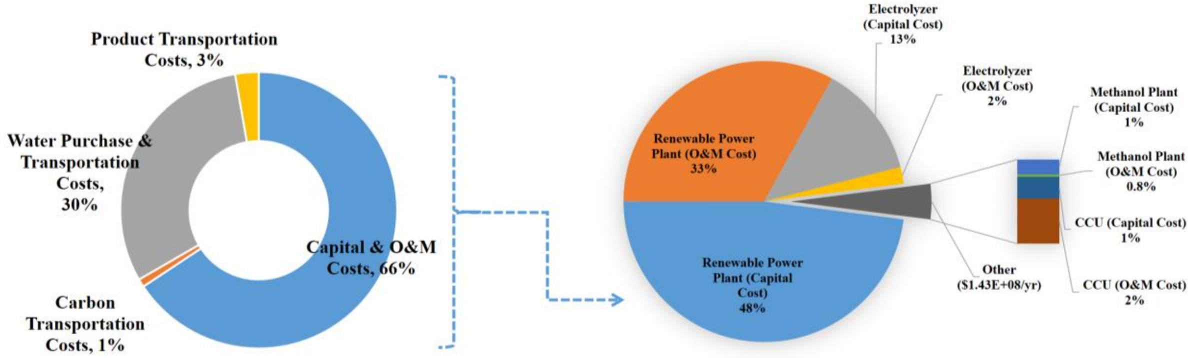


Figure 23. Cost Breakdown of Base Case 1.

As can be seen from the above table and pie chart (only Base Case 1 shown as all other cases are close to identical), the majority of the cost associated with building a renewable energy generated methanol plant comes from the costs associated with the construction and maintenance of the renewable power plant, which accounts for 53.46% to 54.78% of total cost for Base Cases 1 to 4. Compared to the capital and operating costs, product transportation costs and carbon transportation costs are only responsible for a very small portion of the total annualized cost. On the other hand, water purchase and transportation costs accounts for 30% of the total annualized cost, of which water purchase is responsible for roughly 96 to 97% and water transportation is responsible for less than 4%. This is because the model has considered a water purchase fee of $2.50/ft^3 (equivalent to $88.28/ton$H_2O$)[44] in the state of Texas compared to a cost value of $0.50/ton$H_2O$ which is a typical purchase cost for seawater. Further sensitivity analysis of water purchase cost respect to the total LCOE was conducted and reported in section 4.2. The cost of energy carrier production, which consists of all the cost associated with electrolyzer systems, methanol production plants, and carbon capture units, only accounts for 14% of the total annualize cost. This is a rather small percentage of the total cost associated with the production of renewable energy generated methanol as energy carriers.

Variation of the percentage of the capital and O&M costs respect to the total cost can depend on several factors. However, the most influential factor in this model is due to the variation of renewable energy potentials at candidate locations and the transportation cost based on the variation of the distance between two points of interest. The capacity factor ($CF_{r,1}$) and the renewable energy scaling factor ($RF_{r,1}$) determines the majority of the capital cost associated with the renewable power plant and impacts the selection of candidate locations in this model. The following map of Texas shows the geographical locations of the selected facility sites for Base Case 1 where the type of renewable energy selected, renewable energy power plant capacity, and CO_2 and water source locations are also shown.

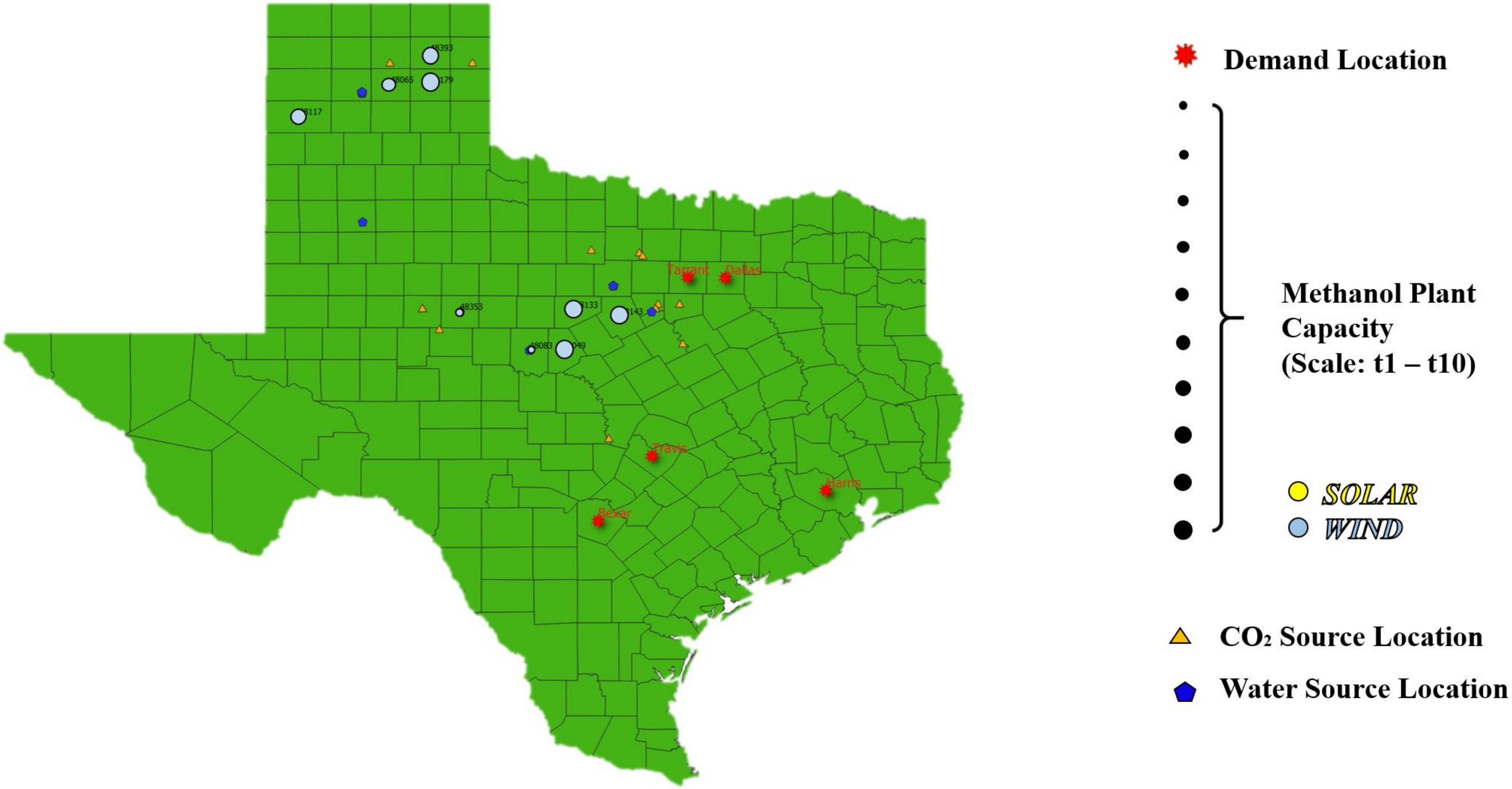


Figure 24. Selected candidate locations for Base Case 1.

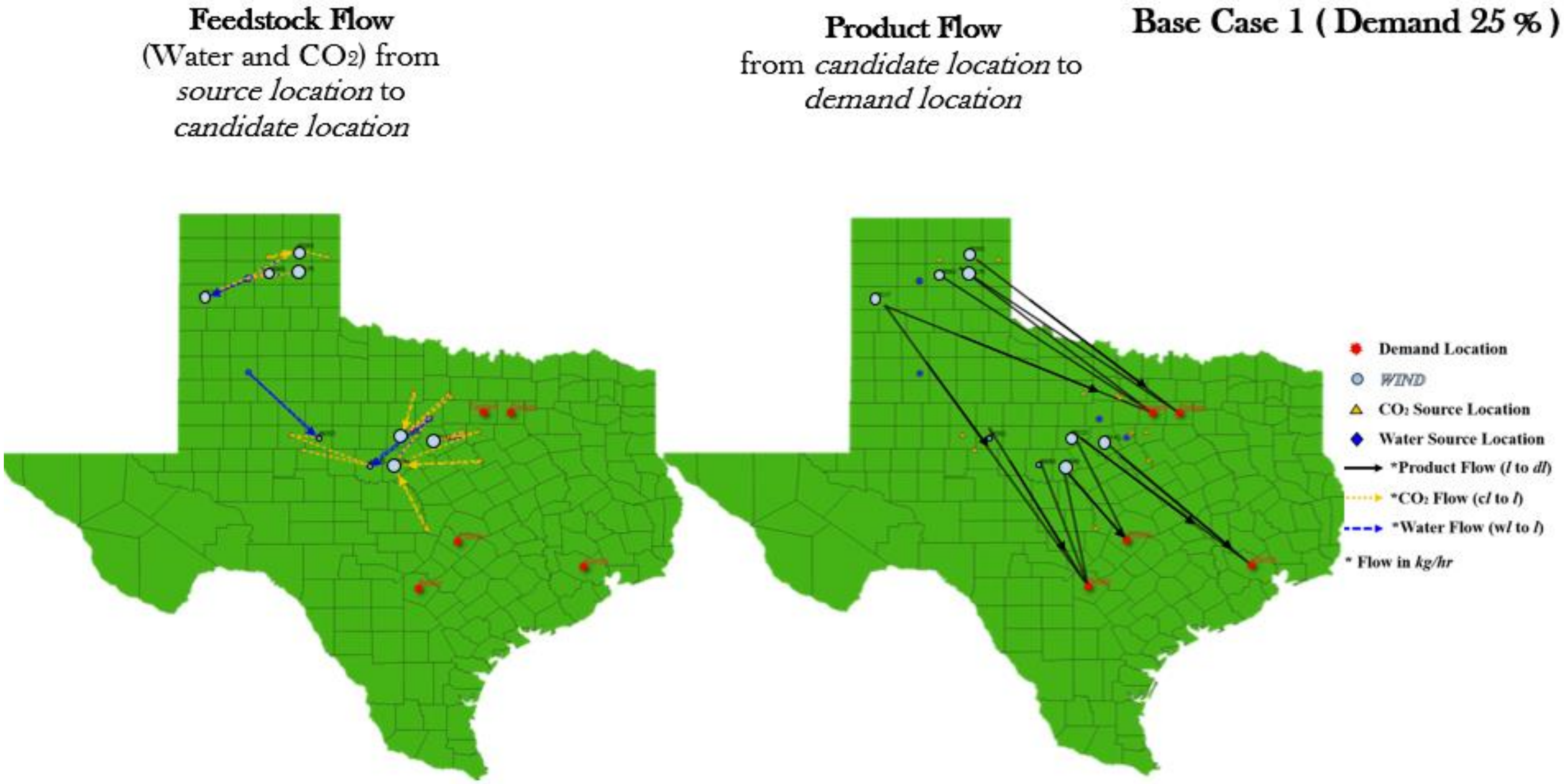
Table 20. Summary of plant selection and mass flows for Base Cases.

	BC1	**BC2**	**BC3**	**BC4**
Demand Requirement (Percentage)	**25%**	**50%**	**75%**	**100%**
Renewable Power Plant Characteristics				
Type/No. of Renewable Energy Selected	Wind (9)	Wind (12)	Wind (17)	Wind (22)
Capacities Selected	t1(2) t6(1) t8(1) t9(1) t10 (4)	t1(1) t10 (11)	t1 (1) t10 (16)	t1 (1) t10 (21)
Average $RF_{r,l}$ (wind)	0.638	0.638	0.649	0.656
Average $CF_{r,l}$ (wind)	0.495	0.491	0.483	0.478
Average LF_l	0.572	0.652	0.6	0.578
Product Transportation Characteristic				
Average Transportation Distance (mi) (Mass flowrate weighted)	254	259	273	282
Total Product Transportation Cost ($/yr)	1.63E+09	3.09E+08	4.73E+08	6.41E+08
Water Transportation Characteristic				
No. Water Sources Selected	5	8	10	13
No. of Water Flows	9	13	19	28
Average Transportation Distance (mi) (Mass flowrate weighted)	49	59	49	57
Transportation Cost ($/yr)	5.84E+07	1.23E+08	1.75E+08	2.34E+08
Water Purchase Cost ($/yr)	1.58E+09	3.26E+09	4.74E+09	6.22E+09
Total Water Purchase & Transportation Cost ($/yr)	1.63E+09	3.38E+09	4.92E+09	6.46E+09
CO_2 Transportation Characteristic				
No. CO_2 Sources Selected	16	36	50	54
No. of CO_2 Flows	22	44	64	74
Average Transportation Distance (mi) (Mass weighted flowrate)	58	73	71	93
Total CO_2 Transportation Cost ($/yr)	5.08E+07	1.40E+08	1.99E+08	3.58E+08

The above table summarizes the candidate location selection, production transportation characteristics, water transportation characteristics, and carbon transportation characteristics for all Base Cases.

The renewable energy scaling factor increases and capacity factor decreases with larger demand, which indicates that the model is choosing candidate locations with higher renewable energy potential first and then moves on to less energy intensive locations. As mentioned in section 3.4.2, the renewable energy scaling factor is the inverse of the renewable energy potential to the reference energy potential and will decrease with higher energy potential locations to indicate the decrease of cost for renewable power plant construction and operations. In addition, it can be seen from the model results that with more demand to meet the feedstock sources and products are traveling further from start to destination locations. This can be seen by the increase of average transportation distance for production and CO_2 source for Base Case 1 to 4.

The following figures geographically show the mass flows for water source, CO_2 source, and product for Base Case 1 and 4. In both figures, there is a general trend for feedstock flow and product flow. First of all, most selected renewable energy power plants are located in the North, Central, and North-West regions of Texas than the East. This is due to the presence of higher wind energy potentials at selected facility sites compared to the demand locations in the East. As a result, water and CO_2 sources are being transported to the North-West regions and the produced products are being transported South-East regions.

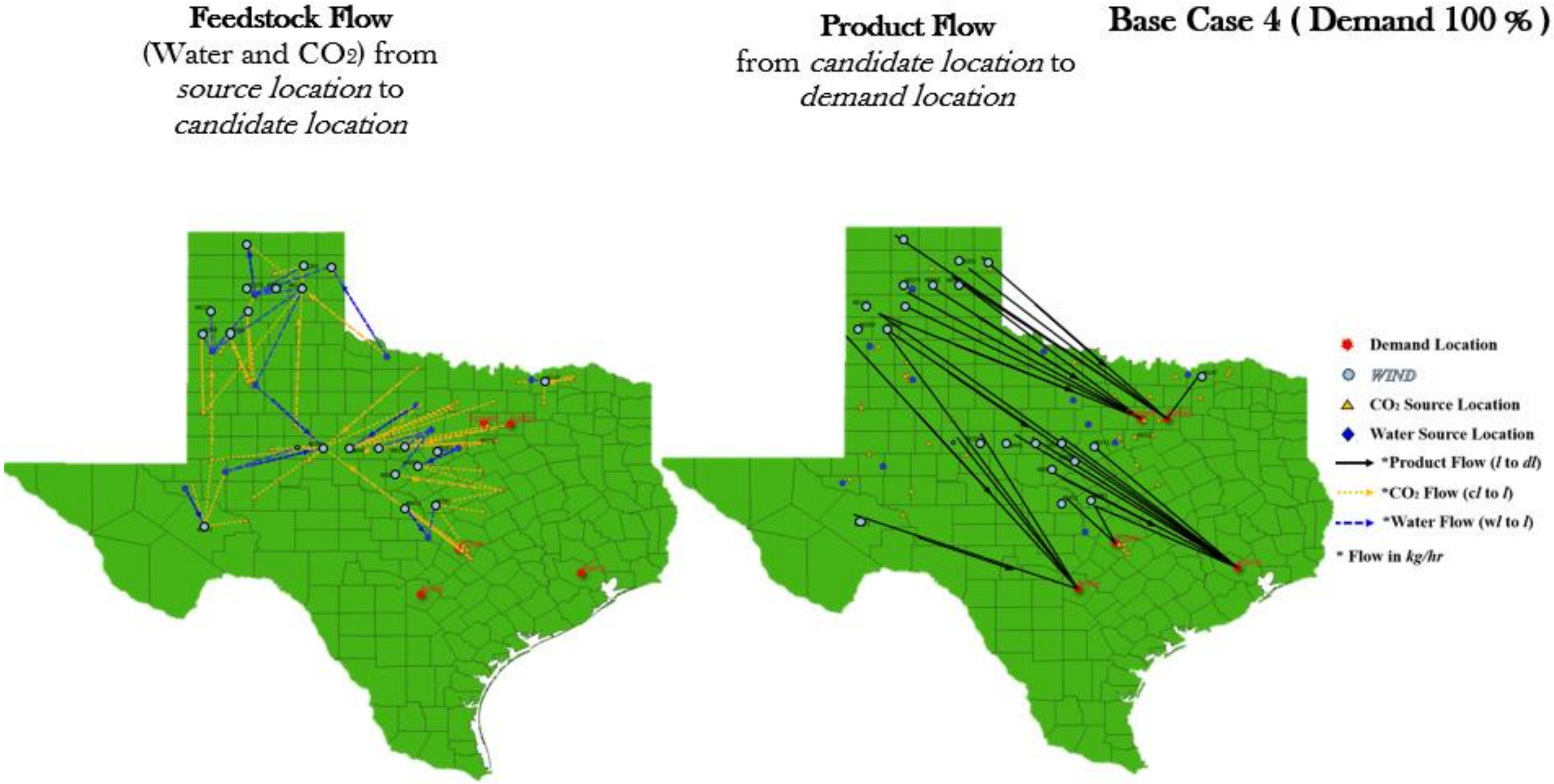


Feedstock Flow
(Water and CO2) from
source location to
candidate location

Product Flow
from *candidate location* to
demand location

Base Case 1 (Demand 25 %)

Figure 25. (Left) Water and CO_2 flows from source locations to plant locations for Base Case 1. (Right) Product flows from plant locations to demand locations for Base Case 1.



Feedstock Flow
(Water and CO_2) from *source location* to *candidate location*

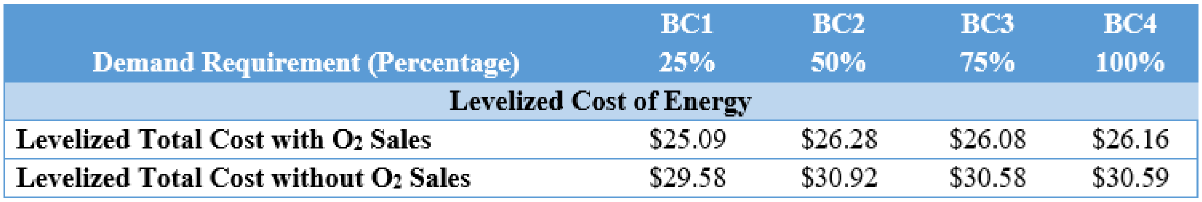
Product Flow
from *candidate location* to *demand location*

Base Case 4 (Demand 100 %)

Figure 26. (Left) Water and CO_2 flows from source locations to plant locations for Base Case 4. (Right) Product flows from plant locations to demand locations for Base Case 4.

Finally, the levelized cost of energy (LCOE) in US dollars per GJ were calculated from the model results.

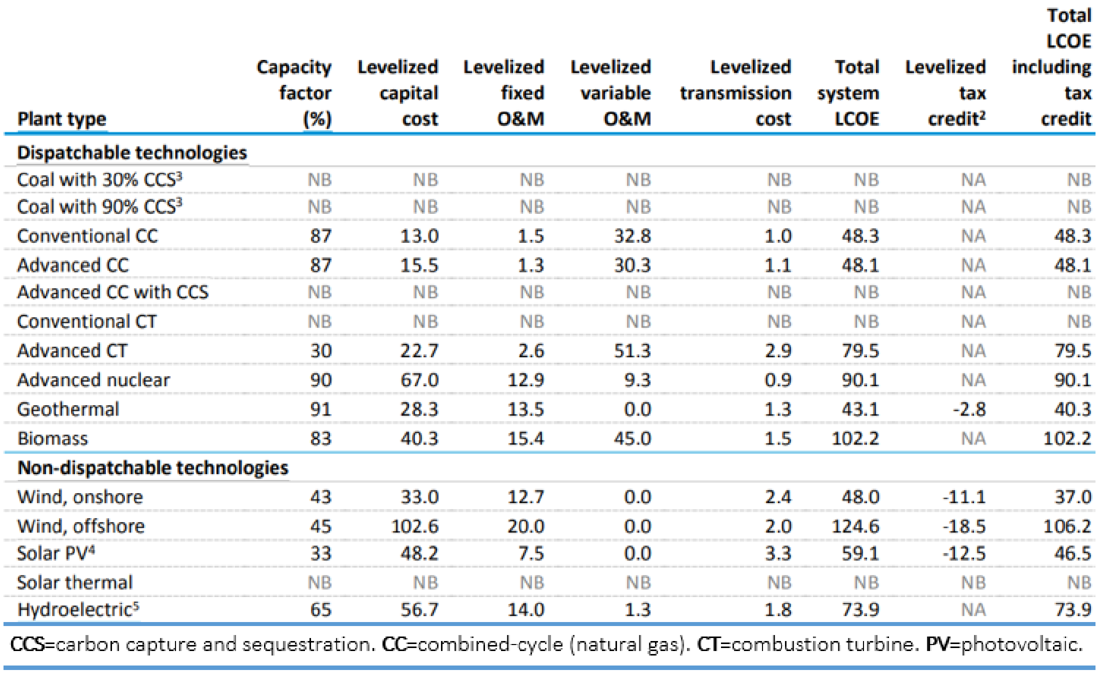
Table 21. Levelized Cost of Energy (LCOE) for Base Cases.



Demand Requirement (Percentage)	BC1 25%	BC2 50%	BC3 75%	BC4 100%
Levelized Cost of Energy				
Levelized Total Cost with O_2 Sales	$25.09	$26.28	$26.08	$26.16
Levelized Total Cost without O_2 Sales	$29.58	$30.92	$30.58	$30.59

The LCOE for the base cases are in the range of $29.58/GJ to $30.92/GJ without considering oxygen sales. The LCOE does not vary significantly with the increase of production to meet respected demand. This indicates that the cost values and equations incorporated in this model increase relatively linearly even through the equations used to generate the input values were not necessarily linear. Additionally, the LCOE value with oxygen gas sales were calculated. The shown LCOE with oxygen sales is only considering half the current market price of pure oxygen to take into consideration market elasticity. The model results shows that oxygen gas sales decrease the LCOE by roughly $4.60 and makes renewable energy generated methanol more price competitive. However, the LCOE with oxygen sales value have to be considered with caution as this estimation was made based on the market price of oxygen gas which is highly uncertain in the future.

The LCOE values for conventional forms of energy[47] can be seen in the below figure for a rudimentary comparison of the calculated LCOE of renewable energy generated methanol.



Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmission cost	Total system LCOE	Levelized tax credit[2]	Total LCOE including tax credit
Dispatchable technologies								
Coal with 30% CCS[3]	NB	NB	NB	NB	NB	NB	NA	NB
Coal with 90% CCS[3]	NB	NB	NB	NB	NB	NB	NA	NB
Conventional CC	87	13.0	1.5	32.8	1.0	48.3	NA	48.3
Advanced CC	87	15.5	1.3	30.3	1.1	48.1	NA	48.1
Advanced CC with CCS	NB	NB	NB	NB	NB	NB	NA	NB
Conventional CT	NB	NB	NB	NB	NB	NB	NA	NB
Advanced CT	30	22.7	2.6	51.3	2.9	79.5	NA	79.5
Advanced nuclear	90	67.0	12.9	9.3	0.9	90.1	NA	90.1
Geothermal	91	28.3	13.5	0.0	1.3	43.1	-2.8	40.3
Biomass	83	40.3	15.4	45.0	1.5	102.2	NA	102.2
Non-dispatchable technologies								
Wind, onshore	43	33.0	12.7	0.0	2.4	48.0	-11.1	37.0
Wind, offshore	45	102.6	20.0	0.0	2.0	124.6	-18.5	106.2
Solar PV[4]	33	48.2	7.5	0.0	3.3	59.1	-12.5	46.5
Solar thermal	NB	NB	NB	NB	NB	NB	NB	NB
Hydroelectric[5]	65	56.7	14.0	1.3	1.8	73.9	NA	73.9

CCS=carbon capture and sequestration. **CC**=combined-cycle (natural gas). **CT**=combustion turbine. **PV**=photovoltaic.

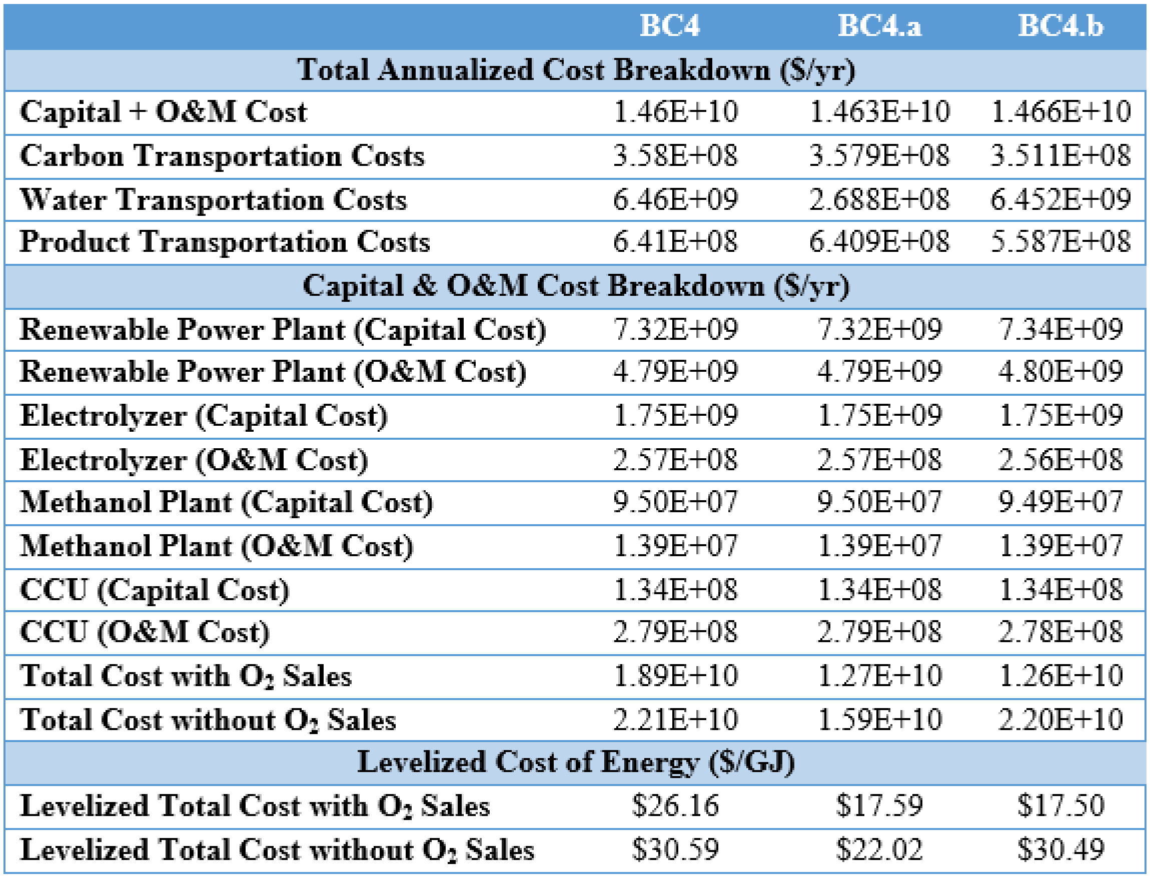
Figure 27. Estimated LCOE for new generation resources entering energy market in 2022 (Units of 2017 USD/MWh). (Reprinted from [47])

The estimated LCOE for new generation sources entering the energy market by 2022 is reported to be $48.80/MWh ($13.56/GJ) for conventional combined-cycle in 2017 USD currency.[47] The report also shows that the LCOE values for wind (onshore) and solar PV by 2022 are estimated to be $48.00/MWh ($13.33/GJ) and $59.10/MWh ($16.42/GJ)[47].

4.2 Sensitivity Study of Base Case with varying Water Cost and Demand Locations

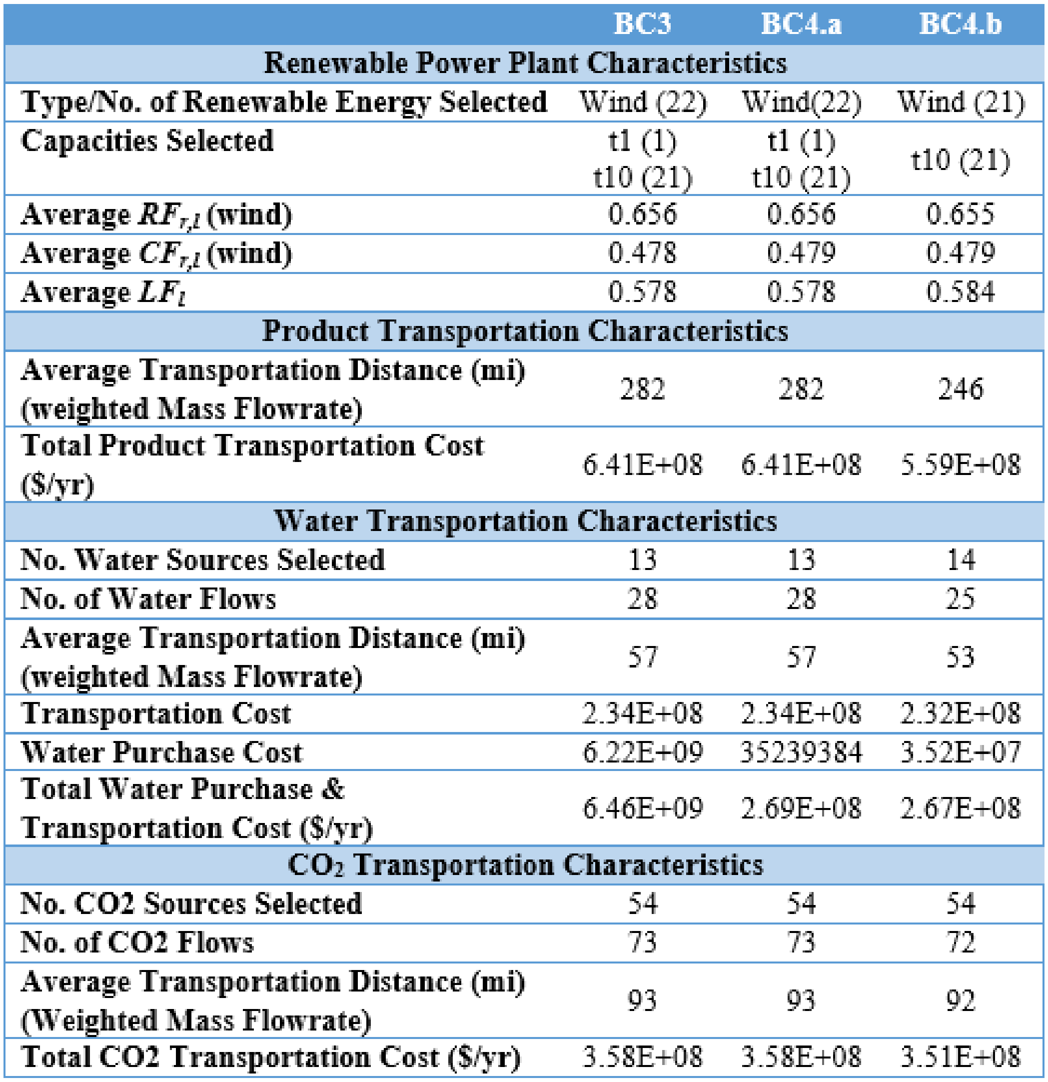
Two sensitivity study was conducted on Base Case 4 (100% demand fraction). The water purchase cost was modified for Base Case 4.a (BC4.a) from $88/ton to $0.50/ton to see how the cost breakdown and LCOE varies with such change. In addition, Base Case 4.b (BC4.b) was conducted by changing the demand locations of top five energy consuming counties of Texas (equivalent to 44% of the total Texas energy consumption) to the next number of counties that consist of 44% of total Texas energy consumption. Such case study was conducted because in all Base Cases, most product flows were flowing North to South-East when most selected plant locations are located in North-Central regions of Texas. The following cost breakdowns and material flow summaries can be seen from the two case studies.

Table 22. Cost Breakdown ($/yr) and LCOE ($/GJ) for BC4.a and BC4.b.



	BC4	BC4.a	BC4.b
Total Annualized Cost Breakdown ($/yr)			
Capital + O&M Cost	1.46E+10	1.463E+10	1.466E+10
Carbon Transportation Costs	3.58E+08	3.579E+08	3.511E+08
Water Transportation Costs	6.46E+09	2.688E+08	6.452E+09
Product Transportation Costs	6.41E+08	6.409E+08	5.587E+08
Capital & O&M Cost Breakdown ($/yr)			
Renewable Power Plant (Capital Cost)	7.32E+09	7.32E+09	7.34E+09
Renewable Power Plant (O&M Cost)	4.79E+09	4.79E+09	4.80E+09
Electrolyzer (Capital Cost)	1.75E+09	1.75E+09	1.75E+09
Electrolyzer (O&M Cost)	2.57E+08	2.57E+08	2.56E+08
Methanol Plant (Capital Cost)	9.50E+07	9.50E+07	9.49E+07
Methanol Plant (O&M Cost)	1.39E+07	1.39E+07	1.39E+07
CCU (Capital Cost)	1.34E+08	1.34E+08	1.34E+08
CCU (O&M Cost)	2.79E+08	2.79E+08	2.78E+08
Total Cost with O_2 Sales	1.89E+10	1.27E+10	1.26E+10
Total Cost without O_2 Sales	2.21E+10	1.59E+10	2.20E+10
Levelized Cost of Energy ($/GJ)			
Levelized Total Cost with O_2 Sales	$26.16	$17.59	$17.50
Levelized Total Cost without O_2 Sales	$30.59	$22.02	$30.49

Table 23. Summary of plant selection and mass flows for Base Case, BC4.a and BC4.b.



	BC3	BC4.a	BC4.b
Renewable Power Plant Characteristics			
Type/No. of Renewable Energy Selected	Wind (22)	Wind(22)	Wind (21)
Capacities Selected	t1 (1) t10 (21)	t1 (1) t10 (21)	t10 (21)
Average $RF_{r,l}$ (wind)	0.656	0.656	0.655
Average $CF_{r,l}$ (wind)	0.478	0.479	0.479
Average LF_l	0.578	0.578	0.584
Product Transportation Characteristics			
Average Transportation Distance (mi) (weighted Mass Flowrate)	282	282	246
Total Product Transportation Cost ($/yr)	6.41E+08	6.41E+08	5.59E+08
Water Transportation Characteristics			
No. Water Sources Selected	13	13	14
No. of Water Flows	28	28	25
Average Transportation Distance (mi) (weighted Mass Flowrate)	57	57	53
Transportation Cost	2.34E+08	2.34E+08	2.32E+08
Water Purchase Cost	6.22E+09	35239384	3.52E+07
Total Water Purchase & Transportation Cost ($/yr)	6.46E+09	2.69E+08	2.67E+08
CO_2 Transportation Characteristics			
No. CO2 Sources Selected	54	54	54
No. of CO2 Flows	73	73	72
Average Transportation Distance (mi) (Weighted Mass Flowrate)	93	93	92
Total CO2 Transportation Cost ($/yr)	3.58E+08	3.58E+08	3.51E+08

For Base Case 4.a (BC4.a), the water purchase cost was modified from $88/ton in Base Case 4 to $0.50/ton and the following cost breakdowns were observed.

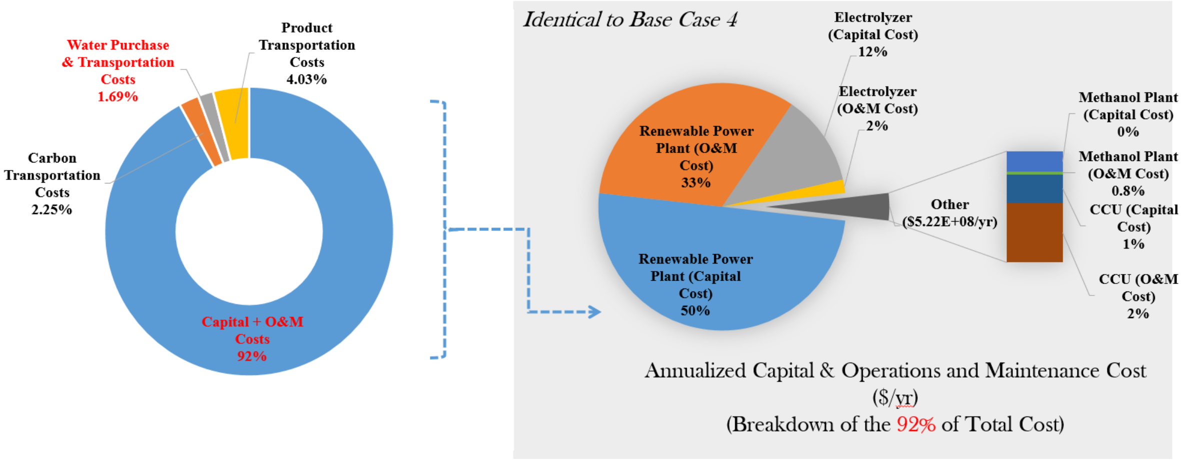
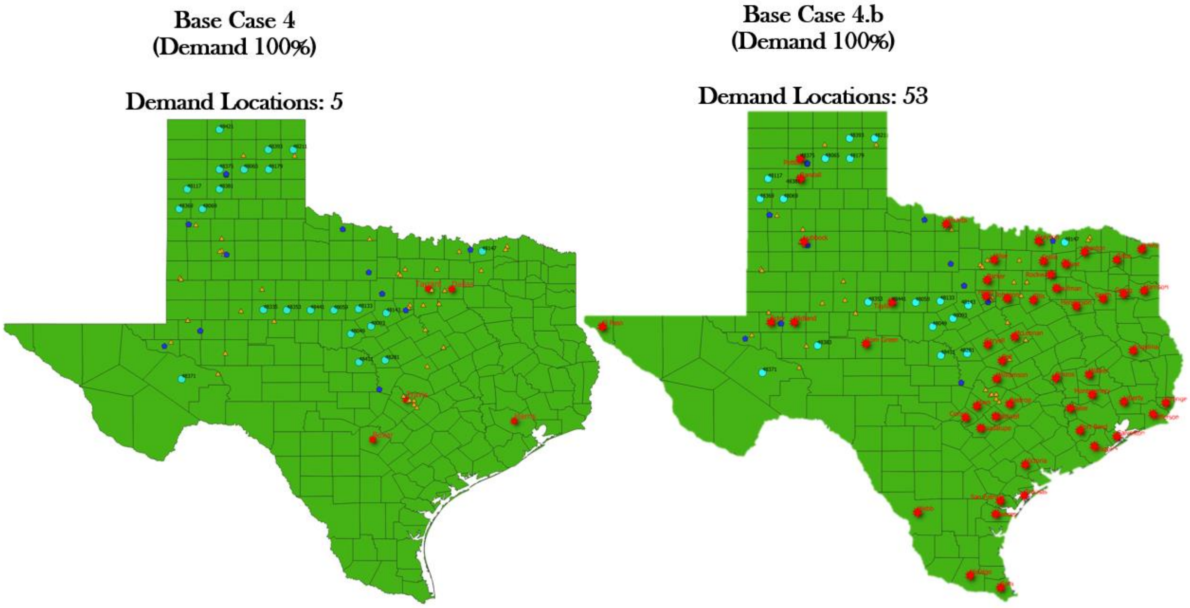


Figure 28. Cost Breakdown of Base Case 4.a.

From Base Case 4 to Base Case 4.a, the total capital and operations cost has increased from 66% to 92% of total annualized cost, whereas the breakdown and the costs of the annualized capital and operations cost did not change. Respectively, the water purchase and transportation cost has decreased from 30% to 1.7% of total annualized cost. The water purchase price decrease from $88/ton to $0.50/ton is also reflected in the $8.57/GJ decrease of LCOE from $30.59/GJ to $22.02/GJ.

Such result shows that the water purchase cost can be a cost determining factor for water electrolysis based hydrogen carrier production. In addition, the price of water resources are heavily depended on availability in the region and can vary with the annual precipitation in the region. A reliable estimation of water purchase price should be considered in order to obtain rational results from a model based supply chain network analysis.

For Base Case 4.b (BC4.b), the demand locations were changed from 5 to 53 as can be seen in the below figure.



Base Case 4
(Demand 100%)

Demand Locations: *5*

Base Case 4.b
(Demand 100%)

Demand Locations: *53*

Figure 29. Demand locations for Base Case 4 (no. 5) and Base Case 4.b (no.53).

A geographical representation of the product flows can be seen in the below figure for Base Case 4 and Base Case 4.b.

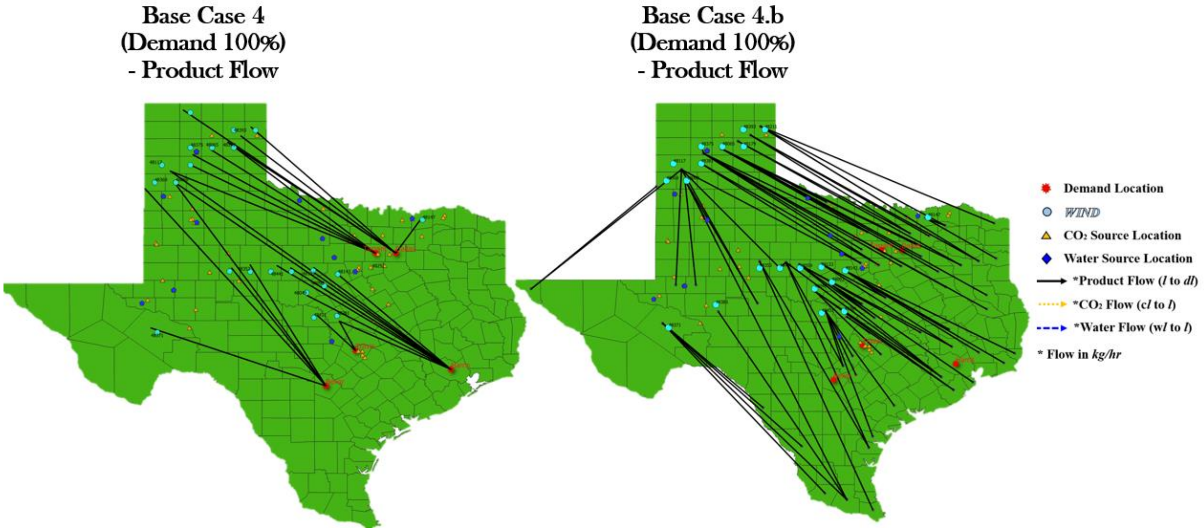


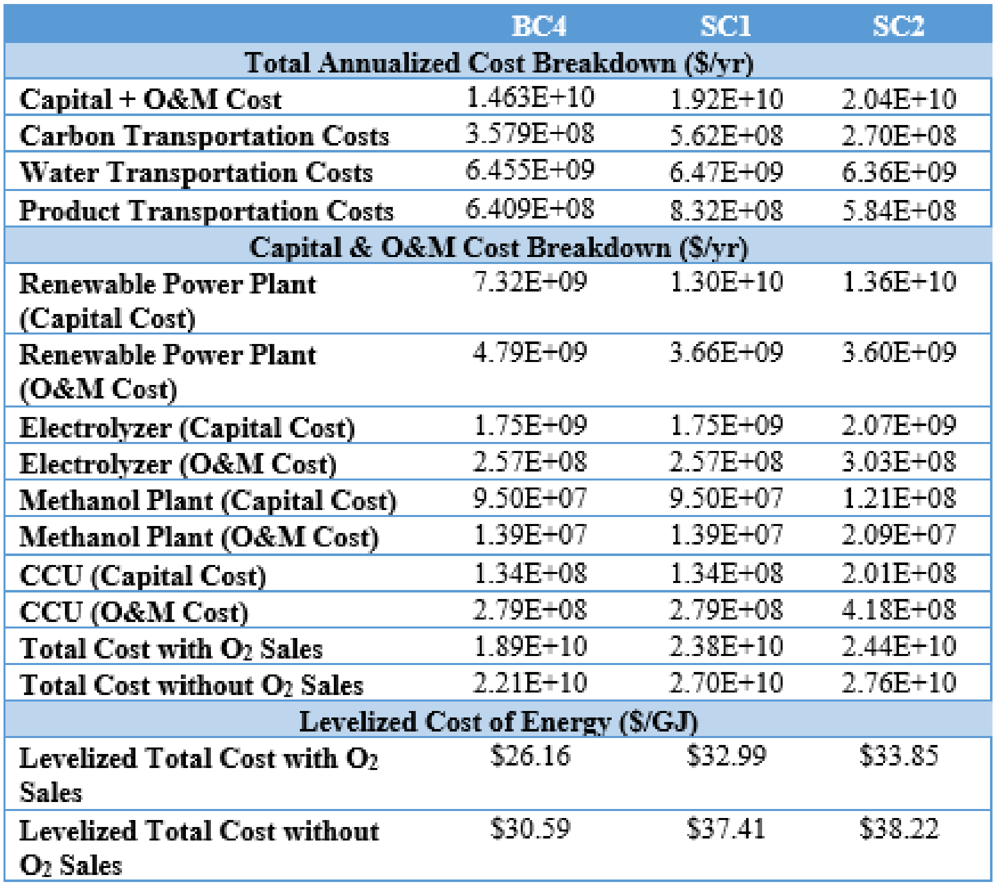
Figure 30. Product flow of Base Case 4 and Base Case 4.b.

With the increase in number of destinations, the average distance traveled for products have decreased from 282 miles to 246 miles as demand locations are more distributed and not as centralized. As a result, all transportation costs associated with production, CO_2 and water sources have decreased for Base Case 4.b. However, the LCOE has only decreased by $0.10/GJ between the Base Case 4 and Base Case 4.b. This is because transportation cost is only a small fraction of the overall annualized cost.

4.3 Case Study of Solar Power Plant

Model results for all base cases and sensitivity studies conducted in previous section choose wind power plants over solar power plants. This was by part an expected result as the LCOE with renewable energy scaling factor for wind power plant is lower than solar power plant. For this section, the LCOE for solar power plants were quantified for the production of renewable energy generated methanol to meet the energy demands of the top five counties in Texas. Two cases for solar power plant was conducted in this case study. For Solar Case 1 (SC1), wind power plants were deselected and the model can choose to build methanol production plants up to a maximum capacity of 5,014 ton/day (capacity of t10). However, to produce 5,014 ton of methanol per day with solar energy, a solar power plant capacity of 9,410 MW_{DC} has to be constructed at a region of 24% capacity factor with 1-axis tracking PV module. Such solar power plant capacity is not a reasonable size in the current and near future market. As a result, Solar Case 2 (SC2) will consider solar power plants of maximum 2,823 MW_{DC} capacity, which can produce 1,504 ton/day of methanol (capacity of t7).

Table 24. Cost Breakdown ($/yr) and Levelized Cost of Energy (LCOE) ($/GJ) for Solar Case 1 (SC1) and Solar Case 2 (SC2).



	BC4	SC1	SC2
Total Annualized Cost Breakdown ($/yr)			
Capital + O&M Cost	1.463E+10	1.92E+10	2.04E+10
Carbon Transportation Costs	3.579E+08	5.62E+08	2.70E+08
Water Transportation Costs	6.455E+09	6.47E+09	6.36E+09
Product Transportation Costs	6.409E+08	8.32E+08	5.84E+08
Capital & O&M Cost Breakdown ($/yr)			
Renewable Power Plant (Capital Cost)	7.32E+09	1.30E+10	1.36E+10
Renewable Power Plant (O&M Cost)	4.79E+09	3.66E+09	3.60E+09
Electrolyzer (Capital Cost)	1.75E+09	1.75E+09	2.07E+09
Electrolyzer (O&M Cost)	2.57E+08	2.57E+08	3.03E+08
Methanol Plant (Capital Cost)	9.50E+07	9.50E+07	1.21E+08
Methanol Plant (O&M Cost)	1.39E+07	1.39E+07	2.09E+07
CCU (Capital Cost)	1.34E+08	1.34E+08	2.01E+08
CCU (O&M Cost)	2.79E+08	2.79E+08	4.18E+08
Total Cost with O_2 Sales	1.89E+10	2.38E+10	2.44E+10
Total Cost without O_2 Sales	2.21E+10	2.70E+10	2.76E+10
Levelized Cost of Energy ($/GJ)			
Levelized Total Cost with O_2 Sales	$26.16	$32.99	$33.85
Levelized Total Cost without O_2 Sales	$30.59	$37.41	$38.22

The cost breakdown for Solar Case 2 is represented in a pie chart in the below figure.

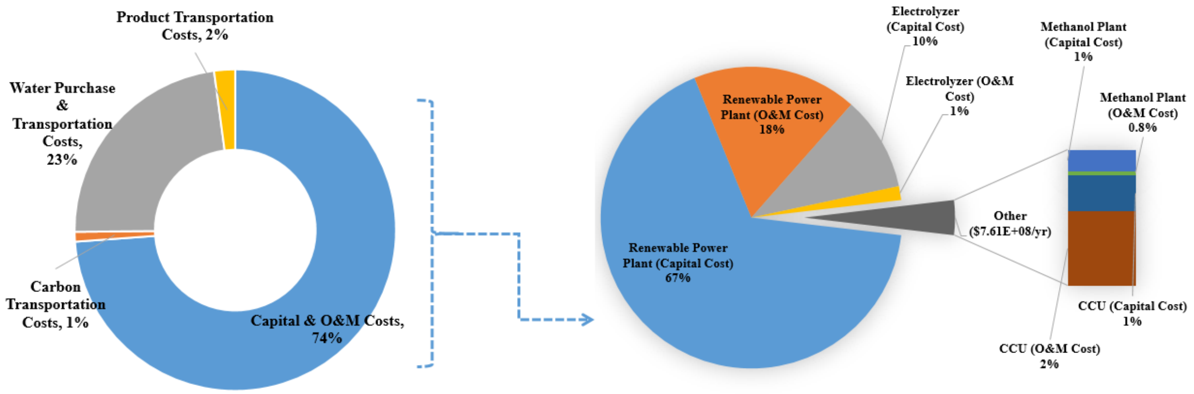
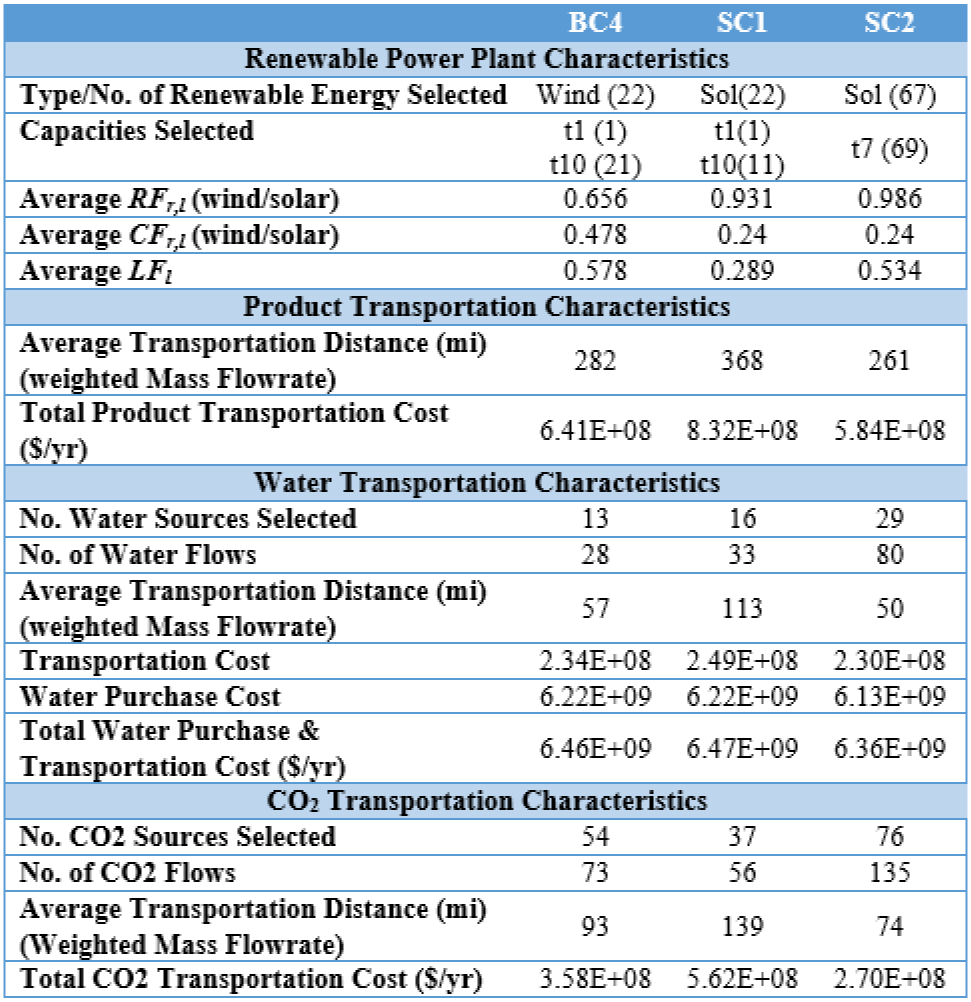


Figure 31. Cost Breakdown of Solar Case 2.

As expected, the portion of capital and operation cost of solar power plant is higher than the portion of wind power plant. The capital and operational costs of solar power plant is 63% of the total annualized cost, whereas it is 53% for wind power plants. In addition, the LCOE has increased from $30.59/GJ to $38.22/GJ by switching from wind to solar energy. The summary of plant selection and mass flows for Solar Case can be seen in the below table.

Table 25. Summary of plant selection and mass flows for Base Case, SC1, and SC2.



	BC4	SC1	SC2
Renewable Power Plant Characteristics			
Type/No. of Renewable Energy Selected	Wind (22)	Sol(22)	Sol (67)
Capacities Selected	t1 (1) t10 (21)	t1(1) t10(11)	t7 (69)
Average $RF_{r,l}$ (wind/solar)	0.656	0.931	0.986
Average $CF_{r,l}$ (wind/solar)	0.478	0.24	0.24
Average LF_l	0.578	0.289	0.534
Product Transportation Characteristics			
Average Transportation Distance (mi) (weighted Mass Flowrate)	282	368	261
Total Product Transportation Cost ($/yr)	6.41E+08	8.32E+08	5.84E+08
Water Transportation Characteristics			
No. Water Sources Selected	13	16	29
No. of Water Flows	28	33	80
Average Transportation Distance (mi) (weighted Mass Flowrate)	57	113	50
Transportation Cost	2.34E+08	2.49E+08	2.30E+08
Water Purchase Cost	6.22E+09	6.22E+09	6.13E+09
Total Water Purchase & Transportation Cost ($/yr)	6.46E+09	6.47E+09	6.36E+09
CO_2 Transportation Characteristics			
No. CO2 Sources Selected	54	37	76
No. of CO2 Flows	73	56	135
Average Transportation Distance (mi) (Weighted Mass Flowrate)	93	139	74
Total CO2 Transportation Cost ($/yr)	3.58E+08	5.62E+08	2.70E+08

Due to the limitation of solar power plant capacity for Solar Case 2, the number of solar power plants constructed between Solar Case 1 to Solar Case 2 has increased from 22 to 67 plants and the LCOE has increased from $37.41/GJ to $38.22/GJ. Such minor increase of LCOE indicates that economy of scale is not reflected in the model and the production cost increases in a linear manner with increase in capacity. Additionally, as already observed in Base Case 4.b with distributed and decentralized systems, decrease of average transportation distance and transportation costs were observed in Solar Case 1 to Solar Case 2. The following maps graphically show the selected candidate locations for Solar Case 1 and Solar Case 2.

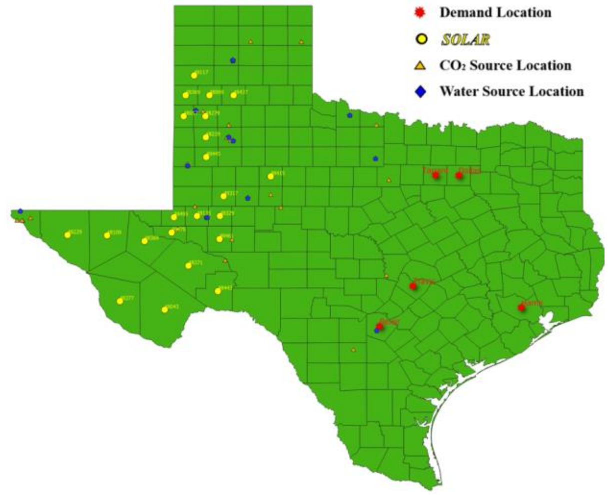


Figure 32. Selected candidate locations for Solar Case 1.

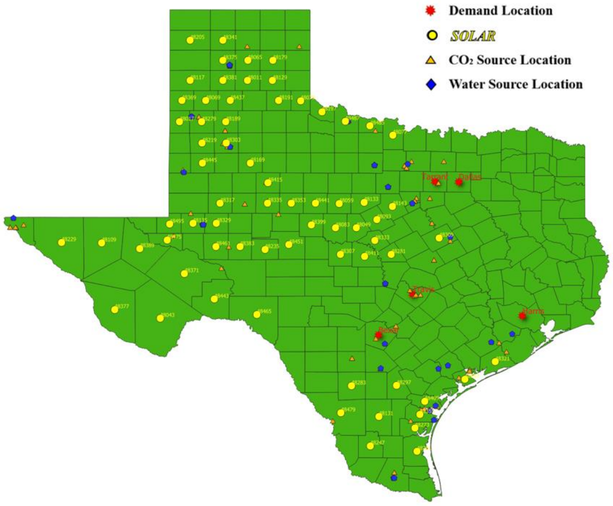


Figure 33. Selected candidate locations for Solar Case 2.

Comparing the selected candidate locations for wind (*Figure 26*) and solar (*Figure 32*), East regions where high solar energy potential are present are selected over North regions where wind energy potentials are strong. Between Solar Case 1 and 2, North and South regions are additionally selected to meet the production demands but limited maximum production capacity.

5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

This methanol supply chain network optimization study using renewable production technologies to meet the energy demands in Texas demonstrates that the production of renewable energy generated methanol is feasible with a Levelied Cost of Energy (LCOE) of $29.58/GJ to $30.92/GJ without the sale of oxygen gas. The LCOE for renewable energy generated methanol can decrease to roughly $26/GJ considering the sale of oxygen gas with a 50% discount of the current market price. The supply chain model selected wind power plants over solar power plants. As a result, regions with high wind energy potentials in North of Texas were predominantly selected over other regions for base case analysis. The LCOE for solar energy generated methanol was estimated as a case study and described in section 4.3. A LCOE of roughly $38/GJ was obtained without the sale of oxygen for solar energy based methanol production.

Construction and operation costs of renewable power plants account for the largest share of the overall production cost of renewable energy generated methanol followed by the costs of the electrolyzer system; renewable power plant and electrolyzer system are responsible for 53% and 10% of the total annualized cost, respectively.

As large volumes of water is required for renewable production technologies that use water electrolysis, water can act as a constraining resource for renewable energy generated methanol and can significantly influence the LCOE. The sensitivity study of water purchase price in section 4.2 shows that water is a geographically depended resource and can also fluctuate with seasonal availability. As a result, a reliable estimation of water purchase price is crucial in order to obtain rational results from a model based supply chain network analysis.

When compared to other conventional forms of energy, the LCOE values for renewable energy generated methanol is approximately more than double the LCOE of conventional technologies. Based on reports by EIA, the LCOE for new generation sources entering the energy market by 2022 is \$48.80/MWh (\$13.56/GJ) for conventional combined-cycle in 2017 USD currency.[47] However, such results also verify that the renewable energy generated methanol are within a reasonable range of production cost and proves that the utilization of energy carriers can be an option for stranded forms of renewable energy sources. In addition, the overall cost breakdown indicates that the largest cost contributor is the renewable power plant (53% of total annualized cost) which production cost is projected to decrease in the future. Such projections in renewable energy conversion technology advancement and respective cost decrease will allow methanol and other forms of energy carriers to be more price competitive at locations with high energy potentials but vastly isolated regions.

5.2 Future Work

In this supply chain network optimization study using renewable production technologies to meet the energy demands in Texas, only methanol was considered as an energy carrier. Future work could be conducted to compare the cost of implementing compressed or liquefied hydrogen as energy carriers to meet the energy demands of Texas.

However, one thing to note from this methanol supply chain network study is that the cost of energy carrier production (excluding cost of renewable energy power plants) was only 14% of the total annualized cost; of the 14%, 90% was from the electrolyzer system costs and 10% was from methanol production and carbon capture costs. Such cost breakdown displays that the cost of methanol production is a very small portion of the total annualized cost. This cost of methanol production should be compared with the additional cost required to implement a hydrogen system into the current energy system, which should consider the cost of storage, transportation, and conversion of hydrogen to energy.

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APPENDIX A

NOMENCLATURE

INDICES	
l	Location index
p	Production index
t	Capacity index
r	Renewable index
d	Demand location index
m	Transportation mode index
c	Feed source index

SET	
L^F	Candidate facility locations (254 counties of Texas)
R	Renewable energy
P	Products
P^{MeOH}	Methanol
T	Facility capacities (ton/day)
M	Transportation for production
DL	Demand Locations (counties) in TX
SL	Seat Locations (counties) in TX with railroad
CL	Source locations of CO_2 for Methanol
WL	Water locations
PD_l	Population Density per county (people/km2)

PARAMETERS		
N	-	Maximum number of facilities selected in Texas
N_t^{max}	-	Maximum number of facility of capacity t selected in Texas

N_t^{min}	-	Minimum number of facility of capacity t selected in Texas
yr	-	Number of operation years
i	-	Interest rate over the facility operation lifespan for financing (Used for Present value of annuity factor calculation)
TEC	GJ/yr	Total Electricity Consumption in demand locations in Texas per year
$AF_{i,yr}$	yr	Present value of annuity factor

Renewable Power Plant		
$RC_{r,t}$	$/MW	Renewable plant investment unit Cost for renewable technology r (excluding land acquisition cost)
LR_r	$/MW	Land cost of Renewable plant r
$RF_{r,l}$	-	Renewable energy scaling Factor for technology r at location l
LF_l	-	Land price scaling Factor at location l
ROM_r	$/kW/yr	Renewable plant Operation & Maintenance cost for renewable technology r
$CF_{r,l}$	-	Capacity Factor of renewable energy at location l
$ER_{p,t}$	MW	Electricity Required to produce production p of capacity t
Electrolyzer System		
$EC_{p,t}$	$/MW	Electrolyze Cost to produce production p of capacity t
$EOM_{p,t}$	$/MW/yr	Electrolyze Operation & Maintenance cost to produce product p of capacity t
$HO_{p,t}$	kg/hr	Hydrogen Output to produce production p of capacity t
SP_{O_2}	$/kg	Selling price of O_2
$O2Discount$		Discount rate of oxygen sales (units percentage) ->0.5
$OO_{p,t}$	kg/hr	Oxygen Output to produce production p of capacity t

Chemical Production Plant		
$PC_{p,t}$	$/(kg/hr)	Chemical Production plant investment Cost for capacity t
$POM_{p,t}$	$/(kg/hr)	Chemical Production plant Operation & Maintenance cost for capacity t
$PR_{p,t}$	kg/hr	amount of Product p produced from plant capacity t
Feed Source (C^C) Requirement		
$CC_{p,t}$	$/(kg/hr)	CO_2 capture investment Cost to produce product p of capacity t
$COM_{p,t}$	$/(kg/hr)/yr	CO_2 Capture plant Operation & Maintenance cost to produce product p of capacity t
$FC_{p,t}$	kg/hr	Feedstock 90% CO_2 input required to produce product p of capacity t
CA_{cl}	kg/hr	CO_2 Available at location cdl
$Cost^{CP}_{cl}$	$/kg	CO_2 purchase cost (0 or negative-incentives)
Water Requirement		
$FW_{p,t}$	kg/hr	Feed Water required to produce p of capacity t
WA_{wl}	kg/hr	Water Available at location wl
$Cost^{WP}_{wl}$	$/kg	Water Purchase cost
Transportation		
$DI^{L^F}_{l,dl,m}$	mi	Distance between facility location l and demand location dl via transportation m
$DI^{L^F \in s(l)}_{sl,l,m}$	mi	Distance between county seat sl and county centroid l (applicable only for transportation railroad)
$DI^{W}_{wl,l}$	mi	Distance between water source location wl and candidate

		location l
$DI^{C}_{cl,l}$	mi	Distance between CO_2 source location cl and candidate location l
	For Water transportation via pipeline	
DM	-	Distance factor
DFC^{W}	\$/kg	Distance Fixed Cost for water
DVC^{W}	\$/ kg/mi	Distance Variable Cost for water
D^{max}_{wl}	mi	Maximum distance from water source, wl to candidate location l for transportation via pipeline
	For CO_2 transportation via pipeline	
D^{max}_{cl}	mi	Maximum distance from feed source cl to candidate location l for transportation via pipeline
	For production transportation via transportation m	
$TMC_{p,m}$	\$	Total Cost of establishing transportation m of product p
FP_{m}	\$/L	Fuel Price
FE_{m}	Kg-km/L	Fuel Efficiency
$TCap_{p,m}$	kg	Capacity of Transportation
DW_{m}	\$/hr	Driver's wage
SP_{m}	km/hr	Average Speed of transportation
LUT_{m}	hr	Load/unload time
ME_{m}	\$/km	Maintenance expenses
GE_{m}	\$/day	General expenses (insurance, license & registration, outstanding finances)
TMA_{m}	hr/day	Availability of transportation

Demand		
$DR_{p,d}$	kg/hr	Demand of production p at d to meet TEC
$DemandFrac$	%	Fraction of total demand being met

x	MJ/kg	Lower Heating Value of product p
CONTINUOUS VARIABLE		
CR_l	kg/hr	CO_2 required at location l
$cd_{cl,l}$	kg/hr	CO_2 flow from location cdl to l
WR_l	kg/hr	Water Required at location l
$w_{wl,l}$	kg/hr	Water flow from location wl to l
$z_{p,l,dl,m}$	kg/hr	Flow of product p from location l to demand location d using transportation m
$z_{H_2,l}$	kg/hr	Flow of H_2 Produced at location l
$z_{O_2,l}$	kg/hr	Flow of O_2 produced at location l
$Cost_l^I$	\$/GJ	levelized capital Investment cost at location l
$Cost_l^{OM}$	\$/GJ	levelized Operation and Maintenance cost at location l
$Sales_l^{O_2}$	\$/GJ	Levelized cost of O_2 sales
$Cost_{cl,l}^{CT}$	\$/yr	Cost of CO_2 transportation by pipeline from cl to l
$Cost_{wl,l}^{WT}$	\$/yr	Cost of water transportation by pipeline from wl to l
TCC	\$	Transportation Capital Cost for all productions
TOC	\$/day	Transportation Operating Cost for all productions
NTU	-	Number of Transportation Unit
$FuelC$	\$/day	Fuel Cost
$LaborC$	\$/day	Labor Cost
$MaintC$	\$/day	Maintenance Cost
$GenC$	\$/day	General Cost

BINARY VARIABLE		
$y_{r,p,t,dl}$	-	Renewable plant r with chemical plant capacity of t is built at location l

APPENDIX B

LIST OF RENEWABLE ENERGY DATA

Table B.1 Solar[28] and Wind Energy Potentials[30] and corresponding renewable scaling factors ($RF_{r,l}$) and capacity factors ($CF_{r,l}$).

County	**FIPS**	**Solar Energy Potential (kWh/m^2/day)**	***RF* *('Sol', l)***	***CF* *('Sol', l)***	**Wind Energy Potential (m/s)**	***RF* *('Wind', l)***	***CF* *('Wind', l)***
Anderson	48001	4.622	1.106	0.240	6.595	1.329	0.371
Andrews	48003	5.504	0.928	0.240	7.554	0.884	0.388
Angelina	48005	4.582	1.115	0.240	6.400	1.454	0.352
Aransas	48007	4.836	1.057	0.240	7.212	1.016	0.377
Archer	48009	4.953	1.032	0.240	7.986	0.748	0.453
Armstrong	48011	5.180	0.987	0.240	7.872	0.781	0.413
Atascosa	48013	4.823	1.060	0.240	7.380	0.948	0.450
Austin	48015	4.655	1.098	0.240	7.000	1.111	0.410
Bailey	48017	5.413	0.944	0.240	7.809	0.800	0.407
Bandera	48019	4.756	1.074	0.240	7.336	0.965	0.419
Bastrop	48021	4.704	1.086	0.240	7.260	0.996	0.434
Baylor	48023	5.016	1.019	0.240	7.575	0.877	0.415
Bee	48025	4.746	1.077	0.240	7.075	1.076	0.391
Bell	48027	4.758	1.074	0.240	7.264	0.994	0.436
Bexar	48029	4.746	1.077	0.240	6.559	1.350	0.361
Blanco	48031	4.810	1.062	0.240	7.417	0.934	0.436
Borden	48033	5.318	0.961	0.240	7.800	0.803	0.413
Bosque	48035	4.803	1.064	0.240	7.402	0.940	0.435
Bowie	48037	4.528	1.129	0.240	6.450	1.420	0.356
Brazoria	48039	4.663	1.096	0.240	6.748	1.240	0.382
Brazos	48041	4.659	1.097	0.240	6.630	1.308	0.374
Brewster	48043	5.726	0.892	0.240	6.545	1.359	0.308
Briscoe	48045	5.187	0.985	0.240	8.250	0.679	0.425
Brooks	48047	4.914	1.040	0.240	7.170	1.034	0.424
Brown	48049	5.008	1.020	0.240	8.340	0.657	0.527

Burleson	48051	4.686	1.090	0.240	7.140	1.047	0.426
Burnet	48053	4.847	1.054	0.240	7.615	0.863	0.447
Caldwell	48055	4.724	1.082	0.240	6.890	1.165	0.393
Calhoun	48057	4.804	1.064	0.240	7.052	1.086	0.357
Callahan	48059	5.047	1.013	0.240	8.066	0.726	0.472
Cameron	48061	4.920	1.039	0.240	7.556	0.884	0.414
Camp	48063	4.583	1.115	0.240	6.670	1.284	0.380
Carson	48065	5.180	0.986	0.240	8.616	0.596	0.489
Cass	48067	4.554	1.122	0.240	6.960	1.130	0.405
Castro	48069	5.344	0.956	0.240	8.355	0.653	0.460
Chambers	48071	4.681	1.092	0.240	6.698	1.268	0.361
Cherokee	48073	4.583	1.115	0.240	6.940	1.140	0.403
Childress	48075	5.074	1.007	0.240	7.695	0.836	0.418
Clay	48077	4.876	1.048	0.240	7.738	0.823	0.460
Cochran	48079	5.454	0.937	0.240	7.825	0.795	0.409
Coke	48081	5.200	0.983	0.240	7.499	0.904	0.411
Coleman	48083	5.058	1.010	0.240	7.897	0.774	0.485
Collin	48085	4.679	1.092	0.240	7.353	0.958	0.423
Collingsworth	48087	5.081	1.006	0.240	7.780	0.809	0.425
Colorado	48089	4.669	1.095	0.240	6.890	1.165	0.399
Comal	48091	4.712	1.084	0.240	7.155	1.040	0.411
Comanche	48093	4.953	1.032	0.240	8.116	0.713	0.513
Concho	48095	5.120	0.998	0.240	8.535	0.613	0.532
Cooke	48097	4.734	1.079	0.240	7.990	0.747	0.470
Coryell	48099	4.819	1.060	0.240	7.407	0.938	0.448
Cottle	48101	5.103	1.001	0.240	8.130	0.709	0.454
Crane	48103	5.531	0.924	0.240	8.390	0.645	0.462
Crockett	48105	5.274	0.969	0.240	8.026	0.737	0.440
Crosby	48107	5.266	0.970	0.240	8.471	0.627	0.441
Culberson	48109	5.706	0.895	0.240	7.801	0.803	0.373
Dallam	48111	5.293	0.965	0.240	8.222	0.686	0.442
Dallas	48113	4.704	1.086	0.240	7.277	0.989	0.460
Dawson	48115	5.400	0.946	0.240	7.930	0.764	0.423
Deaf Smith	48117	5.351	0.955	0.240	8.525	0.615	0.458

Delta	48119	4.595	1.112	0.240	6.920	1.150	0.401
Denton	48121	4.743	1.077	0.240	6.989	1.116	0.428
DeWitt	48123	4.720	1.083	0.240	7.080	1.074	0.419
Dickens	48125	5.206	0.981	0.240	8.455	0.630	0.439
Dimmit	48127	4.999	1.022	0.240	6.898	1.161	0.382
Donley	48129	5.140	0.994	0.240	8.117	0.712	0.436
Duval	48131	4.919	1.039	0.240	7.427	0.930	0.437
Eastland	48133	4.982	1.026	0.240	8.403	0.642	0.520
Ector	48135	5.517	0.926	0.240	8.048	0.731	0.427
Edwards	48137	4.995	1.023	0.240	8.250	0.679	0.504
Ellis	48139	4.717	1.083	0.240	5.921	1.836	0.287
El Paso	48141	5.829	0.877	0.240	7.582	0.874	0.462
Erath	48143	4.901	1.043	0.240	8.423	0.638	0.527
Falls	48145	4.719	1.083	0.240	7.280	0.988	0.440
Fannin	48147	4.610	1.108	0.240	8.140	0.707	0.467
Fayette	48149	4.695	1.088	0.240	7.080	1.074	0.418
Fisher	48151	5.189	0.985	0.240	8.470	0.627	0.481
Floyd	48153	5.254	0.973	0.240	8.542	0.611	0.433
Foard	48155	5.057	1.010	0.240	8.070	0.725	0.452
Fort Bend	48157	4.626	1.105	0.240	6.270	1.546	0.346
Franklin	48159	4.588	1.114	0.240	6.470	1.407	0.358
Freestone	48161	4.665	1.095	0.240	6.895	1.163	0.403
Frio	48163	4.874	1.048	0.240	6.480	1.401	0.345
Gaines	48165	5.465	0.935	0.240	7.493	0.906	0.398
Galveston	48167	4.747	1.076	0.240	6.687	1.274	0.363
Garza	48169	5.274	0.969	0.240	8.126	0.710	0.428
Gillespie	48171	4.885	1.046	0.240	8.291	0.669	0.487
Glasscock	48173	5.372	0.951	0.240	8.341	0.657	0.466
Goliad	48175	4.701	1.087	0.240	6.790	1.217	0.383
Gonzales	48177	4.728	1.081	0.240	7.340	0.964	0.444
Gray	48179	5.126	0.997	0.240	8.597	0.600	0.486
Grayson	48181	4.666	1.095	0.240	7.681	0.841	0.478
Gregg	48183	4.583	1.115	0.240	6.450	1.420	0.356
Grimes	48185	4.628	1.104	0.240	6.580	1.338	0.366

Guadalupe	48187	4.737	1.079	0.240	6.584	1.335	0.365
Hale	48189	5.315	0.961	0.240	8.083	0.722	0.440
Hall	48191	5.130	0.996	0.240	6.518	1.376	0.315
Hamilton	48193	4.886	1.046	0.240	6.965	1.128	0.391
Hansford	48195	5.148	0.993	0.240	8.271	0.673	0.462
Hardeman	48197	5.030	1.016	0.240	7.930	0.764	0.442
Hardin	48199	4.546	1.124	0.240	6.310	1.517	0.337
Harris	48201	4.580	1.116	0.240	6.049	1.722	0.328
Harrison	48203	4.571	1.118	0.240	6.080	1.696	0.316
Hartley	48205	5.323	0.960	0.240	8.247	0.680	0.448
Haskell	48207	5.109	1.000	0.240	7.620	0.861	0.416
Hays	48209	4.737	1.079	0.240	7.618	0.862	0.450
Hemphill	48211	5.045	1.013	0.240	8.336	0.658	0.465
Henderson	48213	4.652	1.098	0.240	6.860	1.180	0.398
Hidalgo	48215	4.997	1.023	0.240	7.013	1.105	0.405
Hill	48217	4.752	1.075	0.240	7.123	1.054	0.403
Hockley	48219	5.402	0.946	0.240	8.110	0.714	0.437
Hood	48221	4.843	1.055	0.240	8.040	0.733	0.456
Hopkins	48223	4.609	1.109	0.240	7.212	1.016	0.432
Houston	48225	4.601	1.111	0.240	6.620	1.314	0.374
Howard	48227	5.337	0.957	0.240	8.139	0.707	0.448
Hudspeth	48229	5.784	0.883	0.240	6.120	1.662	0.283
Hunt	48231	4.628	1.104	0.240	7.572	0.878	0.457
Hutchinson	48233	5.171	0.988	0.240	8.184	0.695	0.448
Irion	48235	5.244	0.974	0.240	6.999	1.112	0.376
Jack	48237	4.886	1.046	0.240	8.196	0.692	0.510
Jackson	48239	4.668	1.095	0.240	7.080	1.074	0.349
Jasper	48241	4.551	1.123	0.240	6.880	1.170	0.397
Jeff Davis	48243	5.632	0.907	0.240	6.820	1.201	0.324
Jefferson	48245	4.640	1.101	0.240	6.637	1.303	0.363
Jim Hogg	48247	5.019	1.018	0.240	7.196	1.023	0.417
Jim Wells	48249	4.821	1.060	0.240	6.960	1.130	0.402
Johnson	48251	4.795	1.066	0.240	8.120	0.712	0.464
Jones	48253	5.127	0.997	0.240	7.660	0.848	0.415

Karnes	48255	4.777	1.070	0.240	6.845	1.188	0.372
Kaufman	48257	4.674	1.093	0.240	7.123	1.055	0.424
Kendall	48259	4.764	1.073	0.240	8.173	0.698	0.459
Kenedy	48261	4.890	1.045	0.240	7.556	0.883	0.418
Kent	48263	5.214	0.980	0.240	8.024	0.738	0.434
Kerr	48265	4.853	1.053	0.240	7.898	0.773	0.471
Kimble	48267	5.019	1.018	0.240	8.223	0.685	0.513
King	48269	5.143	0.994	0.240	7.627	0.859	0.405
Kinney	48271	4.922	1.038	0.240	7.042	1.091	0.405
Kleberg	48273	4.880	1.047	0.240	7.252	0.999	0.420
Knox	48275	5.084	1.005	0.240	7.760	0.816	0.426
Lamar	48277	4.568	1.119	0.240	6.757	1.235	0.374
Lamb	48279	5.373	0.951	0.240	7.530	0.893	0.463
Lampasas	48281	4.892	1.045	0.240	8.240	0.681	0.447
La Salle	48283	4.940	1.034	0.240	7.529	0.893	0.450
Lavaca	48285	4.685	1.091	0.240	7.040	1.092	0.411
Lee	48287	4.703	1.087	0.240	7.150	1.043	0.425
Leon	48289	4.640	1.101	0.240	7.040	1.092	0.418
Liberty	48291	4.578	1.116	0.240	6.570	1.344	0.364
Limestone	48293	4.694	1.089	0.240	7.560	0.882	0.415
Lipscomb	48295	5.030	1.016	0.240	8.502	0.620	0.485
Live Oak	48297	4.819	1.060	0.240	7.035	1.094	0.403
Llano	48299	4.911	1.041	0.240	6.508	1.382	0.354
Loving	48301	5.626	0.908	0.240	6.860	1.180	0.366
Lubbock	48303	5.325	0.960	0.240	7.934	0.763	0.432
Lynn	48305	5.350	0.955	0.240	7.665	0.846	0.397
McCulloch	48307	5.055	1.011	0.240	6.720	1.256	0.384
McLennan	48309	4.747	1.077	0.240	6.460	1.414	0.352
McMullen	48311	4.897	1.043	0.240	7.613	0.864	0.396
Madison	48313	4.629	1.104	0.240	8.380	0.648	0.523
Marion	48315	4.573	1.117	0.240	7.220	1.013	0.364
Martin	48317	5.421	0.943	0.240	6.466	1.410	0.345
Mason	48319	4.987	1.025	0.240	8.500	0.621	0.525
Matagorda	48321	4.748	1.076	0.240	7.055	1.085	0.415

Maverick	48323	4.994	1.023	0.240	6.736	1.247	0.351
Medina	48325	4.779	1.069	0.240	7.050	1.088	0.386
Menard	48327	5.082	1.006	0.240	8.750	0.569	0.561
Midland	48329	5.453	0.937	0.240	8.080	0.722	0.442
Milam	48331	4.721	1.082	0.240	7.070	1.078	0.418
Mills	48333	4.958	1.031	0.240	7.804	0.802	0.476
Mitchell	48335	5.267	0.970	0.240	8.165	0.700	0.456
Montague	48337	4.805	1.063	0.240	7.695	0.836	0.449
Montgomery	48339	4.574	1.117	0.240	6.470	1.407	0.354
Moore	48341	5.216	0.980	0.240	8.186	0.695	0.445
Morris	48343	4.567	1.119	0.240	6.980	1.121	0.407
Motley	48345	5.170	0.988	0.240	8.265	0.675	0.426
Nacogdoches	48347	4.571	1.118	0.240	6.930	1.145	0.402
Navarro	48349	4.699	1.088	0.240	6.983	1.119	0.418
Newton	48351	4.542	1.125	0.240	6.840	1.191	0.393
Nolan	48353	5.189	0.985	0.240	8.488	0.623	0.480
Nueces	48355	4.847	1.054	0.240	7.143	1.046	0.414
Ochiltree	48357	5.099	1.002	0.240	8.424	0.637	0.478
Oldham	48359	5.335	0.958	0.240	8.606	0.598	0.446
Orange	48361	4.563	1.120	0.240	6.560	1.350	0.354
Palo Pinto	48363	4.885	1.046	0.240	7.820	0.797	0.487
Panola	48365	4.566	1.119	0.240	6.460	1.414	0.354
Parker	48367	4.846	1.054	0.240	7.815	0.798	0.469
Parmer	48369	5.406	0.945	0.240	8.348	0.655	0.458
Pecos	48371	5.559	0.919	0.240	8.387	0.646	0.454
Polk	48373	4.578	1.116	0.240	6.540	1.362	0.366
Potter	48375	5.237	0.976	0.240	8.430	0.636	0.462
Presidio	48377	5.782	0.884	0.240	6.287	1.534	0.293
Rains	48379	4.612	1.108	0.240	7.180	1.030	0.430
Randall	48381	5.256	0.972	0.240	8.333	0.659	0.456
Reagan	48383	5.366	0.952	0.240	8.276	0.672	0.447
Real	48385	4.875	1.048	0.240	8.152	0.703	0.491
Red River	48387	4.535	1.127	0.240	6.430	1.433	0.352
Reeves	48389	5.607	0.911	0.240	6.212	1.590	0.305

Refugio	48391	4.726	1.081	0.240	6.875	1.173	0.331
Roberts	48393	5.116	0.999	0.240	8.597	0.600	0.485
Robertson	48395	4.687	1.090	0.240	7.060	1.083	0.418
Rockwall	48397	4.655	1.098	0.240	7.670	0.845	0.424
Runnels	48399	5.123	0.997	0.240	7.365	0.954	0.423
Rusk	48401	4.573	1.118	0.240	6.820	1.201	0.391
Sabine	48403	4.582	1.115	0.240	6.690	1.273	0.376
San Augustine	48405	4.588	1.114	0.240	6.610	1.320	0.369
San Jacinto	48407	4.585	1.115	0.240	6.370	1.474	0.347
San Patricio	48409	4.793	1.066	0.240	7.187	1.027	0.394
San Saba	48411	4.965	1.029	0.240	7.950	0.758	0.494
Schleicher	48413	5.150	0.992	0.240	8.163	0.701	0.499
Scurry	48415	5.261	0.971	0.240	8.141	0.706	0.447
Shackelford	48417	5.047	1.013	0.240	8.200	0.691	0.474
Shelby	48419	4.570	1.118	0.240	6.410	1.447	0.351
Sherman	48421	5.193	0.984	0.240	8.342	0.656	0.465
Smith	48423	4.608	1.109	0.240	7.260	0.996	0.436
Somervell	48425	4.831	1.058	0.240	8.400	0.643	0.527
Starr	48427	5.100	1.002	0.240	7.101	1.064	0.396
Stephens	48429	4.969	1.028	0.240	7.536	0.890	0.456
Sterling	48431	5.300	0.964	0.240	7.512	0.899	0.396
Stonewall	48433	5.163	0.990	0.240	7.635	0.856	0.410
Sutton	48435	5.114	0.999	0.240	7.570	0.878	0.457
Swisher	48437	5.275	0.969	0.240	8.138	0.707	0.445
Tarrant	48439	4.782	1.069	0.240	7.551	0.885	0.470
Taylor	48441	5.103	1.001	0.240	8.527	0.615	0.486
Terrell	48443	5.454	0.937	0.240	7.102	1.064	0.376
Terry	48445	5.429	0.941	0.240	7.327	0.969	0.377
Throckmorton	48447	5.034	1.015	0.240	7.489	0.907	0.423
Titus	48449	4.573	1.117	0.240	6.670	1.284	0.376
Tom Green	48451	5.188	0.985	0.240	7.971	0.753	0.464
Travis	48453	4.748	1.076	0.240	6.709	1.262	0.385
Trinity	48455	4.589	1.114	0.240	5.940	1.818	0.297
Tyler	48457	4.559	1.121	0.240	6.630	1.308	0.375

Upshur	48459	4.596	1.112	0.240	7.070	1.078	0.415
Upton	48461	5.479	0.933	0.240	8.230	0.684	0.431
Uvalde	48463	4.852	1.053	0.240	7.270	0.992	0.406
Val Verde	48465	5.164	0.989	0.240	7.632	0.857	0.433
Van Zandt	48467	4.641	1.101	0.240	7.067	1.080	0.420
Victoria	48469	4.672	1.094	0.240	6.545	1.359	0.358
Walker	48471	4.596	1.112	0.240	6.430	1.433	0.354
Waller	48473	4.633	1.103	0.240	6.570	1.344	0.369
Ward	48475	5.587	0.915	0.240	7.170	1.034	0.358
Washington	48477	4.672	1.094	0.240	6.647	1.298	0.371
Webb	48479	5.055	1.011	0.240	7.170	1.034	0.396
Wharton	48481	4.652	1.098	0.240	6.643	1.300	0.370
Wheeler	48483	5.068	1.008	0.240	8.409	0.641	0.476
Wichita	48485	4.934	1.036	0.240	7.660	0.848	0.423
Wilbarger	48487	4.993	1.023	0.240	7.788	0.807	0.433
Willacy	48489	4.907	1.041	0.240	7.480	0.910	0.405
Williamson	48491	4.758	1.074	0.240	7.315	0.973	0.448
Wilson	48493	4.776	1.070	0.240	6.661	1.289	0.368
Winkler	48495	5.575	0.917	0.240	8.130	0.709	0.434
Wise	48497	4.814	1.062	0.240	7.408	0.937	0.449
Wood	48499	4.608	1.109	0.240	7.030	1.097	0.413
Yoakum	48501	5.480	0.933	0.240	7.820	0.797	0.406
Young	48503	4.957	1.031	0.240	8.032	0.735	0.479
Zapata	48505	5.117	0.999	0.240	7.656	0.849	0.430
Zavala	48507	4.937	1.035	0.240	6.970	1.125	0.399

APPENDIX C

LIST OF LAND AVAILABILITY

Table C.1 Rural land price (\$/acre)[33] and population density of 2017 per county and the corresponding land price scaling factors (LF_l) and Population Density factors (PD_l).

Name	**FIPS**	**Cost (\$/acre)**	LF_l	**Population Estimation**	**Land Area (km^2)**	PD_l **(people/km^2)**
Anderson	48001	3269	1.024	57,734	2,752	20.98
Andrews	48003	995	0.312	17,760	3,887	4.57
Angelina	48005	3100	0.971	87,791	2,066	42.49
Aransas	48007	3327	1.043	25,721	653	39.39
Archer	48009	1650	0.517	8,703	2,339	3.72
Armstrong	48011	1051	0.329	1,876	2,355	0.80
Atascosa	48013	5523	1.731	48,797	3,158	15.45
Austin	48015	6481	2.031	29,758	1,674	17.77
Bailey	48017	995	0.312	7,181	2,141	3.35
Bandera	48019	8765	2.747	21,776	2,049	10.63
Bastrop	48021	5544	1.737	82,733	2,300	35.96
Baylor	48023	1650	0.517	3,697	2,247	1.65
Bee	48025	3327	1.043	32,750	2,280	14.37
Bell	48027	3172	0.994	340,411	2,722	125.06
Bexar	48029	5523	1.731	1,928,680	3,211	600.64
Blanco	48031	8765	2.747	11,392	1,837	6.20
Borden	48033	1200	0.376	633	2,324	0.27
Bosque	48035	3172	0.994	18,097	2,546	7.11
Bowie	48037	2850	0.893	93,860	2,292	40.95
Brazoria	48039	6481	2.031	354,195	3,516	100.73
Brazos	48041	6020	1.886	220,417	1,516	145.35
Brewster	48043	690	0.216	9,200	16,016	0.57
Briscoe	48045	1051	0.329	1,474	2,331	0.63
Brooks	48047	2181	0.683	7,214	2,443	2.95
Brown	48049	2700	0.846	38,271	2,446	15.65
Burleson	48051	6020	1.886	17,760	1,707	10.41
Burnet	48053	6484	2.032	46,243	2,575	17.96
Caldwell	48055	5544	1.737	41,161	1,412	29.14
Calhoun	48057	3600	1.128	21,965	1,313	16.73
Callahan	48059	2700	0.846	13,820	2,329	5.93

Cameron	48061	4638	1.453	422,135	2,307	182.95
Camp	48063	2850	0.893	12,867	507	25.37
Carson	48065	1051	0.329	6,057	2,383	2.54
Cass	48067	2850	0.893	30,375	2,427	12.52
Castro	48069	1051	0.329	7,669	2,316	3.31
Chambers	48071	6481	2.031	39,899	1,546	25.80
Cherokee	48073	3269	1.024	51,668	2,727	18.95
Childress	48075	1000	0.313	7,052	1,804	3.91
Clay	48077	1650	0.517	10,193	2,820	3.61
Cochran	48079	995	0.312	2,882	2,008	1.44
Coke	48081	1641	0.514	3,264	2,361	1.38
Coleman	48083	2700	0.846	8,420	3,269	2.58
Collin	48085	4707	1.475	939,585	2,179	431.26
Collingsworth	48087	1000	0.313	3,016	2,379	1.27
Colorado	48089	6306	1.976	21,019	2,487	8.45
Comal	48091	5523	1.731	134,788	1,449	93.02
Comanche	48093	2700	0.846	13,484	2,429	5.55
Concho	48095	1641	0.514	4,279	2,548	1.68
Cooke	48097	4526	1.418	39,266	2,266	17.33
Coryell	48099	3172	0.994	74,686	2,725	27.41
Cottle	48101	1000	0.313	1,402	2,333	0.60
Crane	48103	690	0.216	4,830	2,033	2.38
Crockett	48105	1641	0.514	3,675	7,271	0.51
Crosby	48107	1200	0.376	5,992	2,331	2.57
Culberson	48109	690	0.216	2,198	9,875	0.22
Dallam	48111	1753	0.549	7,056	3,894	1.81
Dallas	48113	4707	1.475	2,574,984	2,257	1,141.07
Dawson	48115	1200	0.376	13,111	2,332	5.62
Deaf Smith	48117	1051	0.329	5,215	665	7.84
Delta	48119	2850	0.893	806,180	2,275	354.36
Denton	48121	4707	1.475	20,865	2,354	8.86
DeWitt	48123	6306	1.976	18,830	3,877	4.86
Dickens	48125	1000	0.313	2,184	2,335	0.94
Dimmit	48127	2181	0.683	10,794	3,442	3.14
Donley	48129	1000	0.313	3,405	2,401	1.42
Duval	48131	2181	0.683	11,428	4,645	2.46
Eastland	48133	2700	0.846	18,274	2,400	7.62
Ector	48135	995	0.312	157,462	2,325	67.72
Edwards	48137	1641	0.514	1,911	5,485	0.35

Ellis	48139	4707	1.475	168,499	2,423	69.54
El Paso	48141	11979.5	3.754	837,918	2,623	319.47
Erath	48143	2700	0.846	41,659	2,805	14.85
Falls	48145	3172	0.994	17,273	1,983	8.71
Fannin	48147	4526	1.418	34,031	2,307	14.75
Fayette	48149	6306	1.976	25,149	2,460	10.22
Fisher	48151	1279	0.401	3,854	2,328	1.66
Floyd	48153	1200	0.376	5,917	2,570	2.30
Foard	48155	1650	0.517	1,183	1,824	0.65
Fort Bend	48157	6481	2.031	741,237	2,231	332.21
Franklin	48159	2850	0.893	10,607	737	14.40
Freestone	48161	3172	0.994	19,624	2,273	8.63
Frio	48163	3929	1.231	18,956	2,936	6.46
Gaines	48165	995	0.312	20,478	3,891	5.26
Galveston	48167	6481	2.031	329,431	980	336.14
Garza	48169	1200	0.376	6,442	2,314	2.78
Gillespie	48171	6484	2.032	26,521	2,741	9.68
Glasscock	48173	1641	0.514	1,314	2,331	0.56
Goliad	48175	3327	1.043	7,517	2,207	3.41
Gonzales	48177	6306	1.976	20,876	2,763	7.56
Gray	48179	1051	0.329	22,725	2,398	9.48
Grayson	48181	4526	1.418	128,235	2,416	53.08
Gregg	48183	3269	1.024	123,745	708	174.82
Grimes	48185	6020	1.886	27,671	2,040	13.57
Guadalupe	48187	5523	1.731	155,265	1,842	84.28
Hale	48189	1200	0.376	34,263	2,602	13.17
Hall	48191	1000	0.313	3,138	2,288	1.37
Hamilton	48193	3182	0.997	8,304	2,165	3.84
Hansford	48195	1753	0.549	5,538	2,382	2.32
Hardeman	48197	1650	0.517	3,906	1,800	2.17
Hardin	48199	6481	2.031	56,322	2,307	24.42
Harris	48201	6481	2.031	4,589,928	4,412	1,040.32
Harrison	48203	3269	1.024	66,534	2,331	28.54
Hartley	48205	1753	0.549	5,747	3,787	1.52
Haskell	48207	1650	0.517	5,681	2,339	2.43
Hays	48209	5544	1.737	204,470	1,756	116.44
Hemphill	48211	1192	0.374	4,129	2,347	1.76
Henderson	48213	3269	1.024	79,901	2,263	35.31
Hidalgo	48215	4638	1.453	849,843	4,069	208.88

Hill	48217	3172	0.994	35,077	2,484	14.12
Hockley	48219	995	0.312	23,275	2,353	9.89
Hood	48221	6593	2.066	56,857	1,089	52.19
Hopkins	48223	2850	0.893	36,400	1,987	18.32
Houston	48225	3269	1.024	22,754	3,188	7.14
Howard	48227	995	0.312	36,708	2,333	15.73
Hudspeth	48229	690	0.216	4,053	11,839	0.34
Hunt	48231	4707	1.475	92,073	2,176	42.31
Hutchinson	48233	1192	0.374	21,511	2,298	9.36
Irion	48235	1641	0.514	1,557	2,724	0.57
Jack	48237	1650	0.517	8,744	2,359	3.71
Jackson	48239	3600	1.128	14,869	2,148	6.92
Jasper	48241	3100	0.971	35,648	2,432	14.66
Jeff Davis	48243	690	0.216	2,200	5,865	0.38
Jefferson	48245	6481	2.031	254,679	2,270	112.21
Jim Hogg	48247	2181	0.683	5,146	2,942	1.75
Jim Wells	48249	3327	1.043	41,149	2,240	18.37
Johnson	48251	6593	2.066	163,274	1,877	86.99
Jones	48253	1279	0.401	20,009	2,405	8.32
Karnes	48255	5523	1.731	15,254	1,936	7.88
Kaufman	48257	4707	1.475	118,350	2,022	58.53
Kendall	48259	8765	2.747	42,540	1,716	24.79
Kenedy	48261	2181	0.683	404	3,777	0.11
Kent	48263	1000	0.313	769	2,337	0.33
Kerr	48265	8765	2.747	51,504	2,858	18.02
Kimble	48267	3290	1.031	4,423	3,240	1.37
King	48269	1000	0.313	289	2,359	0.12
Kinney	48271	1641	0.514	3,590	3,523	1.02
Kleberg	48273	3327	1.043	31,690	2,283	13.88
Knox	48275	1650	0.517	3,806	2,203	1.73
Lamar	48277	2850	0.893	49,791	2,350	21.19
Lamb	48279	995	0.312	13,275	2,632	5.04
Lampasas	48281	3182	0.997	20,760	1,846	11.25
La Salle	48283	2181	0.683	7,613	3,851	1.98
Lavaca	48285	6306	1.976	19,809	2,511	7.89
Lee	48287	5544	1.737	17,055	1,629	10.47
Leon	48289	6020	1.886	17,299	2,780	6.22
Liberty	48291	6481	2.031	81,704	3,000	27.23
Limestone	48293	3172	0.994	23,468	2,345	10.01

Lipscomb	48295	1192	0.374	3,487	2,414	1.44
Live Oak	48297	3327	1.043	12,056	2,693	4.48
Llano	48299	6484	2.032	20,362	2,419	8.42
Loving	48301	690	0.216	113	1,732	0.07
Lubbock	48303	1200	0.376	303,137	2,320	130.69
Lynn	48305	1200	0.376	5,711	2,310	2.47
McCulloch	48307	3182	0.997	8,172	2,760	2.96
McLennan	48309	3172	0.994	247,934	2,686	92.30
McMullen	48311	2181	0.683	804	2,951	0.27
Madison	48313	6020	1.886	13,987	1,207	11.59
Marion	48315	2850	0.893	10,147	987	10.29
Martin	48317	995	0.312	5,723	2,370	2.42
Mason	48319	6484	2.032	4,111	2,406	1.71
Matagorda	48321	3600	1.128	37,187	2,850	13.05
Maverick	48323	3929	1.231	57,685	3,313	17.41
Medina	48325	3929	1.231	49,283	3,433	14.36
Menard	48327	3290	1.031	2,123	2,336	0.91
Midland	48329	995	0.312	162,565	2,332	69.72
Milam	48331	5544	1.737	24,871	2,634	9.44
Mills	48333	3182	0.997	4,907	1,938	2.53
Mitchell	48335	1279	0.401	8,720	2,360	3.70
Montague	48337	4526	1.418	19,414	2,411	8.05
Montgomery	48339	6481	2.031	556,203	2,698	206.16
Moore	48341	1753	0.549	22,120	2,330	9.49
Morris	48343	2850	0.893	12,593	653	19.29
Motley	48345	1000	0.313	1,160	2,563	0.45
Nacogdoches	48347	3269	1.024	65,806	2,451	26.84
Navarro	48349	3172	0.994	48,523	2,615	18.56
Newton	48351	3100	0.971	14,003	2,418	5.79
Nolan	48353	1279	0.401	14,993	2,362	6.35
Nueces	48355	3327	1.043	361,350	2,172	166.39
Ochiltree	48357	1753	0.549	10,306	2,377	4.34
Oldham	48359	1192	0.374	2,076	3,886	0.53
Orange	48361	6481	2.031	84,964	864	98.31
Palo Pinto	48363	6593	2.066	28,053	2,465	11.38
Panola	48365	3269	1.024	23,492	2,077	11.31
Parker	48367	6593	2.066	129,441	2,340	55.32
Parmer	48369	1051	0.329	9,776	2,281	4.29
Pecos	48371	690	0.216	15,970	12,338	1.29

Polk	48373	3100	0.971	47,916	2,738	17.50
Potter	48375	1192	0.374	120,832	2,353	51.36
Presidio	48377	690	0.216	6,958	9,985	0.70
Rains	48379	4707	1.475	11,314	594	19.03
Randall	48381	1051	0.329	132,501	2,361	56.13
Reagan	48383	1641	0.514	3,608	3,044	1.19
Real	48385	3290	1.031	3,389	1,811	1.87
Red River	48387	2850	0.893	12,207	2,685	4.55
Reeves	48389	690	0.216	14,921	6,826	2.19
Refugio	48391	3327	1.043	7,321	1,995	3.67
Roberts	48393	1192	0.374	916	2,393	0.38
Robertson	48395	6020	1.886	16,751	2,216	7.56
Rockwall	48397	4707	1.475	93,978	329	285.71
Runnels	48399	1279	0.401	10,448	2,722	3.84
Rusk	48401	3269	1.024	52,732	2,393	22.03
Sabine	48403	3100	0.971	10,303	1,273	8.10
San Augustine	48405	3100	0.971	8,320	1,374	6.05
San Jacinto	48407	6481	2.031	27,707	1,474	18.79
San Patricio	48409	3327	1.043	67,655	1,796	37.67
San Saba	48411	3182	0.997	5,944	2,940	2.02
Schleicher	48413	1641	0.514	3,056	3,394	0.90
Scurry	48415	1279	0.401	17,333	2,345	7.39
Shackelford	48417	1650	0.517	3,315	2,368	1.40
Shelby	48419	3269	1.024	25,579	2,061	12.41
Sherman	48421	1753	0.549	3,068	2,391	1.28
Smith	48423	3269	1.024	225,290	2,387	94.40
Somervell	48425	6593	2.066	8,775	483	18.17
Starr	48427	2181	0.683	64,122	3,168	20.24
Stephens	48429	1650	0.517	9,906	2,322	4.27
Sterling	48431	1641	0.514	1,367	2,392	0.57
Stonewall	48433	1000	0.313	1,426	2,373	0.60
Sutton	48435	1641	0.514	3,869	3,766	1.03
Swisher	48437	1051	0.329	7,466	2,306	3.24
Tarrant	48439	6593	2.066	2,016,872	2,237	901.72
Taylor	48441	1279	0.401	136,535	2,371	57.58
Terrell	48443	690	0.216	812	6,107	0.13
Terry	48445	995	0.312	12,799	2,302	5.56
Throckmorton	48447	1650	0.517	1,533	2,364	0.65
Titus	48449	2850	0.893	32,592	1,052	30.99

Tom Green	48451	1641	0.514	118,386	3,942	30.03
Travis	48453	5544	1.737	1,199,323	2,565	467.65
Trinity	48455	3100	0.971	14,442	1,796	8.04
Tyler	48457	3100	0.971	21,320	2,394	8.90
Upshur	48459	2850	0.893	40,969	1,510	27.13
Upton	48461	1641	0.514	3,673	3,215	1.14
Uvalde	48463	3929	1.231	27,285	4,020	6.79
Val Verde	48465	1641	0.514	48,881	8,145	6.00
Van Zandt	48467	4707	1.475	54,355	2,182	24.91
Victoria	48469	3600	1.128	92,467	2,285	40.47
Walker	48471	6481	2.031	71,484	2,031	35.20
Waller	48473	6481	2.031	50,115	1,330	37.69
Ward	48475	690	0.216	11,600	2,164	5.36
Washington	48477	6020	1.886	35,056	1,564	22.41
Webb	48479	2181	0.683	271,193	8,706	31.15
Wharton	48481	3600	1.128	41,735	2,813	14.84
Wheeler	48483	1000	0.313	5,546	2,369	2.34
Wichita	48485	1650	0.517	131,838	1,626	81.08
Wilbarger	48487	1650	0.517	12,892	2,514	5.13
Willacy	48489	4638	1.453	21,810	1,530	14.26
Williamson	48491	5544	1.737	528,718	2,896	182.55
Wilson	48493	5523	1.731	48,480	2,082	23.29
Winkler	48495	690	0.216	7,893	2,178	3.62
Wise	48497	6593	2.066	64,455	2,342	27.52
Wood	48499	2850	0.893	44,227	1,671	26.47
Yoakum	48501	995	0.312	8,488	2,071	4.10
Young	48503	1650	0.517	18,152	2,369	7.66
Zapata	48505	2181	0.683	14,349	2,586	5.55
Zavala	48507	3929	1.231	12,023	3,360	3.58

APPENDIX D

EQUATIONS AND PARAMETERS FOR PRODUCTION TRANSPORTATION

Equations defined for production transportation estimation.

$$NTU = \sum_{(p,l,dl,m)} \frac{z_{p,l,dl,m} \cdot 24}{TMA_m \cdot TCap_{p,m}} \cdot \left(\frac{2 \cdot \left(DI_{l,dl,m} \cdot 1.60934 \right)}{SP_m} + LUT_m \right)$$

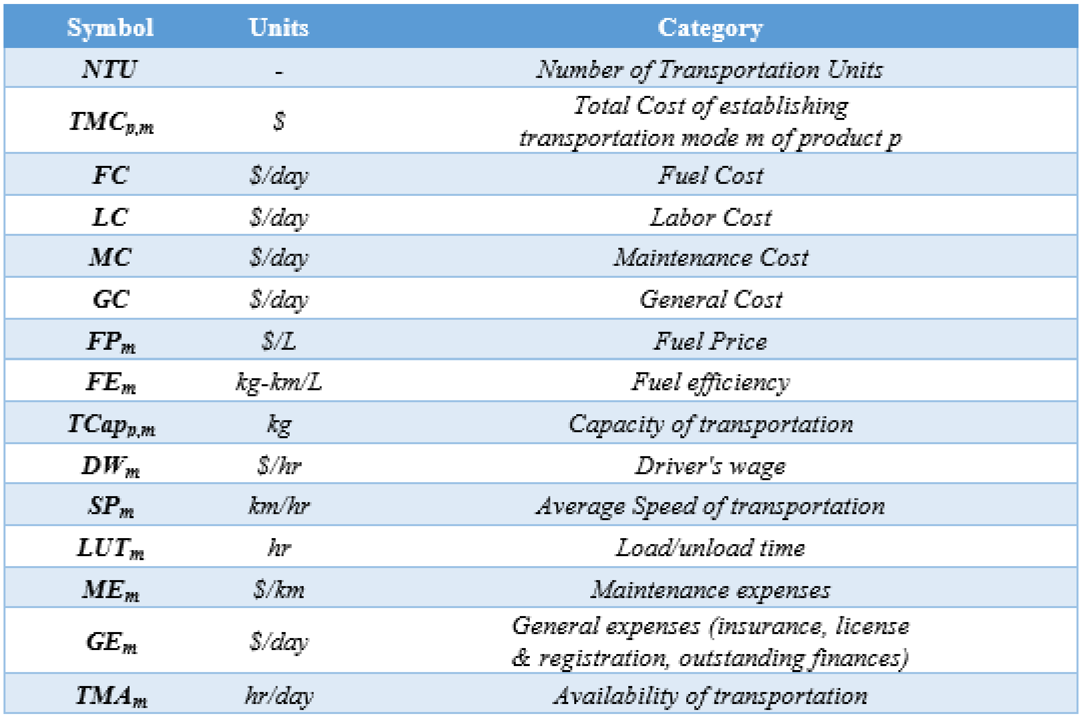
$$FuelC = \sum_{(p,l,dl,m)} FP_m \cdot \left(\frac{2 \cdot \left(DI_{l,dl,m} \cdot 1.60934 \right) \cdot \left(z_{p,l,dl,m} \cdot 24 \right)}{FE_m} \right)$$

$$LaborC = \sum_{(p,l,dl,m)} DW_m \cdot \left(\left(\frac{z_{p,l,dl,m} \cdot 24}{TCap_{p,m}} \right) \cdot \left(\frac{2 \cdot \left(DI_{l,dl,m} \cdot 1.60934 \right)}{SP_m} + LUT_m \right) \right)$$

$$MainC = \sum_{(p,l,dl,m)} ME_m \cdot \left(\frac{2 \cdot \left(DI_{l,dl,m} \cdot 1.60934 \right) \cdot \left(z_{p,l,dl,m} \cdot 24 \right)}{TCap_{p,m}} \right)$$

$$GenC = \sum_{(p,l,dl,m)} GE_m \cdot \left(\left(\frac{z_{p,l,dl,m} \cdot 24}{TMA_m \cdot TCap_{p,m}} \right) \cdot \left(\frac{2 \cdot \left(DI_{l,dl,m} \cdot 1.60934 \right)}{SP_m} + LUT_m \right) \right)$$

Table D.1 Parameters for production transportation cost estimation.



Symbol	Units	Category
NTU	-	*Number of Transportation Units*
$TMC_{p,m}$	*\$*	*Total Cost of establishing transportation mode m of product p*
FC	*\$/day*	*Fuel Cost*
LC	*\$/day*	*Labor Cost*
MC	*\$/day*	*Maintenance Cost*
GC	*\$/day*	*General Cost*
FP_m	*\$/L*	*Fuel Price*
FE_m	*kg-km/L*	*Fuel efficiency*
$TCap_{p,m}$	*kg*	*Capacity of transportation*
DW_m	*\$/hr*	*Driver's wage*
SP_m	*km/hr*	*Average Speed of transportation*
LUT_m	*hr*	*Load/unload time*
ME_m	*\$/km*	*Maintenance expenses*
GE_m	*\$/day*	*General expenses (insurance, license & registration, outstanding finances)*
TMA_m	*hr/day*	*Availability of transportation*

Table D.2 Parameters for production transportation cost estimation.

Category	Symbol	Units	Truck		Railroad	
			Value	Ref.	Value	Ref.
Total Cost of establishing transportation (Tank + Undercarriage + Cab Costs)	$TMC_{p,m}$	$	500,000	(Amos, 1998)[48]	9,800,000	(Assume freight car of 100 per trip)[49]
Capacity of transportation	$TCap_{p,m}$	*kg/trip*	24,000	Federal Railroad Administration (2009)[50]	11,000,000	(Assume freight car of 100 per trip)[49]
Fuel Price	FP_m	*$/L*	0.7790	U.S. E.I.A website	0.8557	U.S. E.I.A website
Fuel Efficiency	$FE_m * TCap_{p,m}$	*kg-km/L*	167,506	(Barnes and Langworthy, 2003)[51]	47,616	(Gattuso, 2014)[52]
Driver's wage	DW_m	*$/hr*	21.28	(Bureau of Labor website, 2017)	28.74	(Bureau of Labor website, 2017)
Average Speed of transportation	SP_m	*km/hr*	105	Assumption	120.7	(DOT, 2013)[53]
Load/unload time	LUT_m	*hr/trip*	2	(Amos, 1998)[48]	12	(Amos, 1998)[48]
Maintenance expenses	ME_m	*$/km*	0.0976	(Barnes and Langworthy, 2003)[51]	0.0621	(Barnes and Langworthy, 2003)[51]
General expenses	GE_m	*$/day*	8.22	(Victoria Transport Policy Institute, 2004)[54]	6.85	(Victoria Transport Policy Institute, 2004)[54]
Availability of transportation	TMA_m	*hr/day*	18	(Amos, 1998)[48]	12	(Amos, 1998)[48]

APPENDIX E

GAMS CODE

```
* Supply Chain Model of Renewable Methanol in TEXAS *
* Phase 1 ---- r = (only) Solar energy & p = (only) MeOH
Set
C feedstock index (Carbon Dioxide) /C/
r renewable energy /Sol, Wind/
t capacity index (ton per day) /t1*t10/
p production /MeOH/
*p product /MeOH, GH2, LH2/
m transportation (TRuck or RaiL) /TR, RR/

Set l /
48001,   48003,   48005,   48007,   48009,   48011,   48013,   48015
48017,   48019,   48021,   48023,   48025,   48027,   48029,   48031
48033,   48035,   48037,   48039,   48041,   48043,   48045,   48047
48049,   48051,   48053,   48055,   48057,   48059,   48061,   48063
48065,   48067,   48069,   48071,   48073,   48075,   48077,   48079
48081,   48083,   48085,   48087,   48089,   48091,   48093,   48095
48097,   48099,   48101,   48103,   48105,   48107,   48109,   48111
48113,   48115,   48117,   48119,   48121,   48123,   48125,   48127
48129,   48131,   48133,   48135,   48137,   48139,   48141,   48143
48145,   48147,   48149,   48151,   48153,   48155,   48157,   48159
48161,   48163,   48165,   48167,   48169,   48171,   48173,   48175
48177,   48179,   48181,   48183,   48185,   48187,   48189,   48191
48193,   48195,   48197,   48199,   48201,   48203,   48205,   48207
48209,   48211,   48213,   48215,   48217,   48219,   48221,   48223
48225,   48227,   48229,   48231,   48233,   48235,   48237,   48239
48241,   48243,   48245,   48247,   48249,   48251,   48253,   48255
48257,   48259,   48261,   48263,   48265,   48267,   48269,   48271
48273,   48275,   48277,   48279,   48281,   48283,   48285,   48287
48289,   48291,   48293,   48295,   48297,   48299,   48301,   48303
48305,   48307,   48309,   48311,   48313,   48315,   48317,   48319
48321,   48323,   48325,   48327,   48329,   48331,   48333,   48335
48337,   48339,   48341,   48343,   48345,   48347,   48349,   48351
48353,   48355,   48357,   48359,   48361,   48363,   48365,   48367
48369,   48371,   48373,   48375,   48377,   48379,   48381,   48383
48385,   48387,   48389,   48391,   48393,   48395,   48397,   48399
48401,   48403,   48405,   48407,   48409,   48411,   48413,   48415
48417,   48419,   48421,   48423,   48425,   48427,   48429,   48431
48433,   48435,   48437,   48439,   48441,   48443,   48445,   48447
48449,   48451,   48453,   48455,   48457,   48459,   48461,   48463
48465,   48467,   48469,   48471,   48473,   48475,   48477,   48479
48481,   48483,   48485,   48487,   48489,   48491,   48493,   48495
48497,   48499,   48501,   48503,   48505,   48507/   ;

$include "PD_l.txt";
Set A(l) Available land with less than population density of 200 people per km2 in county;
A(l) = YES;
```

```
loop(l$(PD(l)  ge 200), A(l) = No;
          );
*Availabla facility locations are only the following (with population density of less than 200 people per
km2 in county)
Set Al /
48001,    48003,    48005,    48007,    48009,    48011,    48013,    48015
48017,    48019,    48021,    48023,    48025,    48027,    48031,    48033
48035,    48037,    48039,    48041,    48043,    48045,    48047,    48049
48051,    48053,    48055,    48057,    48059,    48061,    48063,    48065
48067,    48069,    48071,    48073,    48075,    48077,    48079,    48081
48083,    48087,    48089,    48091,    48093,    48095,    48097,    48099
48101,    48103,    48105,    48107,    48109,    48111,    48115,    48117
48121,    48123,    48125,    48127,    48129,    48131,    48133,    48135
48137,    48139,    48143,    48145,    48147,    48149,    48151,    48153
48155,    48159,    48161,    48163,    48165,    48169,    48171,    48173
48175,    48177,    48179,    48181,    48183,    48185,    48187,    48189
48191,    48193,    48195,    48197,    48199,    48203,    48205,    48207
48209,    48211,    48213,    48217,    48219,    48221,    48223,    48225
48227,    48229,    48231,    48233,    48235,    48237,    48239,    48241
48243,    48245,    48247,    48249,    48251,    48253,    48255,    48257
48259,    48261,    48263,    48265,    48267,    48269,    48271,    48273
48275,    48277,    48279,    48281,    48283,    48285,    48287,    48289
48291,    48293,    48295,    48297,    48299,    48301,    48303,    48305
48307,    48309,    48311,    48313,    48315,    48317,    48319,    48321
48323,    48325,    48327,    48329,    48331,    48333,    48335,    48337
48341,    48343,    48345,    48347,    48349,    48351,    48353,    48355
48357,    48359,    48361,    48363,    48365,    48367,    48369,    48371
48373,    48375,    48377,    48379,    48381,    48383,    48385,    48387
48389,    48391,    48393,    48395,    48399,    48401,    48403,    48405
48407,    48409,    48411,    48413,    48415,    48417,    48419,    48421
48423,    48425,    48427,    48429,    48431,    48433,    48435,    48437
48441,    48443,    48445,    48447,    48449,    48451,    48455,    48457
48459,    48461,    48463,    48465,    48467,    48469,    48471,    48473
48475,    48477,    48479,    48481,    48483,    48485,    48487,    48489
48491,    48493,    48495,    48497,    48499,    48501,    48503,    48505
48507/;

Set s(l) location with seat cities (for RaiL transportation)
/48001, 48005, 48011, 48015, 48017, 48021, 48027, 48029, 48035, 48037, 48039, 48041, 48043, 48049,
48051, 48053, 48055, 48057, 48059, 48061, 48063, 48065, 48069, 48075, 48077, 48083, 48085, 48089,
48091, 48093, 48097, 48109, 48111, 48113, 48117, 48121, 48123, 48129, 48131, 48133, 48135, 48139,
48141, 48143, 48145, 48147, 48149, 48157, 48159, 48163, 48167, 48169, 48177, 48179, 48181, 48183,
48187, 48189, 48191, 48197, 48199, 48201, 48203, 48205, 48209, 48211, 48213, 48215, 48217, 48219,
48221, 48223, 48225, 48229, 48231, 48235, 48239, 48241, 48245, 48247, 48249, 48251, 48261, 48273,
48277, 48279, 48281, 48283, 48287, 48291, 48293, 48297, 48299, 48303, 48307, 48309, 48315, 48317,
48321, 48323, 48325, 48329, 48331, 48333, 48335, 48339, 48341, 48343, 48347, 48349, 48353, 48355,
48361, 48365, 48367, 48369, 48371, 48373, 48375, 48377, 48381, 48383, 48389, 48391, 48393, 48395,
48397, 48399, 48401, 48405, 48409, 48411, 48415, 48419, 48421, 48423, 48437, 48439, 48441, 48443,
48445, 48449, 48451, 48453, 48459, 48461, 48463, 48465, 48469, 48471, 48473, 48475, 48477, 48479,
48481, 48485, 48487, 48489, 48491, 48495, 48497/;;
Set sl /48001, 48005, 48011, 48015, 48017, 48021, 48027, 48029, 48035, 48037, 48039, 48041, 48043,
48049, 48051, 48053, 48055, 48057, 48059, 48061, 48063, 48065, 48069, 48075, 48077, 48083, 48085,
48089, 48091, 48093, 48097, 48109, 48111, 48113, 48117, 48121, 48123, 48129, 48131, 48133, 48135,
```

```
48139, 48141, 48143, 48145, 48147, 48149, 48157, 48159, 48163, 48167, 48169, 48177, 48179, 48181,
48183, 48187, 48189, 48191, 48197, 48199, 48201, 48203, 48205, 48209, 48211, 48213, 48215, 48217,
48219, 48221, 48223, 48225, 48229, 48231, 48235, 48239, 48241, 48245, 48247, 48249, 48251, 48261,
48273, 48277, 48279, 48281, 48283, 48287, 48291, 48293, 48297, 48299, 48303, 48307, 48309, 48315,
48317, 48321, 48323, 48325, 48329, 48331, 48333, 48335, 48339, 48341, 48343, 48347, 48349, 48353,
48355, 48361, 48365, 48367, 48369, 48371, 48373, 48375, 48377, 48381, 48383, 48389, 48391, 48393,
48395, 48397, 48399, 48401, 48405, 48409, 48411, 48415, 48419, 48421, 48423, 48437, 48439, 48441,
48443, 48445, 48449, 48451, 48453, 48459, 48461, 48463, 48465, 48469, 48471, 48473, 48475, 48477,
48479, 48481, 48485, 48487, 48489, 48491, 48495, 48497/;
Set dl demand locations /48029, 48113, 48201, 48439, 48453/
Set
cl CO2 locations /48013201, 48021201, 48021202, 48021203, 48027201, 48029201, 48029202, 48029203,
48029204, 48029205, 48029206, 48035201, 48039201, 48039202, 48039203, 48039204, 48039205,
48039206, 48041201, 48041202, 48041203, 48057201, 48057202, 48057203, 48057204, 48061201,
48071201, 48071202, 48071203, 48071204, 48071205, 48073201, 48081201, 48085201, 48085202,
48089201, 48113201, 48113202, 48121201, 48135201, 48135202, 48135203, 48141201, 48141202,
48141203, 48141204, 48141205, 48139201, 48139202, 48149201, 48149202, 48157201, 48157202,
48157203, 48161201, 48161202, 48163201, 48167201, 48167202, 48167203, 48175201, 48181201,
48183201, 48185201, 48185202, 48187201, 48187202, 48189201, 48189202, 48199201, 48201201,
48201202, 48201203, 48201204, 48201205, 48201206, 48201207, 48201208, 48201209, 48201210,
48201211, 48201212, 48201213, 48201214, 48201215, 48201216, 48201217, 48201218, 48201219,
48201220, 48203201, 48203202, 48203203, 48209201, 48211201, 48213201, 48215201, 48215202,
48215203, 48221201, 48221202, 48221203, 48227201, 48231201, 48233201, 48245201, 48245202,
48245203, 48245204, 48245205, 48245206, 48245207, 48245208, 48251201, 48257201, 48277201,
48277202, 48279201, 48279202, 48293201, 48299201, 48303201, 48303202, 48303203, 48303204,
48315201, 48309201, 48331201, 48331202, 48335201, 48339201, 48343201, 48351201, 48355201,
48355202, 48355203, 48355204, 48355205, 48355206, 48361201, 48361202, 48361203, 48363201,
48371201, 48375201, 48375202, 48395201, 48395202, 48401201, 48401202, 48407201, 48409201,
48409202, 48415201, 48439201, 48449201, 48449202, 48453201, 48453202, 48453203, 48453204,
48453205, 48461201, 48469201, 48469202, 48469203, 48475201, 48479201, 48481201, 48481202,
48481203, 48485201, 48487201, 48497201, 48497202, 48497203, 48501201, 48501202, 48501203,
48503201/
wl water locations /48013101, 48021101, 48021102, 48021103, 48029101, 48029102, 48029103,
48029104, 48029105, 48029106, 48035101, 48039101, 48041101, 48061101, 48071101, 48071102,
48071103, 48073101, 48085101, 48113101, 48113102, 48121101, 48135101, 48135102, 48141101,
48139101, 48147101, 48149101, 48157101, 48157102, 48161101, 48161102, 48163101, 48167101,
48175101, 48183101, 48185101, 48185102, 48187101, 48187102, 48201101, 48201102, 48201103,
48201104, 48201105, 48201106, 48201107, 48201108, 48201109, 48201110, 48203101, 48203102,
48203103, 48209101, 48213101, 48215101, 48215102, 48215103, 48221101, 48227101, 48231101,
48251101, 48257101, 48277101, 48277102, 48279101, 48279102, 48293101, 48299101, 48303101,
48303102, 48303103, 48315101, 48321101, 48309101, 48331101, 48339101, 48341101, 48343101,
48351101, 48355101, 48355102, 48355103, 48361101, 48361102, 48361103, 48363101, 48375101,
48375102, 48395101, 48395102, 48401101, 48401102, 48409101, 48425101, 48439101, 48439102,
48449101, 48449102, 48453101, 48453102, 48469101, 48469102, 48475101, 48481101, 48485101,
48487101, 48497101, 48497102, 48501101, 48503101/;

Parameters
Num Maximum no. of facilities selected in model /200/
Num_max Maximum no. of facilities of capacity t selected in model /200/
Num_min Maximum no. of facilities of capacity t selected in model /0/
yr No. of operation years /25/
i interest rate over facility operation lifespan in percentage /0.05/
TEC Total Electricity Consumption in demand locations in Texas per year (units GJ_per_yr) /722159015/;
```

```
Scalar AF Present value of annuity factor;
        AF = (1-1/power((1+i),yr))/i;

*a.Renewable Plant*
Parameter RC(r,t)  Renewable plant Capital cost (units $_per_MW);
           RC('Sol',t)=985093;
           RC('Sol','t1')=1082073;
           RC('Wind',t)=1590000;
Parameter LR(r)  Land cost of Renewable plant r (units $_per_MW for Sol & $_per_kW_per_yr for Wind );
           LR('Sol')=30000;  LR('Wind')=8.1;
*RF(r,l)  Renewable energy scaling Factor for technology r at location l (unitless)
$include "RF_r_l_new_2.txt";
*LF(l)  Land price scaling Factor at location l (unitless);
$include "LF_l.txt";

Parameter
ROM(r)  Renewable plant Operation & Maintenance cost (units $_per_kW_yr);
        ROM('Sol')=18.5     ;    ROM('Wind')=43.6  ;
Parameter
CF(r,l)  Capacity factor of renewable energy at location l;
         CF('Sol',l)  = 0.24;
$include "CF_wind_l_new.txt";

Table ER(p,t)  Electricity  Required to produce production p of capacity t (units MWh)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    14.3        40.7        68.2        136.4       271.7       452.1       677.6
1002.1      1503.7      2258.3  ;

*b. Electrolyzer  Requirement*
Table EC(p,t)  Electrolyze  Cost to produce product p of capacity t (units $_per_MW)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    1110837     949537      878786      792007      714229      661707      622737
587238      552557      519857    ;

Table EOM(p,t)  Electrolyze  O&M  Cost to produce product p of capacity t (units $_per_MW_per_yr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    11553       9875        9139        8237        7428        6882        6476
6107        5747        5407    ;

Parameter SPO2  Selleing price of oxygen (units $_per_kg) /0.11794/
           O2Discount  Discount rate of oxygen sales (units percentage) /0.50/

Table OO(p,t)  Oxygen  Output to produce production p of capacity t (units kg_per_hr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    2042.85     5814.27     9742.83     19485.66    38814.17    64585.52    96799.7
143156.7    214813.65   322613.33    ;

Table HO(p,t)  Hydrogen Output to produce production p of capacity t (units kg_per_hr)
```

```
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    257.4       732.6       1227.6      2455.2      4890.6      8137.8      12196.8
18037.8     27066.6     40649.4     ;

*c. Chemical  Production Plant*
Table PC(p,t) Chemical  Production plant investment Cost for capacity t (units $_per_kg-hr_per_hr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    1794.09     1244.41     1038.35     814.64      640.09      502         394         309
351.28      304.70      ;

Table POM(p,t) Chemical  Production plant Operation & Maintenance cost for capacity t (units $_per_kg-
hr_per_hr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    18.6586     12.9418     10.7988     8.4723      6.6570      5.5665      4.8297
4.2103      3.6533      3.1689      ;

Table PR(p,t) Product p produced from plant capacity t (units kg_per_hr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    1320        3753        6294        12588       25072       41786       62679
92765       139148      208931      ;

*d. Feed Source Requirement*
Table CC(p,t) CO2  capture investment Cost to produce product p of capacity t (units $_per_kg-hr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    1593.02     1105.2      922.25      723.6       568.55      475.47      412.56
359.66      312.08      270.070     ;

Table COM(p,t) CO2  Capture plant Operation & Maintenance cost to produce product p of capacity t (units
$_per_kg-hr_per_yr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    235.0123    163.0456    136.0565    106.7499    83.8759     70.1439     60.8637
53.0599     46.0399     39.9347  ;

Table FC(p,t) Feedstock CO2  input required to produce product p of capacity t (units kg_per_hr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    2099        5966        10004       20008       39850       66417       99625
147445      221167      332083  ;

*CA(cl) CO2 Available at location cl
$include "CA_cl.txt";
Parameter CP CO2 purchase cost (0 or negative value (subsidy)) /0/    ;

Parameter slope(t) slope value for Ctrans calculation;
slope('t1') = 8.9704        ;
slope('t2') = 5.2109        ;
slope('t3') = 3.9824        ;
```

```
slope('t4') = 2.7773        ;
slope('t5') = 2.1340        ;
slope('t6') = 1.4882        ;
slope('t7') = 1.2053        ;
slope('t8') = 0.983         ;
slope('t9') = 0.7961        ;
slope('t10') = 0.6445       ;

Parameter inter(t) intercept value for Ctrans calculation;
inter('t1') = -122.341      ;
inter('t2') = -71.067       ;
inter('t3') = -54.3133      ;
inter('t4') = -37.8777      ;
inter('t5') = -26.4718      ;
inter('t6') = -20.297       ;
inter('t7') = -16.438       ;
inter('t8') = -13.407       ;
inter('t9') = -10.858       ;
inter('t10')  = -8.789      ;

*4. Water Requirement*
Table FW(p,t) Water input required to produce p of capacity t (units kg_per_hr)
        t1          t2          t3          t4          t5          t6          t7          t8
t9          t10
MeOH    2656        7558        12665       25331       50457       83959       125837
186100      279252      419389  ;


Parameter
WP Water Purchase cost (unit $_per_kg) /0.08828/
*$2.50 per ft3 of water (Texas-FortWorth Reference Price) ~ 0.08828
*$0.5 per ton of water (Seawater Reference Price) = 0.0005
*WA(wl) Water Available at location wl (unit kg_per_hr)
$include "WA_wl.txt";

*************************************************5.
Transportation**************************************************START
*DI(a,b) using Haversine Formula*
$include "Lat_Long_l.txt";
$include "Lat_Long_sl.txt";
$include "Lat_Long_wl.txt";
$include "Lat_Long_dl.txt";
*$include "Lat_Long_dl_next44.txt";
$include "Lat_Long_cl.txt";
$include "Lat_Long_wl.txt";

Scalar r_earth /3961/
        PI /3.14169265/;

*Below text file outputs DIs(sl,l,'RL')  & DIp(l,dl,m),  DIc(cl,l),  DIw(wl,l)  where A(l)
$include "distance_wl_cl_l_dl_3.txt";

********************************************For Water transportation via pipeline
```

```
Scalar DM      Distance factor /1.1/
             DFCw Water - pipeline (unit $_per_kg) /0.003/
             DVCw  Water - pipeline (unit $_per_kg_per_mi) /0.000005/;

Set maxDIw(wl,l);
        maxDIw(wl,l)  = YES;
        loop((wl,l)$(DIw(wl,l)   ge 200  and A(l)), maxDIw(wl,l)  = NO;
        );

*********************************************For CO2 transportation via pipeline

Set maxDIc(cl,l,t);
        maxDIc(cl,l,t)   = YES;
        loop((cl,l,t)$(DIc(cl,l,t)  ge 200  and A(l)), maxDIc(cl,l,t)   = NO;
        );


Parameter Ctrans_lev(cl,l,t);
Ctrans_lev(cl,l,t)  = slope(t)*DIc(cl,l,t)+inter(t)             ;
Ctrans_Lev(cl,l,t)$(Ctrans_Lev(cl,l,t)  lt 0) = 0.00001     ;

*********************************************For product transportation (L & G) via TR or RL
Parameter TMC(p,m)  Total Cost of establishing transportation m of product p (unit $);
              TMC('MeOH','TR')=500000;
              TMC('MeOH','RR')=9800000;
Parameter FP(m)  Fuel Price  - Gasoline for Truck & Diesel for Rail (unit $_per_L);
              FP('TR')=0.7779   ;
              FP('RR')=0.8557   ;
Parameter FE(m)  Fuel Efficiency  (unit kg-km_per_Liter);
              FE('TR')=167506   ;
              FE('RR')=47616  ;
Parameter TCap(p,m)  Capacity of Transportation (unit kg);
              TCap('MeOH','TR')=24000;
              TCap('MeOH','RR')=11000000;
Parameter DW(m)  Drivers  wage (unit $_per_hr);                          DW('TR')=21.28  ;
DW('RR')=28.74   ;
Parameter SP(m)  Average speed of transportation (unit km_per_hr) ; SP('TR')=105   ;     SP('RR')=120.7  ;
Parameter LUT(m)  Load_unload times  (unit hr) ;                        LUT('TR')=2  ;
LUT('RR')=12   ;
Parameter ME(m)  Maintenance expenses (unit $_per_km)  ;                 ME('TR')=0.0976   ;
ME('RR')=0.0621  ;
Parameter GE(m)   General  expenses (unit $_per_day) ;                  GE('TR')=8.22   ;
GE('RR')=6.85  ;
Parameter TMA(m)  Available transportation (unit hr_per_day) ;        TMA('TR')=18  ;
TMA('RR')=12   ;
;
Set onDIp(l,dl,m);
        onDIp(l,dl,m)  = YES;
        loop((l,dl,m)$(DIp(l,dl,'RR')  le  1 and A(l)), onDIp(l,dl,m)  = NO;
              );

*************************************************5.
Transportation*************************************************END
```

```
*6. Demand*
Parameter LHV(p)  Lower Heating Value of product p (unit MJ_per_kg) /MeOH 21.113/

Table DR(p,dl)  Demand of production p at dl to meet TEC  (unit kg_per_hr) using LHV

           48029          48113          48201          48439          48453
MeOH     669889         894369        1594220         700520         416561       ;

Scalar DemandFrac  Fraction of total demand  (if 1 - total demand is being met)  /1/


Binary Variable
y(r,p,t,l)  ;

Variables
TotalCost
LevelCost
TotalCost_noO2Sales
LevelCost_noO2Sales
Ctrans(l)                  variable used for equation CarbonTransportation (unit $)
sumCtrans
;

Positive Variable
*Variables to meet requirement*
CR(l)           CO2 required at location l (units kg_per_hr)
cd(cl,l,t)      CO2 flow from location cdl to l for capacity t (units kg_per_hr)

WR(l)             Water Required at location l (units kg_per_hr)
w(wl,l)          Water flow from location wl to l (units kg_per_hr)
zOP(l)            Flow of O2 Produced at location l    (units kg_per_hr)
z(p,l,dl,m) Flow of product p from location l to demand location dl using transportation m (units kg_per_hr)

Cost_Inv_a(l) Renewable plant
Cost_OM_a(l)
Cost_Inv_b(l) Electrolyzer
Cost_OM_b(l)
Cost_Inv_c(l) Chemical  Production Plant or Compressor Unit
Cost_OM_c(l)
*MeOH = Compressor+Plant*
Cost_Inv_d(l) Feed Source Requirement  (CO2 for MeOH)
Cost_OM_d(l)
SumInvCost
SumOMCost

SalesO2(l)        Cost of O2 sales at location l (unit $)
SumO2                  Sum of SalesO2(l)

Wtrans(l)         variable used for equation WaterTransportation (unit $)
WPurchase(l)
sumWtrans
Ptrans(dl)         variable used for equation ProductTransportation (unit $)
```

```
sumPtrans
*SCC Storage Capital Cost for Hydrogen (unit $)
TCC(dl)                 Transportation Capital Cost for all productions (unit $)
*SOC Storage Operating Cost for Hydrogen (unit $_per_day)
TOC(dl)                 Transportation Operating Cost for all productions (unit $_per_day)
NTU(dl)                 Number of Transportation Unit (unitless)
FuelC(dl)             Fuel Cost (unit $_per_day)
LaborC(dl)            Labor Cost (unit $_per_day)
MaintC(dl)            Maintenance Cost (unit $_per_day)
GenC(dl)                General Cost (unit $_per_day)

NamePlate(l)

;

Equation
* Facility Constraints *
Facility_loc(l)
Facility_ren(r,l)
Facility_pro(p,l)
MaxFacility
*MaxTFacility(t)
*MinTFacility(t)

*Equation to meet requirement*
O2output(l) Oxygen output for sales

CO2Required(l)
CO2Available(cl)
CO2Flow(l)

WAvailable(wl)
WRequired(l)
WFlow(l)

DemandRequired1(p,l)
DemandRequired2(p,dl)
*DemandRequired3

*Equations for Cost*
InvCost_a(l) Renewable plant (units $)
OMCost_a(l) Renewable plant (units $_per_yr)
InvCost_b(l) Electrolyzer (units $)
OMCost_b(l)
InvCost_c(l) Chemical Production Plant or Compressor Unit (units $)
OMCost_c(l)
InvCost_d(l) Feed Source Requirement (CO2 for MeOH) (units $)
OMCost_d(l)
Sum_of_all_InvCost
Sum_of_all_OMCost

SalesOxygen(l) Sale of O2 (units $)
Sum_SalesOxygen Sum of O2 sales
```

```
CarbonTransportation(l)
CarbonTrans

WaterTransportation(l) Cost of water purchase & transportation via pipeline  (units $_per_yr)
WaterPurchase(l) Water Purcase cost at l
WaterTrans
ProductTransportation(dl) Cost of product transportation via truck or railroad  (units $_per_yr)
ProductTrans
*StorageCC
*StorageOC
TransportationCC(dl)
TransportationOC(dl)
NumberofTrans(dl)
FuelCost(dl)
LaborCost(dl)
MaintenanceCost(dl)
GeneralCost(dl)

PowerPlant(l)

OBJ1
OBJ2
OBJ3
OBJ4;
************************************************Equations**************************
***********************
* Facility  Constraints *
Facility_loc(l)..         sum((r,p,t)$A(l),  y(r,p,t,l))  =l=  1;
Facility_ren(r,l)..     sum((p,t)$A(l),  y(r,p,t,l))  =l=  1;
Facility_pro(p,l)..     sum((r,t)$A(l),  y(r,p,t,l))  =l=  1;
MaxFacility..                 sum((r,p,t,l)$A(l),  y(r,p,t,l))  =l=  Num;
*MaxTFacility(t)..     sum((r,p,l),  y(r,p,t,l))  =l=  Num_max;
*MinTFacility(t)..     sum((r,p,l),  y(r,p,t,l))  =g=  Num_min;


******************************************************************************Equ
ation to meet requirement*
O2output(l)..              zOP(l)  =e=  sum((r,p,t)$A(l),  y(r,p,t,l)*OO(p,t)  ) ;

CO2Required(l)..         sum((r,p,t)$A(l),  y(r,p,t,l)*FC(p,t))  =e=  CR(l)  ;
CO2Available(cl)..     sum((l,t)$(maxDIc(cl,l,t)  and A(l)),  cd(cl,l,t))  =l=  CA(cl)  ;
CO2Flow(l)..                 CR(l)  =e=  sum((cl,t),  cd(cl,l,t))  ;

WRequired(l)..             sum((r,p,t)$A(l),  y(r,p,t,l)*FW(p,t))  =e=  WR(l) ;
WAvailable(wl)..         sum((l)$(maxDIw(wl,l)  and A(l)),  w(wl,l))  =l=  WA(wl) ;
WFlow(l)..                    WR(l)  =e=  sum(wl,  w(wl,l))  ;

DemandRequired1(p,l)..     sum((r,t)$A(l),  y(r,p,t,l)*PR(p,t))  =e=  sum((dl,m),  z(p,l,dl,m))  ;
DemandRequired2(p,dl)..  sum((l,m)$(onDIp(l,dl,m)  and A(l)),  z(p,l,dl,m))  =g=  DemandFrac*DR(p,dl)  ;
*DemandRequired3..               sum((p('MeOH'),l,dl,m),  z(p,l,dl,m)*8000*LHV(p)*0.001)  =l=  TEC  ;
```

```
*****************************************************************************************
*******Equations for Cost*

InvCost_a(l)..        Cost_Inv_a(l) =e= sum((r('Sol'),p,t),
y(r,p,t,l)*ER(p,t)/CF(r,l)*(RC(r,t)*RF(r,l)+LR(r)*LF(l)))
                                                       +sum((r('Wind'),p,t),
y(r,p,t,l)*ER(p,t)/CF(r,l)*RC(r,t)*RF(r,l))   ;
OMCost_a(l)..          Cost_OM_a(l) =e= sum((r('Sol'),p,t),  y(r,p,t,l)*ER(p,t)/CF(r,l)*ROM(r)*1000 )
                                                       +sum((r('Wind'),p,t),
y(r,p,t,l)*ER(p,t)/CF(r,l)*(ROM(r)+LR(r)*LF(l))*1000);

InvCost_b(l)..        Cost_Inv_b(l) =e= sum((r,p,t),  y(r,p,t,l)*ER(p,t)*EC(p,t))   ;
OMCost_b(l)..          Cost_OM_b(l) =e= sum((r,p,t),  y(r,p,t,l)*ER(p,t)*EOM(p,t)   ) ;

InvCost_c(l)..        Cost_Inv_c(l) =e= sum((r,p,t),  y(r,p,t,l)*PC(p,t)*PR(p,t)   ) ;
OMCost_c(l)..          Cost_OM_c(l) =e= sum((r,p,t),  y(r,p,t,l)*POM(p,t)*PR(p,t)   ) ;

InvCost_d(l)..        Cost_Inv_d(l) =e= sum((r,p,t),  y(r,p,t,l)*CC(p,t)*FC(p,t)   ) ;
OMCost_d(l)..          Cost_OM_d(l) =e= sum((r,p,t),  y(r,p,t,l)*COM(p,t)*FC(p,t)   ) ;

Sum_of_all_InvCost..  SumInvCost =e= sum(l, Cost_Inv_a(l) + Cost_Inv_b(l) + Cost_Inv_c(l) +
Cost_Inv_d(l));
Sum_of_all_OMCost..    SumOMCost  =e= sum(l, Cost_OM_a(l) + Cost_OM_b(l) + Cost_OM_c(l) +
Cost_OM_d(l));

SalesOxygen(l)..                        SalesO2(l)  =e= O2Discount*SPO2*zOP(l)*8000   ;
Sum_SalesOxygen..                        SumO2  =e= sum(l, SalesO2(l));
***************************************************************************************E
quations for Transportation*
WaterTransportation(l)..       Wtrans(l) =e= sum(wl,  w(wl,l)*8000*(WP   +
(DFCw+DVCw*DIw(wl,l)*DM))   ) ;
WaterPurchase(l)..                  WPurchase(l) =e= sum(wl,  w(wl,l)*8000*WP)        ;
WaterTrans..                              sumWtrans =e= sum(l,  Wtrans(l)) ;

CarbonTransportation(l)..      Ctrans(l) =e= sum((cl,t),  Ctrans_lev(cl,l,t)*cd(cl,l,t))   ;
CarbonTrans..                            sumCtrans =e= sum(l,  Ctrans(l)) ;

NumberofTrans(dl)..                  NTU(dl)  =e= sum((p,l,m),
z(p,l,dl,m)*24/(TMA(m)*TCap(p,m))*(2*DIp(l,dl,m)*1.60934/SP(m)+LUT(m)))   ;
TransportationCC(dl)..            TCC(dl)  =e= sum((p,l,m),
z(p,l,dl,m)*24/(TMA(m)*TCap(p,m))*(2*DIp(l,dl,m)*1.60934/SP(m)+LUT(m))   * TMC(p,m))  ;
FuelCost(dl)..                          FuelC(dl)  =e= sum((p,l,m),
FP(m)*(2*DIp(l,dl,m)*1.60934*z(p,l,dl,m)*24)/FE(m))   ;
LaborCost(dl)..                          LaborC(dl)  =e= sum((p,l,m),
DW(m)*(z(p,l,dl,m)*24/TCap(p,m))*(2*DIp(l,dl,m)*1.60934/SP(m)+LUT(m)))   ;
MaintenanceCost(dl)..              MaintC(dl)  =e= sum((p,l,m),
ME(m)*(2*DIp(l,dl,m)*1.60934*z(p,l,dl,m)*24)/TCap(p,m))   ;
GeneralCost(dl)..                      GenC(dl)  =e= sum((p,l,m),
GE(m)*z(p,l,dl,m)*24/(TMA(m)*TCap(p,m))*(2*DIp(l,dl,m)*1.60934/SP(m)+LUT(m)))   ;

TransportationOC(dl)..            TOC(dl)  =e= FuelC(dl)  + LaborC(dl)  + MaintC(dl)  + GenC(dl)  ;

ProductTransportation(dl).. Ptrans(dl) =e= (TCC(dl))/AF  + (TOC(dl)*365)   ;
```

```
ProductTrans..                    sumPtrans =e= sum(dl, Ptrans(dl));
*ProductTransportation.. Ptrans =e= (SCC+TCC)/AF  + (SOC+TOC)*365

PowerPlant(l)..     NamePlate(l)  =e= sum((r,p,t),  y(r,p,t,l)*ER(p,t)/CF(r,l));

OBJ1..    TotalCost =e= SumInvCost/AF + SumOMCost - SumO2  + sumCtrans + sumWtrans + sumPtrans ;
OBJ2..    TotalCost_noO2Sales =e= SumInvCost/AF + SumOMCost  + sumCtrans  + sumWtrans +
sumPtrans ;
OBJ3..    LevelCost  =e= TotalCost/(TEC*DemandFrac)  ;
OBJ4..    LevelCost_noO2Sales  =e= TotalCost_noO2Sales/(TEC*DemandFrac)   ;

model Code /all/ ;
option reslim  = 7200  ;
solve Code using MIP minimizing   TotalCost_noO2Sales     ;


file Results /Results_DemandF_100_Next44.csv/;
Results.pw=32767;
Results.nr=6;
Results.nd=6;
Results.pc=5;
put Results;
```