DEVELOPING A FRAMEWORK FOR AMMONIA ENERGY CARRIER SUPPLY CHAIN OPTIMIZATION INCORPORATING RENEWABLE PRODUCTION TECHNOLOGIES

A Thesis

by

HANEOL SONG

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Efstratios N. Pistikopoulos
Committee Members,	Faruque Hasan
	Sergiy Butenko
Interdisciplinary Chair,	Efstratios N. Pistikopoulos

August 2018

Major Subject: Energy

ABSTRACT

An optimization-based supply chain management framework for statewide analyses of renewable ammonia production to electricity generation systems for Texas. With optimized renewable ammonia production plants of differing capacities (i.e. 300, 1200, 2100, and 3000 tons per day), renewable technologies (solar and wind), transportation means (railroad and truck), and conversion technologies (gas turbines and fuel cells), the optimal statewide supply chains are obtained by solving a mixed-integer linear programming (MILP) model that minimizes total cost of energy supply chain. The mathematical model includes facilities (renewable power plants and ammonia production pla`nts) and its capacity by county, transportation costs and its mean, type of conversion plant and its costs, water resources, and electricity demand.

The solutions of the proposed MILP optimization model provide meaningful topology of energy supply chain including optimal location of facilities and their configuration, optimal transportation network with means and flows, and configuration of conversion plants. Sensitivity analyses of various cases modifying parameters associated in supply chain problem are completed, and economic study results are compared in different scenarios. The results show that annualized cost for replacing electricity demand of the largest 5 counties in Texas is $41.6/GJ-yr and replacing entire Texas demand is $24.6/GJ-yr.

DEDICATION

To my wife Kyungmin Oh and my daughter April Song, the greatest gifts that came into my life,

To my parents and parents in law who trust and support me indefinitely.

CONTRIBUTORS AND FUNDING SOURCES

This work was supervised by a thesis (or) dissertation committee consisting of Professor Efstratios N. Pistikopoulos and Faraque Hasan of the Department of Chemical Engineering andProfessor Sergei Butenko of the Department of Industrial Engineering.

All work for the thesis was completed by the student, in collaboration with Doga Demirhan and William Tso of the Department of Chemical Engineering.

There are no outside funding contributions to acknowledge related to the research and compilation of this document.

NOMECLATURE

INDEX

s	state index (Texas only)
c	county(demand) index (5 counties, subset of l)
h	water source index (45 counties, subset of l)
p	product index (H2, O2, NH3)
t	plant size index (10, 50, 100, 200, 300, 400)
l	production plant location index (counties)
r	renewable technology index (solar and wind)
m	transportation mode index (vehicle and railroads)
j	conversion technology index (fuel cell and gas turbine)

SETS

S	U.S. States
C	U.S. Counties
C^D	U.S. Counties for demand
H	Freshwater availability locations
P	products (i.e., H_2, O_2, NH_3)
T	Ammonia Production capacities (i.e., 10, 50, 100, 200, 300, 400, 500 TPD)
L	Production facility locations

R		Renewable technologies (i.e., Solar and Wind)
M		Transportation modes (i.e., trucks and railroads)
J		Conversion technologies (i.e., Ammonia gas turbine and fuel cell)

PARAMETERS

N	-	maximum number of facility built in the United States
N_t^{max}	-	maximum number of facility for size t
N_t^{min}	-	minimum number of facility for size t
B	-	maximum number of conversion built in the United States
RC_r	\$/MW-yr	levelized renewable plant investment unit cost for renewable technology r
RLC_r	\$/MW	renewable power plant land unit cost for renewable technology r and location l
RLM_l	-	land price multiplier at location l
RLR_r	km^2/MW	land requirement for renewable power plant for renewable technology r
RLA_l	km^2	land availability at location l
ROM_r	\$/MW	renewable plant O&M cost
$RF_{r,l}$	-	renewable energy scaling factor for renewable technology at location l
$\lambda_{r,l}$	-	capacity factor for renewable technology r at location l
LC_t	\$/yr	levelized production plant investment cost for size t
LO_t	\$	production plant O&M cost for size t

CC_j	\$/MW-yr	levelized conversion plant investment unit cost for conversion technology j
CFO_j	\$/MW	conversion plant O&M fixed cost for conversion technology j
CVO_j	\$/MWh	conversion plant O&M variable cost for conversion technology j
CA_j	-	conversion plant availability for conversion technology j in year
η_j	-	efficiency of conversion plant for conversion technology j
FC	-	partial demand factor (i.e. 100%, 75%, 50%, 25%)
PD	-	factor for partial water availability
DM_c	MWh	demand of electricity at county c (MWH in year of 2015)
$PR_{p,t}$	ton(yr)	amount of ammonia product p for a plant of size t
WA_h	ton(yr)	water availability in location h
FW_t	ton(yr)	ammonia production plant water requirement for capacity t
$El_{t,l}^T$	MWh	electricity required at capacity t and facility l
$cost_{p,l,c,m}^{PT}$	\$/ton(yr)	cost per unit mass to transport product p from facility l to county c and mode m
$FC_{p,l,c,m}^{PT}$	\$/mi	fuel cost for transportation m product p from facility l to county c
$LA_{p,l,c,m}^{PT}$	\$/mi	labor cost for transportation m product p from facility l to county c
$MC_{p,l,c,m}^{PT}$	\$/mi	maintenance cost for transportation m product p from facility l to county c
$GC_{p,l,c,m}^{PT}$	\$/mi	general cost for transportation m product p from facility l to county c

$DI_{l,c,m}$	mi	distance from facility l to county c using transportation m
DC	-	path curvature margin
FP_m	$	fuel price for transportation m
FE_m	mi/gal	fuel economy for transportation m
DW_m	$/mi	driver wage for transportation m
SP_m	mi/hr	average speed for transportation m
LUT_m	hr	loading and unloading time for transportation m
ME_m	$/mi	unit cost of maintenance expense for transportation m
GE_m	$/mi	unit cost of general expense for transportation m
$TCap_m$	ton	transportation capacity for transportation m
TMA_m	-	availability of transportation m
$cost_{h,l}^{WT}$	$/ton(yr)	cost of water transportation by pipeline from source c to facility l
$cost^{WP}$	$/ton(yr)	cost of water purchase per ton
DFC	$	distance fixed cost for water transportation
DVC	$/mi	distance variable cost for water transportation
DC	-	distance curvatures
PC_p	$/ton(yr)	product price at the market for product p
EAC	-	equivalent annual cost

CONTINUOUS VARIABLES

$cost_l^{I,F}$	$/yr	levelized facility investment cost of facility at location l
$cost_l^{OM,F}$	$/yr	facility O&M cost of facility at location l
$cost_c^{I,CV}$	$/yr	levelized conversion plant investment cost of facility at county c
$cost_c^{OM,CV}$	$/yr	conversion plant O&M cost of facility a location c
$El_{r,l}^R$	MW	rated plant capacity at facility l with renewable technology l
WF_l	ton(yr)	freshwater requirement for facility l
$w_{c,l}$	ton(yr)	freshwater flow from source c to facility l
$CV_{c,j}$	MW	conversion plant capacity for conversion technology j at location c
$e_{c,j}$	MW	linearization variable for continuous variable $CV_{c,j}$ and binary variable $x_{c,j}$
CV^{up}	ton(yr)	upper bound for continuous variable CV
$z_{p,l,c,m}$	ton(yr)	flow of product p from facility l to county c using transportation mode m

BINARY VARIABLES

$x_{j,C}$	-	conversion plant binary variable with technology j at location c
$y_{r,t,l}$	-	facility binary variable with renewable r and ammonia production size t at location l

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

1. INTRODUCTION

The development of alternative energy carrier has become crucial research areas for sustainable environment for human being. International agreement called 'Paris Agreement' initiated international and domestic protocols to control temperature rise around the globe from the use of fossil fuels. In the United States, the government, academia, and private cooperation has researched various options of alternative energy carrier to reduce greenhouse gasses in recent decades. Reviews on the ammonia energy carrier chain received noteworthy attention in recent decades with the advantages, which has facilitated research of various applications using ammonia as an energy carrier and fuel to produce electricity.

Ammonia is an attractive candidate for the alternative energy carrier because of its carbon-less molecule structure, mature production, and well-developed supply chain. Ammonia-reaction does not produce carbon emissions, one of the main greenhouse gasses, so it fits to clean and sustainable energy carrier. Furthermore, ammonia supply chain already has well-established production and transportation networks since ammonia has been one of the most essential chemicals used for fertilizer: a feed for the human population growth in history. In addition, an ammonia can be easily stored in the storage as a liquefied form due to its moderate boiling temperature and pressure that requires less energy and process for liquefaction. These facts enable ammonia to become an economic and sustainable energy carrier.

However, conventional ammonia production accounts for 1% of global CO_2 emissions with the use of fossil fuel to obtain hydrogen, the primary molecule for ammonia production.[1] The hydrogen have been conventionally and economically produced through steam-methane reforming (SMR) process which requires methane, mostly from natural gas. [2, 3] To overcome unavoidable greenhouse gas emission, the current research highlights [3] the benefits of ammonia production coupled with renewable energy power plant. Instead of fossil fuel use, new technology incorporates electrolysis splitting water molecules to obtain hydrogen using electricity generated by solar and wind energy plants. With this new idea, ammonia can be produced without fossil fuel energy input realizing carbon-free and external energy-free ammonia production process.

To achieve the essential benefits of using ammonia, the energy carrier chain must be studied at the production scale, network scale, and conversion technology scale to ensure viability of entire supply chain. At the production level, various researches actively incorporate renewable energies to ammonia production with electrolysis. West central Research and Outreach center demonstrated pilot plant scale ammonia plant with production capacity of 25 tons/year incorporating wind-powered electrolysis.[3] Most recently, Yara International plans to install commercial scale ammonia production plant incorporating solar energy as early as 2019.

The network is bounded in the state of Texas in this study to optimize the supply chain in relatively reduced scale compared to the U.S. Texas consumes the largest amount of electricity and generates the largest amount of renewable electricity in the U.S. [4] Also, the capacity of wind energy in Texas is expected to overtake coal in 2018. [5] These facts attract Texas is an exemplary state representing the U.S. to optimize the ammonia supply chain as an energy carrier.

On the conversion technology scale, ammonia is being considered as an alternative fuel for heat and electricity generation. Recent research [6] on gas turbines with ammonia-firing reached the rated power of 50kW coupled with turbine outlet temperature of 630℃, an appropriate condition to construct combined cycle increasing efficiency. A journal article reported experimental data of Solid oxide fuel cells (SOFC) using ammonia with capacity of 300mW/cm^2

efficiency. Electricity generated by the conversion technologies is modeled to meet the demand of every county in Texas.

This dissertation investigates a possibility of ammonia as a new energy carrier for electricity incorporating renewable energy in the future. It focuses on two main features concerning distributed renewable ammonia plants in the state of Texas: its optimized production, supply chain, and conversion technology network and appropriate scale to be competitive in the market.

2. LITERATURE REVIEW

2.1. Ammonia as an Energy Carrier

Ammonia is an attractive candidate for the alternative energy carrier because of its carbon-less molecule structure and matured production and supply chain. Ammonia-reaction does not produce any carbon emission, one of the main greenhouse gasses, so it fits to clean and sustainable energy carrier. Furthermore, ammonia supply chain already has well-established production and transportation networks since ammonia has been one of the most essential chemicals used for fertilizer, a feed for the human population growth in history.

Table 1 Properties of Various Energy Carriers

	Boiling Point (℃ at 101.3 kPa)	Vapor Pressure (Tripple Point) kPa	Liquid Density (at boiling point) g/cm^3	Energy Density kWh/l	Hydrogen Weight %H
Methanol	64.6	32	0.764	4.67	12.6
Hydrogen	-252.8	7	0.071	2.54	100
Methane	-162	12	0.436	6.4	25.1
Liquid Ammonia	-33.43	6.077	0.682	4.32	17.8

In addition, an ammonia has competitive energy density and high hydrogen weight content compared to other alternative energy carriers: hydrogen and methanol, which makes ammonia an attractive medium as an energy carrier. It also can be easily stored in the storage as a liquefied form due to its moderate boiling temperature and pressure that requires less energy and process for liquefaction. Table 1 summarizes major properties to compare ammonia with other alternative energy carriers. These facts enable ammonia to consider a promising option to become an economic and sustainable energy carrier.

2.2. Ammonia Synthesis

Ammonia production is processed by chemical synthesis called Harber-Bosch process, well-developed chemical synthesis and mostly used in the industry over the centuries. The synthesis reaction to produce ammonia requires hydrogen, nitrogen, and iron catalyst and is processed under 200 to 350 bar pressure and 300 to 500 degree Celsius. Through the reaction, only partial amount is converted to the product of ammonia, and the rest is recycled to the process, enhancing the process efficiency. Despite reaction is exothermic, the loss of energy 1.5 GJ t-1 is relatively small compared to energy of the ammonia, 28.4 GJ t-1. [7] This process leads to conversion efficiency of 60-65% from natural gas (mostly methane) to ammonia. [8]

Ammonia production requires external feedstock for operation: electricity, water, and air as shown in Figure 3 [9]. It is important to note that the process requires 2.3 tons of water to produce a ton of ammonia; however, 45% of the consumption, process condensate, recycled back to the process within the system, and the rest shall be continuously filled from external source as summarized in Figure 4. [10]

2.3. Hydrogen Production

Hydrogen is mostly and economically produced from steam methane reforming (SMR) process and partially from electrolyze. Recently, coal gasification, allows an alternative process to produce hydrogen, providing economic solutions using the most abundant resource, coal.

Hydrogen can be extracted from hydrocarbon molecules in fossil fuels. It is mostly and economically produced by steam-methane reforming (SMR) with fossil fuels and has 48% share of global hydrogen production. [7] Coal and oil gasification are the next production methods that accounts for 30% and 18%. [8] The reaction of SMR process is given by Eq. (1):

$$H_2O + CH_4 \rightarrow CO + 3H_2 \qquad \text{Equation 1}$$

These production technologies inevitably require fossil fuel usage and emit carbon monoxide and carbon dioxide and other greenhouse gasses. Furthermore, the hydrogen production technologies are located in large central plants for economies of scale, jeopardizing local environments.

Instead, electrolysis is well known for clean and sustainable process for hydrogen production. It produces hydrogen by splitting water molecule. The process is the interchange of atoms and ions and exploits electric current to force molecules in water to decompose. The overall chemical reaction of a water electrolysis process is given by Eq. (2):

$$H_2O \rightarrow H_2 + (1/2)\, O_2 \qquad \text{Equation 2}$$

Despite of carbon free reaction process, the technology does not yet have meaningful share worldwide, accounting for rest 4% of global production, [9] due to its high capital and operation cost. On the other hand, along with rapid research and development on the technologies, researchers predict that the investment costs for electrolyzer will eventually be economical with large economy of scale in the future; moreover, the prediction is well supported by H2A analysis tool developed by DOE. [10]

2.4. Wind Energy

Wind energy is becoming rapidly prevalent in global energy systems. Wind is a clean energy source that can be transformed to power by wind turbine generator that is under rapid development in terms of capacity. For instance, maximum rated power output of wind turbine is now 5 MW, which is 67 times higher than that of wind turbine, 75 kW, in 1980s as shown in Figure 1. [11] With such drastic improvement in wind turbines, Figure 2 shows that the market capacity expanded to 486 GW in 2016, especially 54 GW added in 2016 which accounts for 11.8% of growth rate in the same year. [12] Its market has become considerably competitive ever since 1980 when it had an almost negligible share in the energy market. Now wind energy systems accounts for 200 GW installed nominal power. This incredible growth could be achieved because of significant wind turbine technology development.

Texas has the largest wind-powered electricity grid in the United States. It consumed 10% of electricity generation from wind-powered plants, of which rated capacity accounts for 16% of total generation capacity in 2015. Despite this huge availability, mismatch in availability and demand creates inefficiency in the grid from long-distance transmission loss and additional infrastructure for transmission.

2.5. Ammonia Conversion Technology

Ammonia containing 17.5 wt% hydrogen is a promising alternative energy carrier for electricity generation due to an ideal carbon-free fuel for fuel cells. The fact that ammonia is easier to be transported than hydrogen with mild liquid state requirements attracts engineering and research fields' attention. Among various conversion technologies, fuel cells and gas turbine with ammonia direction injection are feasible candidates with promising results.

Fuel cells are considered as one of the feasible alternatives to conventional and concentrated power plant with many advantages. They have high thermodynamic efficiency, low emissions of SO_X, NO_X, and CO2, low noise in the absence of rotating machine, and flexible capacities with respect to the applications. Among various ammonia fuel cells technologies as summarized in Table 2, SOFCs has the highest power density, operating temperature, and efficiency, which is an ideal candidate for the combined heat and power generation.

Table 2 Summary of Ammonia Fuel Cell Technologies

	Type	Operating Temperature (℃)	Power Density (W/cm$^{2)}$	Efficiency (%)	References
Alkaline Fuel Cells (AFCs)	KOH electrolyte	50-200	-	-	Cairns and Simons, 1968
	Molten hydroxide NAOH/KOH	200-450	-	-	
	Nickle	450	0.04	-	Ganley, 2008;

					Hejze et al., 2008
Proton Exchange Membrane Fuel Cells (PEMFCs)	TBC	TBC	TBC	-	Boggs and Botte, 2009
Alkaline Membrane Fuel Cells (AMFCs)	Nickle anode and MnO_2 cathode	Room Temp.	Low	-	Lan and Tao, 2010
Solid Oxide Fuel Cells (SOFCs)	Oxygen-conducting $Ce_{0.8}Sm_{0.2}O_{1.9}$ electrolyte	650-800	0.3-1.19	30%-60%	Cinti et al., 2014 Meng et al., 2007

Furthermore, ammonia is being recognized as one of the direct fuel sources for combustion process for gas turbines. Ammonia combustion process is advantageous to the natural gas-fired combustion: CO2 free combustion, alternative fuel suitable to storage and transport, and mature technology of combustion facility. It has been reported that an ammonia-fueled gas turbine is being developed with power output of approximate 41.8kW, 22% efficiency, and turbine exhaust temperature around 600℃. [6] The on-going researches are targeted to increase the efficiency of ammonia-fueled gas turbine to that gas-fired gas turbine. With this future accomplishment, it would be possible to reach 60% combined cycle power plant efficiency replacing the conventional ones.

2.6. Mixed Integer Linear Programming (MILP)

Mixed Integer Linear Programming (hereunder “MILP”) is an optimization technique that optimizes objective function under given linear constraints. The technique can capture relationships between variables very effectively that the qualitative approach could not achieve. It has been used in various areas: operational research, microeconomics, network flow optimization, and etc. Especially, it supports the industries to use the available resources with the maximum efficiency and provides better decision making across the industries.

Among various research areas, an energy carrier supply chain optimization benefits from the mathematical technique. MILP is more accurate and more rigorous in terms of finding optimized solutions within the design model representation from quantitative and qualitative information in the industries. Though its computation cost may be substantial due to the size of variables and data, state-of-the-art hardware and invention of powerful software, such as CPLEX and GAMS, enable large and complex scale problem feasible. [13]

3. SUPPLY CHAIN NETWORK DESCRIPTION FOR TEXAS CASE STUDY

3.1. Background

Texas is the most electricity consuming state within U.S., and 80% of electricity consumption was generated by fossil-fueled power plants in 2015. Significant amount of effort is being put in the industries in accordance with Paris Agreement as it is a well known fact that fossil fueled power plants are the major source of Greenhouse Gas. (GHG) The world is seeking for alternative means to reduce GHG and restrain temperature increase around the globe.

Ammonia has a great potential in substitution of current energy supply chain eliminating Greenhouse Gases. One of the required feedstock for ammonia synthesis process is hydrogen, which has been produced from Steam-methane reforming (SMR) or coal gasification process that, again, still emits GHG to the atmosphere. Instead, hydrogen can be obtained from electrolysis process with electricity that no GHG emission is guaranteed through the process. Previous researches [10, 14, 15] provided meaning full results that renewable ammonia production is viable by a combination of previously existing mature technologies.

Texas is a good example where demand and supply does not match. Most of wind and solar energy power plants are located northwestern area whose potential energy is largely available, whereas large amount of energy demand is located in southern area due to the existence of major cities: Houston, Austin, Dallas-Fort worth, and San Antonio. Texas also has 254 counties within the state well interconnected with inter-intra state highways and railroads.

In the study, the model seeks the best geographical and process combination within ammonia energy supply chain to minimize the cost.

3.2. Objectives

The main objectives of the thesis dissertation is to model ammonia energy supply chain network and to optimize the model in the state of Texas using mathematical tool: mixed integer linear programming. (MILP) The following objectives are considered in the thesis.

- Modeling ammonia energy supply chain superstructure networks using MILP
- Case studies of the ammonia energy supply chain networks to seek the best-optimized solution
- Sensitivity analyses to understand the network

3.3. Problem Formulation

The ammonia energy carrier model is to minimize the cost associated in the network. Previous sub-chapters defined the necessary parameters to formulate the energy supply chain optimization model. These inputs include (i) renewable technologies, (ii) ammonia production technologies, (iii) transportation model, (iv) conversion technologies, (v) demand, and (vi) water resources. Given the size of parameters and model, the optimization model is formulated as MILP problem to achieve (a) strategic location of facilities (renewable power plants and ammonia production plants) (b) the capacity of facilities (c) the topology for ammonia supply chain (d) costs associated within the supply chain, and (e) sensitivity analysis for related variables and parameters. The complete mathematical model is defined as follows.

Eq. (3) restricts the number of facility to one at each location l. Eq. (4) provides maximum number N of facilities built in the state of Texas.

$$\sum_{(r,t)} y_{r,t,l} \leq 1 \qquad \text{Equation 3}$$

$$\sum_{(r,t,l)} y_{r,t,l} \leq N \qquad \text{Equation 4}$$

Eq. (5) introduces electricity constraint related to the rated capacity of renewable power plants. Renewable technologies(r) consist of solar and wind energy plants. They exist to meet the electricity demand (El_t^T) required by ammonia synthesis process at capacity t. The electricity requirement is satisfied by rated renewable power capacity ($El_{r,l}^R$) with renewable technologies r and location l. Scaling factor ($\mathrm{RF}_{r,l}$) and capacity factor($\lambda_{r,l}$) consider variation of availability and potential of renewable energy (wind velocity and solar radiation) at each location l with respect to the reference renewable power plant model given by NREL.

$$\sum_{r,t} y_{r,t,l} El_l^T = \sum_{r \in FL} 8760 \cdot \lambda_{r,l} RF_{r,l} El_{r,l}^R \qquad \forall l \in L^F \qquad \text{Equation 5}$$

Eq. (6) introduces land availability constraint that limits land use of renewable power plant at location l. Land requirement, a product of land requirement per unit electricity (RLR_r) and rated capacity of renewable power plant($El_{r,l}^R$), should be less than the land available at each location l (RLA_l).

$$RLA_l \geq \sum_r RLR_r El_{r,l}^R \qquad \forall l \in L^F \qquad \text{Equation 6}$$

Eq. (7) constrains that product produced at production facility ($PR_{p,t}$) should match to the product flow ($z_{p,l,c,m}$) with product p from location l to demand site c with transportation m.

$$\sum_{(p('NH3')c,m)} z_{p,l,c,m} = \sum_{(p('NH3'),r,t)} y_{r,t,l}\, PR_{p,t} \qquad \forall l \in L^F, p('NH3') \in P \qquad \text{Equation 7}$$

Eq. (8) constrains the number of conversion power plant (ammonia to electricity) to one per county. Ammonia product flow ($z_{p,l,c,m}$) is used as an fuel for conversion plant to generate electricity in Eq. (9). A sum of conversion plant capacity ($CV_{c,j}$) considering yearly operation (8760hrs) should be equal to the energy input converted from ammonia product flow with constant 5.2 MWh/ton$_{NH3}$. Eq. (10) satisfies the electricity demand (DM_c) of Texas by generation from conversion power plants considering conversion plant availability (CA_j) and efficiency (η_j) at demand site c.

$$\sum_{j \in FL} x_{j,c} \leq 1 \qquad \forall c \in L^F \qquad \text{Equation 8}$$

$$\sum_{j} x_{c,j} \cdot CV_{c,j} = \sum_{p('NH3'),l,j,m} 5.2 \cdot z_{p,l,c,m} \qquad \text{Equation 9}$$

$$\sum_{(p('NH3'),l,m,j) \in PT} x_{c,j}(CV_{c,j} \cdot 8760 \cdot \eta_j \cdot CA_j) \leq DM_c \cdot PD \qquad \forall (c) \in C_P \qquad \text{Equation 10}$$

In Eq. (11) and (12), as the constraints for conversion plant are non-linear, linearization of equations is essential to solve MILP model. A product of continuous variable $cv_{c,j}$ and binary variable $x_{c,j}$ is substituted by linearization variable $e_{c,j}$. Linearization of the equations takes a place. Accordingly, Eq. (11) to (12) substitute Eq. (9) to (10).

$$\sum_{j} e_{c,j} \cdot 8760 \cdot CA_j \eta_j = \sum_{p('NH3'),l,j,m} 5.2 \cdot z_{p,l,c,m} \qquad \text{Equation 11}$$

$$\sum_{(p('NH3'),l,m,j)\in PT} e_{c,j}(8760 \cdot \eta_j \cdot CA_j) \leq DM_c \cdot PD \qquad \forall(c) \in C_P \qquad \text{Equation 12}$$

The following equations 13~15 linearize the production of binary and continuous variable. The linearization variable $e_{c,j}$ is bounded below by zero and bounded above (CV^{up}) by the pre-calculated capacity.

$$e_{c,j} \leq CV^{up} \cdot x_{c,j} \qquad \text{Equation 13}$$

$$e_{c,j} \leq CV_{c,j} \qquad \text{Equation 14}$$

$$e_{c,j} \geq CV_{c,j} - \left(1 - x_{c,j}\right) \cdot CV^{up} \qquad \text{Equation 15}$$

$$e_{c,j} \geq 0 \qquad \text{Equation 16}$$

Eq. (17) – (19) introduce water constraints. A sum of water requirement (FW_t) for ammonia production plant with capacity t should be equal to the water requirement at location l (WF_l) where facilities are located. Eq. (18) states that a sum of water flow to location l should be equal to the water requirement at location l. Water reservoir availability (WA_h) should be more than or equal to the water flow from h.

$$\sum_{r,t} y_{r,l,t} FW_t = WF_l \quad \text{Equation 17}$$

$$WF_l = \sum_{h \in H_w} w_{h,l} \quad \text{Equation 18}$$

$$\sum_{l} w_{h,l} \leq WA_h \quad \text{Equation 19}$$

3.3.1. Facility Cost (Renewable & Ammonia Production)

As the renewable power plants and ammonia production plants selected for location l are located as a package, so called 'Facility,' investment cost of facility at location l ($Cost_l^{I,F}$) is a sum of investment cost for renewable power plant and ammonia production plant at location l.

Investment cost for facilities considers both renewable power plants and ammonia production plants. It is a product of rated capacity of selected renewable power plants with technology r at facility l ($El_{r,l}^{R}$) and unit cost for different renewable technologies r. (RC_r) Binary variable for facility ($y_{r,t,l}$) allows to consider investment cost for ammonia production plant (LC_t) for capacity t.

Investment costs for facility at location l consists of renewable power plant and ammonia production plant as addressed in Eq. (20). Cost for renewable power plant is a product of rated plant capacity ($El_{r,l}^{R}$) and annualized unit investment cost per megawatt (RC_r). In addition, cost for ammonia production plant is a product of binary variable for facility with capacity t at location l ($y_{r,t,l}$) and annualized investment cost. (LC_t)

$$\sum_{r,t \in FL} El_{r,l}^{R} RC_r + y_{r,t,l} LC_t = Cost_l^{I,F} \quad \text{Equation 20}$$

O&M cost for facility at location l is a sum of that of renewable power plant and ammonia production plant as addressed in Eq. (21). O&M cost for renewable power plant consists of overall O&M cost (ROM_r) and land lease cost (RLC_r) as provided by NREL reports. [16] For land lease cost, land price multiplier at location l (RLM_l) introduces factor to scale actual market price of land at each county. [17]

$$\sum_{r,t \in FL} El_{r,l}^{R}(ROM_r + RLC_r RLM_l) + y_{r,t,l} LO_t = Cost_l^{OM,F} \qquad \text{Equation 21}$$

3.3.2. Conversion Plant Cost

Total Conversion Technology Cost for both Investment and O&M

Total cost of conversion power plant at demand site c is a product of binary variable for conversion power plants ($x_{c,j}$) and investment & O&M costs. (variable and fixed) Investment cost (CC_j) and fixed O&M costs (CFO_j) are a function of rated conversion plant capacity. In addition, variable O&M cost (CVO_j) is a function of electricity generation; therefore, multiplied by electricity requirement at demand site c. (DM_c)

$$\sum_{j \in FL} x_{c,j}(CV_{c,j}(CC_j + CFO_j) + DM_c CVO_j) = Cost_c^{CV} \quad \forall c \in L^F \qquad \text{Equation 22}$$

3.3.3. Transportation cost

Almansoori et al., constructed transportation cost model in energy supply chain. Accordingly, transportation costs ($cost_{p,l,c,m}^{PT}$) are calculated using Equation XX-XX, consisting of fuel cost (FC), labor cost (LC), maintenance cost (MC), and general cost (GC). [18]

The yearly fuel cost per unit product is a main contributor to transportation cost and is a function of yearly fuel usage and fuel price as shown in Eq. (23).

$$FC_{p,l,c,m}^{PT} = \frac{FP_m}{FE_m} \qquad \text{Equation 23}$$

Eq. (24) states labor costs per unit product is a product of driver's wage and total delivery times within a year: the first and second term respectively.

$$LC_{p,l,c,m}^{PT} = \frac{DW_m}{TCap_m SP_m} + \frac{DW_m LUT_m}{TCap_m} \qquad \text{Equation 24}$$

Eq. (25) explains maintenance cost per unit product is associated with cost for maintenance activities of transportation systems. It accounts for a multiplication of maintenance cost per unit distance driven and total yearly distance traveled.

$$MC_{p,l,c,m}^{PT} = \frac{ME_m}{TCap_m} \qquad \text{Equation 25}$$

Eq. (26) states general cost represents insurance, registration and license, and miscellaneous costs. It is a function of general expenses and transportation units.

$$GC_{p,l,c,m}^{PT} = \frac{GE_m}{TMA_m TCap_m SP_m} + \frac{GE_m LUT_m}{TMA_m TCap_m} \qquad \text{Equation 26}$$

Parameters used in transportation is summarized in Table 13. These parameters and equations are a function of distance in each equation. Accordingly, distance is a key-driven factor in transportation for cost. Therefore, Eq. (27) indicates that cost of transportation for product p from location l to demand c using transportation mean m is a product of *DC* (Distance Curvature) and a sum of 4 costs addressed above. As distance between two location ($DI_{l,c,m}$) is calculated as straight line, *DC* is considered 1.1 to compensate curvature.

$$cost_{p,l,c,m}^{PT} = 2DI_{l,c,m}(FC_{p,l,c,m}^{PT} + LC_{p,l,c,m}^{PT} + MC_{p,l,c,m}^{PT} + GE_{p,l,c,m}^{PT}) \cdot DC \qquad \text{Equation 27}$$

Water has well established pipeline network across the state of Texas being the most economical means of transportation. *DFC* is a distance-fixed cost for water and is only dependent upon the flow of water. *DVC* is a distance-variable cost associated with both flow of water and distance traveled. *DC* is also introduced in this equation so as to compensate the curvature as addressed in Eq. (28). [19]

$$cost_{h,l}^{WT} = DFC + DVC \cdot DI_{h,l} \cdot DC \qquad \text{Equation 28}$$

3.3.4. Objective Function

The objective function Eq. (29) includes and minimizes the overall cost associated in the ammonia energy supply chain, modeling (i) investment cost for facilities, (ii) O&M cost for facilities, (iii) overall cost for conversion power plants, (iv) product sales of oxygen, (v) water purchase and transportation, and (vi) ammonia transportation cost.

$$min \sum_{l \in L^F} cost_l^{I,F} + \sum_{l \in L^F} cost_l^{OM,F} + \sum_{c \in C} cost_c^{CV} - \sum_{p('O2'),l,c,m} z_{p,l,c,m} PC_{O2} + \sum_{h \in H} \sum_{l \in L^F} w_{h,l} \left(cost^{PT} + cost_{h,l}^{WT}\right) + \sum_{(p('NH3'),c,l,m) \in PT} z_{p,l,c,m}\, cost_{p,c,l,m}^{PT} \qquad \text{Equation 29}$$

The MILP optimization model is solved using CPLEX by GAMS.(General Algebraic Modeling System) The model has 2,047 binary variables, 20,127 continuous variables, and 9,011 constraints.

3.4. Ammonia Energy Network Superstructure

In the study, entire ammonia energy network is established to meet the electricity demand at county c utilizing renewable energy-ammonia production plant and conversion plant. Electricity requirement for ammonia production process, mainly air separation unit, (hereunder 'ASU') electrolysis, and Haber-bosch process is met by renewable energy power plant utilizing solar and wind energy from nature. ASU produces nitrogen and oxygen using cryogenic process and electrolysis process produces hydrogen and oxygen by splitting water. Furthermore, Haber-bosch process produces ammonia with nitrogen and hydrogen from previous process. Transportation means, truck and railroad, transport ammonia to conversion plant where it generates electricity from ammonia as fuel. The conversion plants consist of fuel cell, conventional gas turbine, and advanced gas turbine whose main objectives are to meet the electricity demand at county c. Water requirement is satisfied by available water source previously used for thermoelectric power plant. Figure 1. shows superstructure of overall ammonia supply chain network being used in the study.

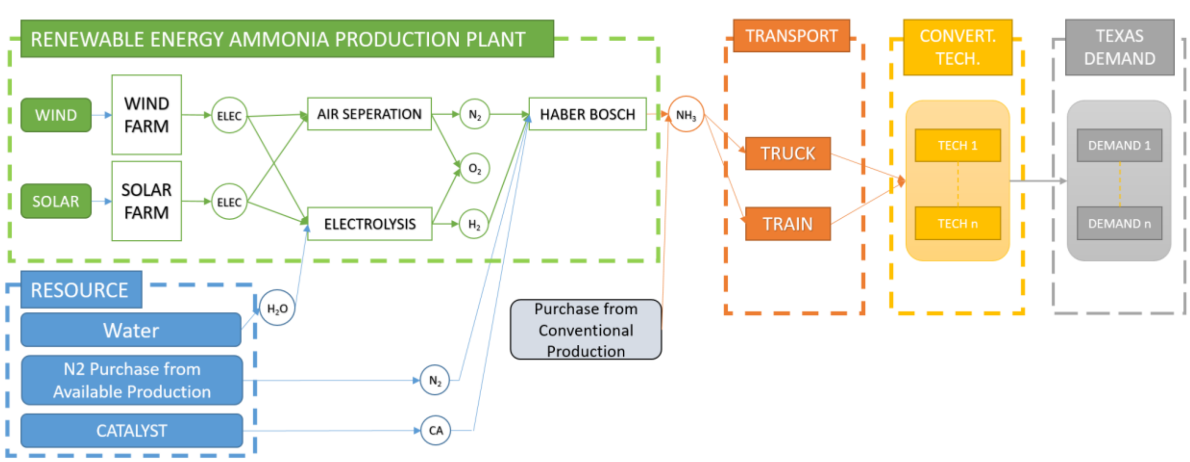

Figure 1 Ammonia Supply Chain Network

3.5. Time Horizon

The supply chain model only considers the year of 2015. All the parameters associated in the model are discrete for the year of 2015. For this purpose, investment cost that is entirely put at the beginning of the year is levelized using EAC. (Equivalent Annual Cost)

3.6. Electricity Demand

A data set for electricity demand in the state of Texas can be obtained from EIA database. [20] Though it provides state-level of electricity generation dataset, the study presumes that generation data set is equal to the demand as generation usually occurs to fulfill the electricity demand. Furthermore, demand data set for county-level are not available on EIA database; therefore, they are calculated using population based-estimation. [21]

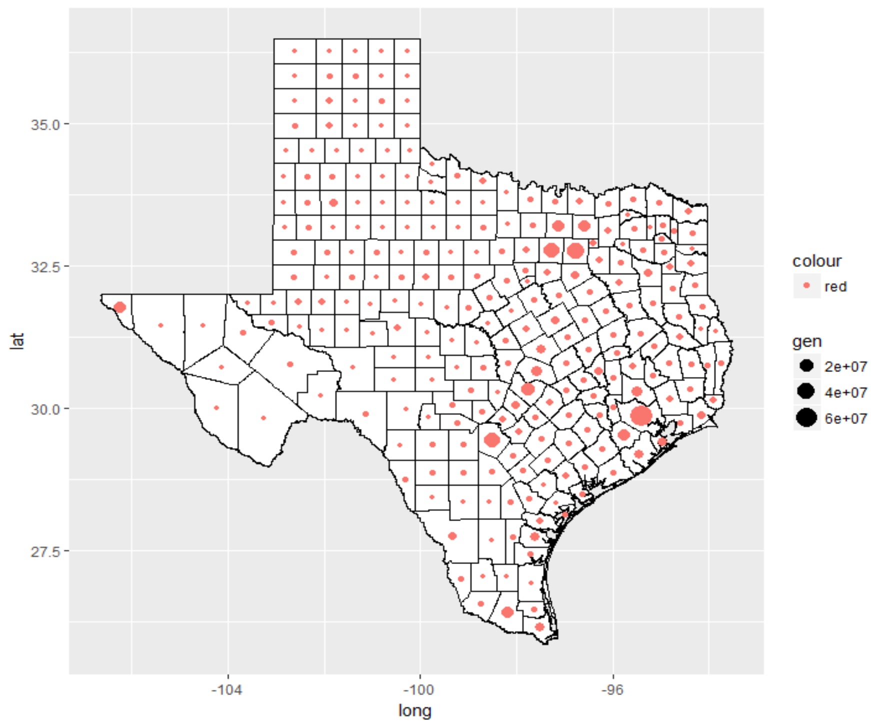

Figure 2 Demand Location and its Quantity

As of 2015, electricity consumption for Texas is recorded 449,826,336 MWH, of which renewable electricity —solar and wind— accounts for 10%, 45,234,124 MWH and fossil fueled electricity–coal, natural gas, and petroleum— for 80%, 359,527,275 MWH as shown in Table 3. This study only considers complete and partial replacement of fossil-fueled electricity and utilizes the rest of infrastructure as they are relatively carbon neutral.

Table 3 Electricity Demand Profiles of Texas

Population Rank	Demand Location Index (l)	County Name	FIPS Code	Texas Population	Percentage	Texas 2015 Net Generation (MWH)
Total				27,862,596	100%	449,826,336
1	l_1	Harris	48201	4,589,928	16.473%	74,101,871
2	l_2	Dallas	48113	2,574,984	9.242%	41,571,705
3	l_3	Tarrant	48439	2,016,872	7.239%	32,561,293
4	l_4	Bexar	48029	1,928,680	6.922%	31,137,481
5	l_5	Travis	48453	1,199,323	4.304%	19,362,412
...	...	...		...	...	...
250	L_{250}	McMullen	48311	804	0.003%	12,980
251	L_{251}	Kent	48263	769	0.003%	12,415
252	L_{252}	Borden	48033	633	0.002%	10,219
253	L_{253}	Kenedy	48261	404	0.001%	6,522
254	L_{254}	King	48269	289	0.001%	4,666

Based on the data set, the study considers 3 different scenarios in the new energy supply chain as summarized in Table 4. First, the 5 most electricity -consuming counties: Harris, Dallas, Tarrant, Bexar, and Travis in Texas are modeled in Case 1. These counties account for 44.18% of entire Texas electricity demand and include major cities in Texas: Houston, Dallas, Fort Worth, San Antonio, and Austin. Also, Case 2 considers 50% of Case 1 to see the geographical changes in results. It should be noted that these counties have no or insignificant capacity of renewable power plants; therefore, entire demand will be replaced with the new energy supply chain. In addition,,Case 3 considers Top 10 electricity consuming counties in Texas, which accounts for 60% for fossil-fueled energy consumption. Finally, Case 4 considers entire counties in Texas covering entire fossil-fueled electricity consumption that is 80% of Texas energy consumption.

Table 4 Case Scenarios and Demand Profiles

Consumption Category		Case 1 TOP 5 Counties 100%	Case 2 TOP 5 Counties 50%	Case 3 TOP 10 Counties 100%	Case 4 254 Counties 100%
Total electricity (MWH)	DM_c	198,734,762 (44.18% of Texas demand)	99,367,381 (22.09% of Base Case)	266,134,022 (60% of Base Case)	359,527,275 (80% of Base Case)
Fossil-fueled Electricity (Coal+Natural gas+Petro.)	-	198,734,762	99,367,381	266,134,022	359,527,275

3.7. Renewable Technologies

Capacity of renewable power plants varies with energy potential, capacity factor, and other losses at the location. Both wind and solar energy are intermittent and fluctuate in continuous stream. NREL dataset provides different energy potential profile in United States. With the dataset, the model can implement variation of potential at location l with scaling factors. Also, the model assumes that the energy potential in the year of 2015 is constant; however, intermittency is corrected with capacity factor.

Capacity factor ($\lambda_{r,l}$) is a ratio of actual power generation to available power capacity within given time. The factor differs by location and greatly influences capacity of renewable power plants as it indicates availability of renewable energy potential at the location. In case of wind energy, the capacity factors at each location l are drawn from NREL data set. [22] On the other hand, capacity factor for solar energy is fixed with 0.24 due to its unavailability of sources.

Scaling factor($RF_{r,l}$) compensates renewable power plant capacity with respect to different energy potential among counties within Texas. Eq. 22-23 are directly multiplied to the energy balance equations to calculate a capacity of renewable power plants at location l.

$$RF_{r,l} = RF_{\prime WD\prime,l} = \left(\frac{v_l}{v_{base}}\right)^3 \qquad \text{Equation 30}$$

$$RF_{r,l} = RF_{\prime PV\prime,l} = \frac{GHI_l}{GHI_{base}} \qquad \text{Equation 31}$$

Average energy potential is drawn from NREL data set [22, 23] GHI Solar Energy (kWh/m2/day) and wind velocity (m/s) represents solar and wind potential respectively. Capacity of renewable power plants is greatly dependent upon available energy potential. Therefore, it is important to scale the capacity with respect to its location.

It should be noted that as NREL data set does not include relevant information for Anderson county, capacity factor and scaling factor were averaged from adjacent counties: Henderson, Cherokee, Freestone, and Houston.

3.7.1. Solar Energy

Between two major technologies to convert solar energy to electricity: photovoltaic (PV) and concentrated solar thermal power (CSP), the model only considers PV as ammonia synthesis process in the study only requires electricity in terms of energy. Though rapid innovations has dramatically reduced cost of CSPs, it has been reported that degree of decline is not comparable to PV. Furthermore, CSPs that have been recently built and are under operation shows unsatisfactory results as opposed to the design and expected performance. [24] Among various PV technologies, the model considers crystalline silicon(c-Si) module type over thin-films module type due to cost effectiveness and tracking type over fixed-tilt type due to better energy production. These facts lead the model only to consider PV technology with c-Si module and tracking type in consideration of economics and sustainability. Table 5 shows reference data of solar power plants used for the study. [25]

Table 5 Reference Solar Plant Cost Model Parameters Reprinted from [25]

PV Plants		unit	Value	Remarks
Investment Cost	RC_r	\$/MW	985,093	PV
O&M Cost	ROM_r	\$/MW	18,500	
Land Lease Cost	RLC_r	\$/MW	66,920	
Land Requirement	RLR_r	km^2/MW	0.03	

3.7.2. Wind Energy

Wind turbine generator converts wind energy, in the form of wind speed, to electricity. The energy that contacts blades creates uneven pressure, higher in on side and lower on the other, causing them to spin around the center. Therefore, power output is a function of wind speed (v), blade diameter (D), and rotor peak (Cp) as illustrated in Eq. (3).

$$P_{theoretical}(v) = c_p(v) \cdot P_{wind}(v) = c_p(v) \cdot \frac{\rho}{2}\frac{\pi D^2}{4} \cdot v^3 \quad \text{Equation 32}$$

$$P_{actual}(v) = P_{theoretical}(v) \cdot RF_{r,l} \cdot \omega \quad \text{Equation 33}$$

Wind Toolkit on NERL (National Renewable Energy Laboratory) provides wind resource data in entire region of United States. Among data, the wind speeds at a height of 90m above ground are averaged with 5 min time series wind data in the year of 2012. The rest of parameters, diameter and rotor peak, refers to reference wind turbine information. Each wind turbine has capacity of 2 MW, multiplied to meet energy requirement of the ammonia production. Table 6 contains information and cost parameters of reference wind power plant. [16]

Table 6 Reference Wind Turbine Cost Model Parameters Reprinted from [16]

Wind Turbine		unit	Value	Remarks
Rated power		MW	2	
Rotor diameter		m	102	
Hub height		m	82.1	
Drivetrain design		-	Geared	
Rotor peak		-	0.47	

Wake Effect Loss	ω	%	1.25	Hoon et al., 2018
Capacity Factor	RF	%	39.9	DOE, 2015
Wind Speed	v	m/s	7.25	
Investment Cost	RC_r	\$/MW-yr	145,020	EAC (Annualized)
O&M Cost	ROM_r	\$/MW	43,000	
Land Lease Cost	RLC_r	\$/MW	8,000	
Land Requirement	RLR_r	km^2/MW	0.345	

Furthermore, Wake effect is a loss of wind kinetic energy across the rotor blades and it reduces wind speeds and power output accordingly at locations where multiple wind turbines are installed. It is an important factor to estimate actual power generation at large MW wind farm installations, which inadvertently require multiple wind turbines, resulting in unavoidable wake effects. Data-driven models with data from commercially operating wind turbines available estimates the loss of annual power between 0.5 ~ 2.0% for six turbine pairs. [26] Though actual wind farm model may have more than six turbine pairs, the study considers 1.25% loss in annual wind power generation, the average between two numbers, to pursue precise wind farm generation model, the rest, such as layout and design of wind farm, is beyond the scope of this work.

3.8. Ammonia Production Process

3.8.1. Electrolyzers

Electrolysis differentiates the new energy carrier chain from the conventional reforming process utilizing fossil-fuel in terms of hydrogen production. It splits the water molecule into its separate entities: hydrogen and oxygen as addressed below.

$$H_2O + Energy\ (Electricity) \rightarrow H_{2(g)} + \frac{1}{2}O_{2(g)} \qquad \text{Equation 34}$$

Equation (5) shows that the process is endothermic, requiring external energy input, in the form of electricity, which makes the process attractive to be coupled with renewable energy.

There are two well-developed electrolysis technologies: polymer electrolyte membrane (PEM) electrolysis and alkaline electrolysis. Both technologies are commercially available and nearly indistinguishable in terms of performance and output quality as required by ammonia production system. However, PEM electrolysis is relatively new technology and is known for fast response and shutdown. Also, its production capacity is available and economically competitive at relatively smaller scale compared to alkaline electrolysis. On the other hand, alkaline electrolysis has more flexible and broader range of production capacity from lab-scale to large-scale plant production. In addition, the process is well-optimized in terms of efficiency and cost from extended operation period and is expected to have economic advantage in the future. [27]

Table 7 Comparison of Alkaline and PEM Electrolysis Technologies Reprinted from [28, 29]

	Unit	Alkaline	PEM
Production Capacity	Nm3H2/h	0.25 – 760	0.01 - 240
	Kg H2/day		1,500

Electrical Input	kW	1.8 – 5,300	0.2 – 1,150
Operating Temperature	℃	40 – 90	20 - 100
Operating Pressure	bar	<30	<200
Hydrogen Purity	%	99.5 – 99.9998	99.9 – 99.9999
Investment Cost (currency in 2018)	€/kW ($/kW)	1400-1700 [28] (1650-2004)	1500 [29] (1768)

As a result, the model incorporates alkaline electrolysis technology for central production (over 60,000 kg/day as defined by US DOE) and PEM electrolysis for distributed production. In this model, reference data for alkaline electrolyzers is based on Norsk Hydro Atmopheric Type No.5040 as it has the largest-commercial product available in the market. [30]

Table 8 Electrolyzer Mass Balance Sheet Reprinted from [30]

Manufacturer	Type	H_2O	H_2	O_2	Conversion Efficiency	WTR Removal
-	-	kg/hr	kg/hr	kg/hr	%	kg/hr
Stuart	Alkaline	60	5.4	43	80	11.8
Teledyne	Alkaline	42	3.77	30.01	80	8.21
Proton	PEM	8.4	0.9	7.1	95	0.4
Norsk	Alkaline	485	43.59	346.51	80	94.82
Avlance	Alkaline	4.5	0.45	3.57	89	0.48

3.8.2. Air Separation Unit

Nitrogen is an essential feedstock for ammonia synthesis along with hydrogen and is processed from air. There are three different technologies for nitrogen separation from air: cryogenic air separation process, (ASU) pressure swing adsorption, (PSA) and membrane. Ammonia synthesis requires huge amount of nitrogen, especially covering electricity demand of Texas. However, PSA and membrane technologies are incapable of producing such a huge amount of nitrogen at the moment, whereas cryogenic ASU process is mature to produce large volume of both nitrogen and oxygen. Additionally, oxygen separated from ASU can be sold in the market, providing extra revue in the supply chain.

3.8.3. Water Treatment Unit

Water in Texas has high-TDS primarily with sodium chloride or table salt, namely high salinity. (previous climate hot and arid, the climate was very hot and arid, and the water in the Gulf of Mexico evaporated, leaving behind layers of salt nearly a mile thick. This evaporite deposit (so named because it consists of minerals evaporated from water) lies under most of the Gulf Coastal Plains and contributes to high TDS values in Gulf Coast aquifers. (150 to 400 mg/L, 150 PPM to 400 PPM)[31] On the other hand, Product purity requirement for alkaline electrolysis is about 10 ppm TDS, distilled water.

As an electrolysis production requires relatively large water consumption (1.6 ton of H2O for 1 ton of Ammonia production), securing continuous water supply is essential to maintain the energy supply chain stable and sustainable. The state of Texas has well-developed water pipeline network and well systems available. The main water supply comes from water municipal network available. In case of shortage or inaccessibility due to the distance from the network, the study considers well water from the ground as secondary resources.

An alkaline electrolysis typically requires water purity about 10 ppm TDS. Municipal water supply complies EPA secondary standards where TDS limit is 500 PPM. Moreover, well water in Texas has high-TDS value (150 to 500 ppm) with high salinity from sodium chloride or table salt. This strongly suggests all the water supplies considered in this study require water purification process to meet the purity requirement of alkaline electrolysis.

Among three different technologies for purification, mainly desalting, system that are commonly and commercially applicable in the related industry are multi-effect distillation (MED), mechanical vapor compression (MVC), and reverse osmosis (RO) as summarized in Table 8. Although RO has several advantages in low energy consumption and high production capacity, it is not suitable to meet the water purity requirement of alkaline electrolysis due to its risk of damaging the stacks. MED is not suitable for the application as its feedwater quality requires relatively high quality around 500 ppm while water may contain much higher salinity. MVC is preferable for small-medium size by 3000 m3/day capacity with renewable electricity. It has medium energy consumption rate and production cost and it meets the water purity requirement. Therefore, the study incorporates MVC technology for water purification.

3.8.4. Ammonia Synthesis Loop

The model implements conventional Haber-bosch process where it requires nitrogen, hydrogen, catalyst and electricity to produce ammonia. Due to computational expense in the model, the study does not aim to calculate precise process and cost parameters for every size of ammonia production plant, rather estimates with respect to reference model using cost function.

Table 9 Ammonia Plant Production Capacity within United States Reprinted from [32]

COMPANY	*LOCATION*	*TPYr*	TPD
Agrium Inc.	Borger, TX	490	1,342
Do.	Kennewick, WA	180	493
CF Industries Holdings, Inc.	Donaldsonville, LA	2,490	6,822
Do.	Port Neal, IA	336	921
Do.	Verdigris, OK	953	2,611
Do.	Woodward, OK	399	1,093
Do.	Yazoo, City, MS	454	1,244
Coffeyville Resources Nitrogen Fertilizers, LLC	Coffeyville, KS	375	1,027
Dakota Gasification Co.	Beulah, ND	363	995
Dyno Nobel Inc.	Cheyenne, WY	174	477
Do.	St. Helens, OR	101	277
Green Valley Chemical Corp.	Creston, IA	32	88
Honeywell International Inc.	Hopewell, VA	530	1,452
Koch Nitrogen Co., LLC	Beatrice, NE	265	726
Do.	Dodge City, KS	280	767
Do.	Enid, OK	930	2,548
Do.	Fort Dodge, IA	350	959
Do.	Sterlington, LA	1,110	3,041
LSB Industries, Inc.	Cherokee, AL	159	436
Do.	Pryor, OK	210	575

Mosaic Co., The	Faustina, LA	508	1,392
OCI North America	Beaumont, TX	231	633
PCS Nitrogen, Inc.	Augusta, GA	644	1,764
Do.	Geismar, LA	483	1,323
Do.	Lima, OH	535	1,466
Rentech Energy Midwest Corp.	East Dubuque, IL	278	762

In this data, a range of production capacity is selected from 300 to 3000 ton per day excluding the lowest and highest capacity as outliers. [10, 32] Therefore, set t consists of 4 cases: 300, 1,200, 2,100 and 3,000 tons per day.

Figure 3 shows process parameters at each node upstream and downstream of the production process for 300 TPD (ton per day) ammonia production plant with electrolyzer.

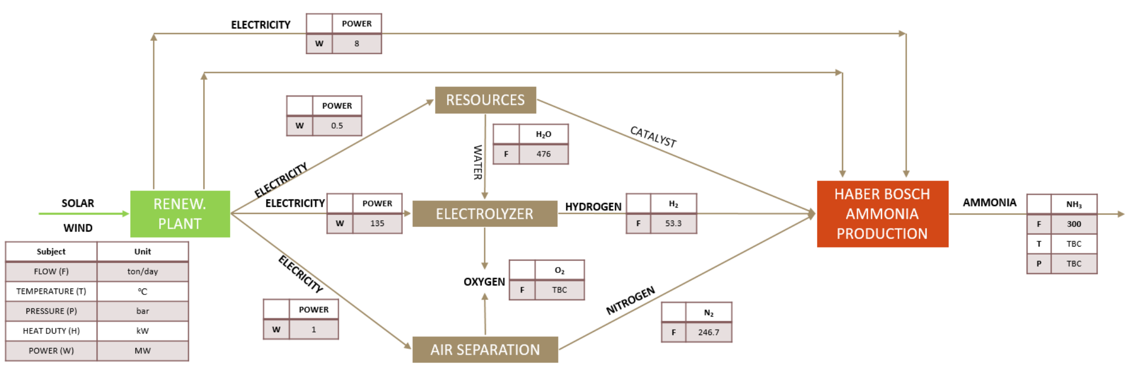

Figure 3 Reference Ammonia Synthesis Heat and Mass Balance Diagram

Process parameters form this heat and mass balance diagram are set as base case for estimating those with larger plant capacity. As per engineering judgement, it should be noted that process parameters are linearly scalable, but cost parameters are not. Ref [10] introduces reference process information for 300 TPD ammonia production plant where it incorporates the use of renewable energy scheme and the model assumes that the process parameters given in the first column in Table 10 and are linearly scalable with respect to the ammonia production capacity. O&M cost for ammonia production plant is about 3% of investment cost according to industrial practice. [10]

Table 10 Ammonia Synthesis Loop Technical Specification

set	t	unit	1	2	3	4
Capacity	Nomen.	TPD	300	1,200	2,100	3,000
Investment Cost	LC_t	$	142,500,000	415,522,174	644,544,027	854,290,734
Annualized Investment Cost	ELC_t	$/yr	12,227,999	39,728,885	48,026,384	1,008,822,743
O&M Cost	LO_t	$/yr	4,275,000	12,465,665	19,336,321	25,628,722
Electricity Requirement	El_t^T	MWh /yr	1,270,200	5,080,800	8,891,400	12,702,000
Water Requirement	$FW_{r,t}$	TPYr	173,740	694,960	1,216,180	1,737,400
Hydrogen Requirement	$PR_{p(H2),t}$	TPYr	123,355	493,420	863,485	1,233,550

It is known that 65% of cost for the renewable ammonia production plants is electrolyzers and the rest consists of synthesis loop, ASU and water treatment system. Therefore the study considers two different cost function Eq. (35) – (36) to calculate the investment cost for facility

(LC_t). It should be noted that the model used relatively high power factor, 0.85 as opposed to sixth-tenth rule, the significant portion of investment cost within facility consists of electrolyzer and they are not subject to economy of scale from being modular and prepackaged. The rest 35% including ammonia synthesis loop, ASU, and water treatment system, uses sixth tenth rule. [10, 29]

$$Investment\ Cost = Electrolyzer_{300TPD}\left(\frac{Capacity}{300}\right)^{0.85} \quad \text{Equation 35}$$

$$Investment\ Cost = The\ Rest_{300TPD}\left(\frac{Capacity}{300}\right)^{0.6} \quad \text{Equation 36}$$

Equation 37 annualizes investment cost per year using EAC (Equivalent Annual Cost) technique. Accordingly, base scenario discount rate and number of operation period is 7% and 25 years following industrial practice. Process parameters such as process requirement (electricity and water) and production rate. (Ammonia, Hydrogen, and Oxygen) are linearly incremental with the plant capacity to base case (300 ton per day)

$$EAC = \frac{Investment\ Cost * Discount\ Rate}{1 - (1 + Discount\ Rate)^{Number\ of\ Periods}} \quad \text{Equation 37}$$

Another product that can be a profitable revenue in the market is oxygen produced from electrolyzer and air separation unit (ASU). Oxygen is widely used in chemical process, such as partial oxidation, and pharmaceutical/medical industries. As oxygen is not used in ammonia synthesis process, it is practical to sell oxygen in the market. Oxygen produced through the process is summarized in Table 11 below.

Table 11 Facility Production Specification

set	t		1	2	3	4
Capacity	Nomen.	TPD	300	1,200	2,100	3,000
NH_3	$PR_{p(NH3),t}$	TPYr	109,500	438,000	766,500	1,095,000
O_2 (Electrolyzer)	$PR_{p(O2),t}$	TPYr	15,637	62,548	109,459	156,370
O_2 (ASU)	$PR_{p(O2),t}$	TPYr	27,014	108,055	135,068	162,082

3.8.5. Conversion Technologies

Technical and cost parameters of ammonia gas turbines and ammonia fuel cells follow the closet commercial product available in the market: gas turbines and hydrogen SOFCs. Though ammonia-related power generation equipment are under rapid development, relevant information is readily unavailable as not commercially in operation. In the study, the model assumes that those equipment will be available in near future and have equal performance to them. Relevant parameters are summarized in Table 12.

Table 12 Summary of Ammonia Conversion Technologies Reprinted from [33,34]

	j	unit	CT [33]	ACT [33]	FUC [34]
Subject			Conventional Gas Turbine	Advanced Gas Turbine	Fuel Cell
Reference Output	Nomen.	MW	100	237	0.25
Capital Cost	CC_j	\$/kW (EAC)	1101 (94.51)	678 (58.2)	1600 (137.34)
Fixed O&M	CFO_j	\$/kW-yr	17.5	6.8	16
Variable O&M	CVO_j	\$/MWh	3.5	10.7	30

Availability	CA_j	%	91.3	91.3	98
Electrical Efficiency	η_j	%	0.4	0.4	0.59
Reference		-	LM 6000 (GE)	F-Class (GE)	Hydrogen SOFC

First conversion technology is gas turbines: conventional gas turbine (*CT*) and advanced gas turbine. (*ACT*) CT represents aerodynamic gas turbines that is a reference of LM 60000 with 100 MW. Also, ACT is referred to GE F-class gas turbines with 237 MW. Based on these references, EIA report provides 'Capital Cost Estimates for Utility Scale Electricity Generating Plants' that summarizes unit capital cost per MW for both CTs and ACTs. The unit capital cost includes civil and structural costs, mechanical equipment supply and installation, electrical and instrumentation control, project indirect costs, and owner costs, which covers overall costs to install and operate power plants. [33]

Another conversion technology is fuel cell. Fuel cell has high efficiency and availability compared to gas turbine technology, but with higher costs. Among various fuel cell types, SOFC is known for the concentrated power generation with fuel and catalysts flexibility. [35] Though it has comparatively longer start up time to other fuel cell technologies, the model considers SOFC technology as used for base load operation.

3.8.6. Transportation

Transportation is crucial part in the proposed energy supply chain as it enables remote location of facilities from demand sites. In the model, all the transportation departs and arrives at the centroids of each counties where all the facilities and conversion power plants are located. Detailed location of individual plant within county considering miscellaneous factors is not a scope of the research.

In this study, the ammonia supply chain considers two transportation means: trucks and railroads. Texas has more than 313,220 miles of public roads and 10,539 miles of freight rail, the longest in U.S., and the second-largest state highway system in U.S. [36] These well-developed infrastructures enable ammonia transportation to wherever needed to meet the energy demand in Texas.

Transportation means are trains, trucks with tank lorry in U.S. mainland. Transportation container regulation restricts the capacity of individual transportation means. For truck transportation, specification MC 331 (Code of Federal Regulations for Transportation) regulates capacity of tank truck shall be of maximum 11,500 gal(43.5m^3) under 300 psi. Highway systems and routes are modeled in accordance with Texas Highway Systems.

Moreover, for railroad transportation, D.O.T 112J340 regulates capacity of tank on rail car shall be maximum 33,500gal (127.8 m^3). George et al. indicated that ammonia distribution means are analogous to that of liquefied propane (LPG). [37] Accordingly, information of transportation equipment specifically unavailable for Ammonia is obtained from that LPG transportation equipment. Railroad systems and routes are modeled in accordance with Texas Railroad Systems.

For truck transportation, straight distance among counties ($DI_{l,c,TR}$) given their longitudes and latitudes are calculated by 'Haversine' equation. Reference coordinates are set at the centroid of 254 counties in Texas where all the facilities including renewable energy power plants, ammonia production plants, and conversion plants are assumed to be located in the model. Due to path curvatures (*DC*) in reality, multiplication of 1.1 is introduced to calculated-straight distance.

Distance among counties for railroad transportation ($DI_{l,c,'RR'}$) are calculated using Dijkstra's algorithm. The algorithm is a heuristic approach to find an optimization solution in shortest path problem. Railroad routes follows actual connection operated under Texas Department of Transportation. [38] Train can attach railcar as many as it can, but the model assumes that railroad stops exist within each county only if the route passes through county seat: an administrative center and capital city of a county. Accordingly, counties where the railroad path does not go through county seat are not considered for railroad transportation.

Table 13 Transportation Parameter Summary Reprinted from [14,18,39,40]

		Unit	Truck	Railroad	Reference
Capacity	Nomen.	ton/trip/car	43.5	11,000	[14] [39]
Fuel Economy	FE_m	Ton-km/l (Ton-mi/gal)	110.9 (262.3)	193.2 (457)	[18, 40]
Average Speed	SP_m	km/hr (mi/hr)	55 (34.4)	45 (28.1)	
Mode Availability	TMA_m	hr/day	18	12	
Load/Unload Time	LUT_m	hr/trip	2	12	
Driver Wage	DW_m	$/hr	23	23	
Fuel Price	FP_m	$/L ($/gal)	1.16 (4.38)	0.28 (1.06)	

Maintenance Expenses	ME_m	\$/km (\$/mi)	0.0976 (0.16)	0.0621 (0.1)	
General Expenses	GE_m	\$/d	8.22	6.85	

Parameters used in transportation cost function is summarized in Table 13. [14, 18] For economic and feasible solutions, maximum travel distance ($DMax_{'TR'}$) for truck transportation is applied to truck transportation: 480 mile per trip. If distance between location l to demand c is more than 480 mile, then the model selects railroad transportation for transporting ammonia.

3.8.7. Water Resources

Water is an essential resource for renewable ammonia production, especially for electrolysis process where water is decomposed into hydrogen and oxygen. At the same time, it is a limited resource and the current water network infrastructure has limited capacity of supply. This study considers current thermoelectric water consumption data as an amount of water available for electrolysis since it pursues entire and partial replacement of fossil-fueled power plants to renewable ammonia energy carrier.

Thermoelectric power refers to electricity generated with steam-driven turbine generators defined by USGS. Its water consumption from current water network infrastructure would become available for use once new energy carrier chain is in charge. Accordingly, estimated water consumption data in 2015 for each power plant are the water resource available per year at the counties where the plants are located. Thermoelectric power water consumption on 2015 is linearly interpolated with respect to the power generation capacity in megawatt-hour from the data in USGS report in 2010. [41] Water shortage beyond the availability at each county can be purchased from near counties or supplied from wells available at each county with purchasing cost (*COSTWP*)

Water is transported by pipe network already existing in Texas. Cost of water transportation is addressed in Eq. (38)

$$COST^{WT} = w_{h,l}(DFC + DVC \cdot DI_{h,l} \cdot DC) \qquad \text{Equation 38}$$

DFC is a distance fixed cost with $3/ton and DVC is a distance variable cost with $0.005/ton-mi. DC is a distance curvature that compensates the straight distance between two locations with 1.1. Again, the model assumes that water is available at the centroid of each county, so is the destination.

4. SUPPLY CHAIN NETWORK SCENARIOS AND OPTIMIZATION

4.1. Results and Discussion

4.1.1. Summary

Table 14 Summary of Optimization Result for Different Cases

		Case 1	Case 2	Case 3	Case 4	Biomass
Number of Counties Considered	EA	5	5	10	254	-
% of Demand Considered	%	100	50	100	100	-
Total Annualized Cost	$/yr	2.98E+10	1.43E+10	3.64E+10	4.98E+10	-
Annualized Cost	$/GJ/yr	41.6	39.9	38	24.6	22.18
Annualized Cost	$/MWH/yr	150	144	137	88.6	-
Portion of Renewable Plant	%	42	38	43	43	-
Portion of Ammonia Plant	%	29	29	31	31	-
Portion of Conversion Plant	%	20	22	22	22	-
Portion of	%	7	9	2	2	-

Transportation Cost						
Portion of Water Cost	%	2	2	2	2	-
Number of Facilities	EA	61	31	83	111	-
Capacity & # of Wind Plants	EA MW	61 7.25E+4	31 3.15E+4	83 8.96E+4	111 1.25E+5	-
Capacity & # of Solar Plants	EA MW	0 0	0 0	0 0	0 0	-
Reference	-					[19]

4.1.2. Case 1 Scenario

Case 1 considers top 5 electricity consuming counties in the state of Texas, which accounts for 44.8% of entire Texas electricity consumption. The result shows annualized cost for the energy supply chain is \$ 41.6 / GJ-yr.

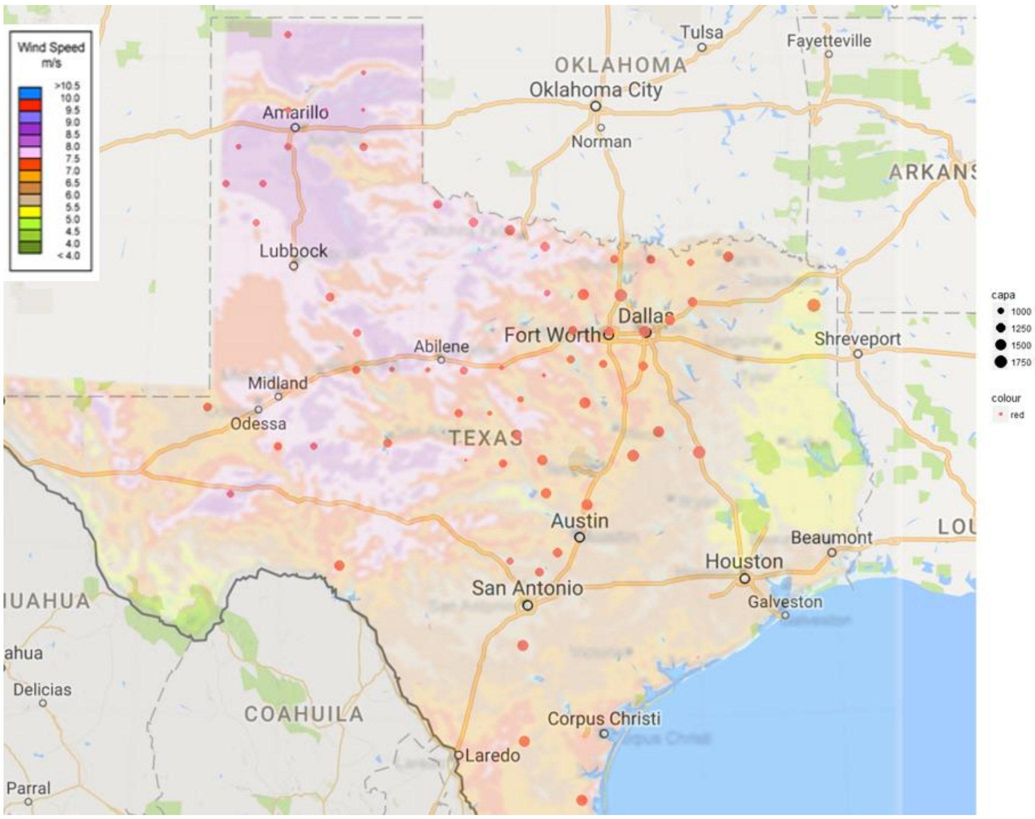

Figure 4 Case-1 Facilities Location and Renewable Power Plant Capacity (MW)

There are 61 facilities (Renewable power plants and ammonia production plants) selected by program as shown in Figure 4. All of the renewable power plants are selected with wind technology and all of them are the capacity of 3000 TPD, the maximum of capacity set t. The outcomes may have been somewhat expected as the program would like to take a full advantage of favorable locations with high renewable potential and shortest distance from the demand sites. It should be noted that though all the electricity requirement are the same across all locations l due to the same capacity of ammonia production plants, capacity of renewable power plants are smaller in counties with high wind speed due to the renewable energy scaling factor. $(RF_{r,l})$

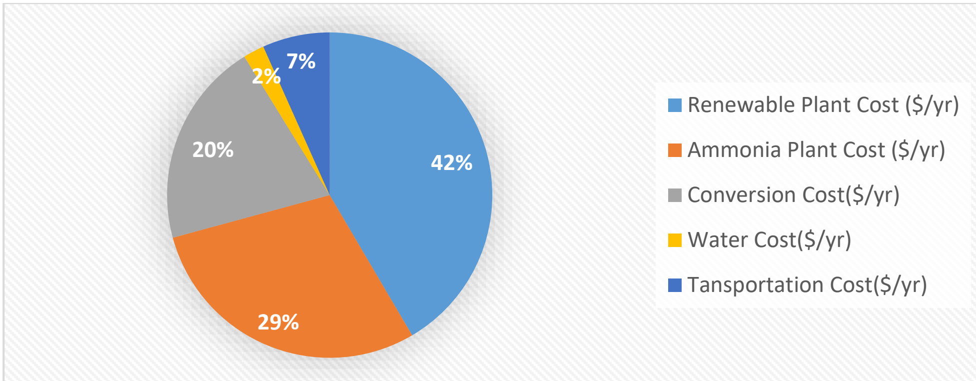

Figure 5 Case-1 Cost Breakdown for the entire energy supply chain network

All renewable power plants are selected with wind technology and are located at the northern Texas and at the counties nearby demand sites c. Reason for wind election is that annaulized investment cost for renewable power plants (RC_r) has comparatively lower value for wind technology implementing current market price. Upon selection of wind technology, the model pursued locations with high wind energy potential. Wind potential in velocity plays a huge role in investment cost for renewable power plants as a capacity of them greatly changes with scaling factor at location $(RF_{r,l})$, which is a function of 3^{rd} power of wind velocity. Accordingly, high wind potential could substantially save the investment cost in the model over increase in transportation cost due to greater distance between location l and demand c.

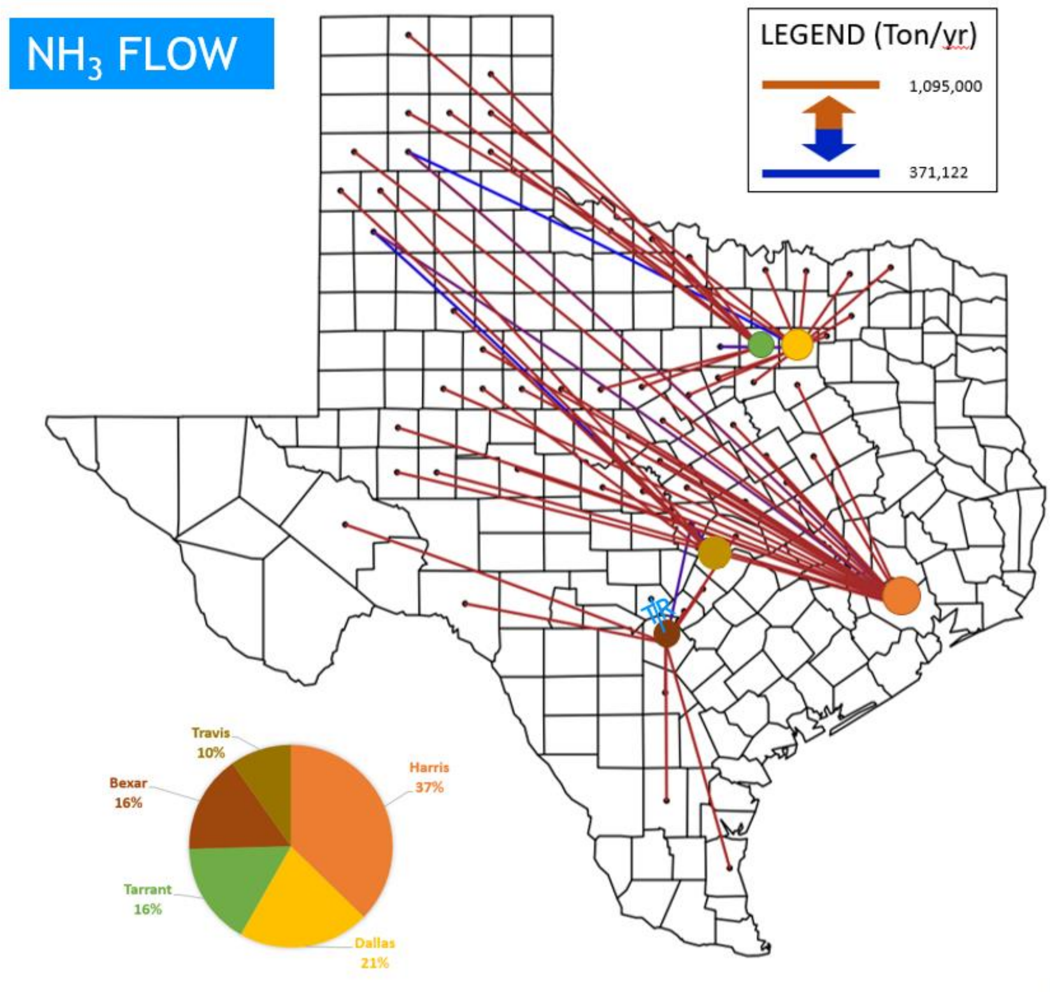

Figure 6 Case-1 Ammonia Flow from Location l to Demand Site c using Transportation m

Major flow heads to Harris County where the city of Houston is located with largest electricity consumption in the model. Major portion of ammonia flow departure starts from northern Texas and the rest from nearby counties where wind potentials (speed) are the most. Most of flow is transported by railroad as shown Figure 6, which is more economical mean of transportation for long-range travel. The rest of flow, minor portion, is transported by truck from counties very close by. Truck transportation, in general, is not favored by the model as it is comparatively inefficient to railroad due to small delivery flow per trip.

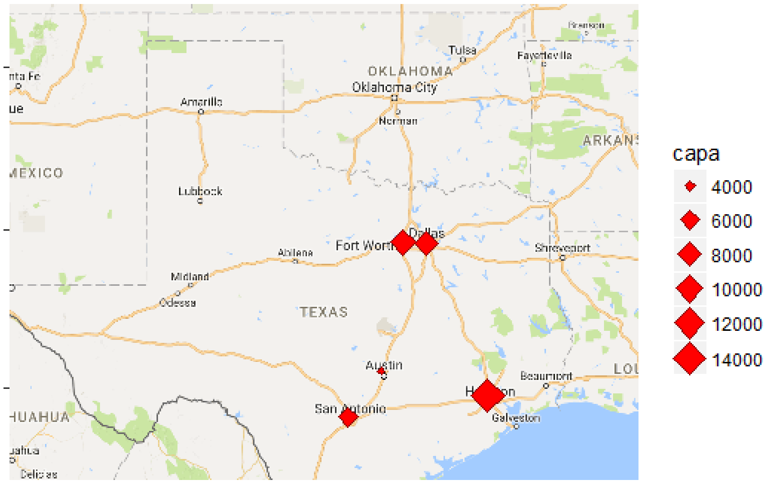

Figure 7 Case–1 Conversion Power Plant Location and Capacity (MW)

All the conversion technologies are selected with ammonia SOFC. Though SOFC is the most expensive technology compared to gas turbines, it has great efficiency and availability in contrary. These factors attracted the model to pursue SOFCs.

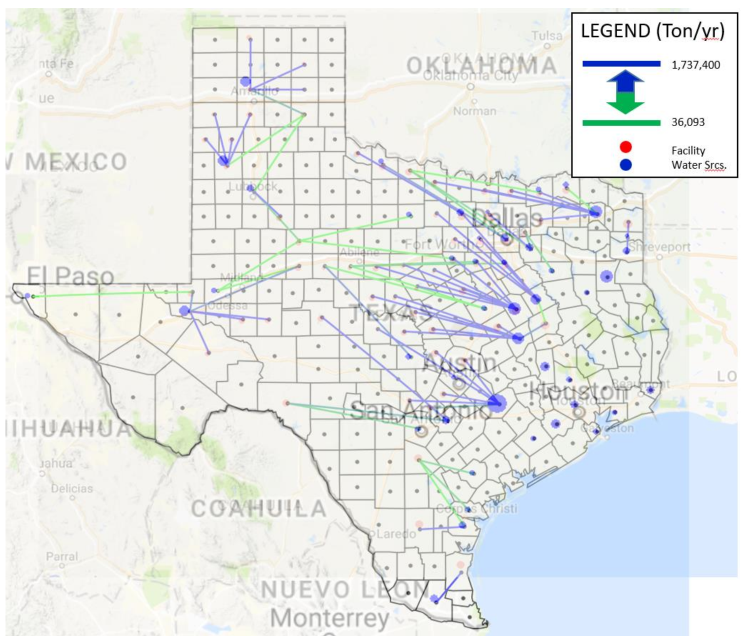

Figure 8 Case-1 Water Network Flow

Water network is shown in figure 8. Water is flowing from the water reservoir h where existing fossil-fueled power plants are currently located. In accordance with thesis purpose replacing fossil-fueled power plants, major water sources are from the water reservoirs h to facility locations l.

4.1.3. Case 2 Scenario

Case 2 considers 50% of top 5 electricity consuming counties in the state of Texas, which accounts for 22.4% of entire Texas electricity consumption. The result shows levelized cost for the energy supply chain is $ 31.29 / GJ and $ 112.6 / MWh. Overall, Case 2 has more competitive cost model for the new energy supply chain: approximately 14% more economical than Case 1.

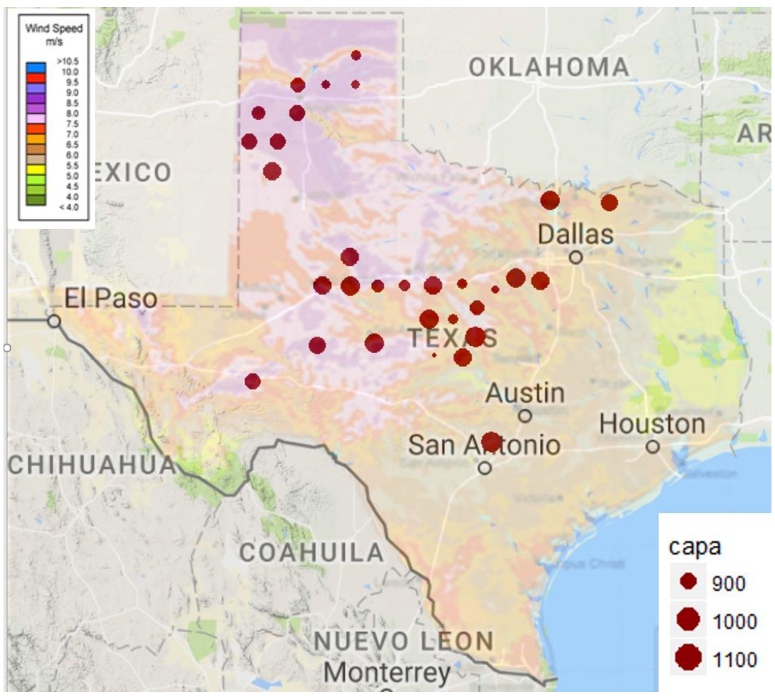

Figure 9 Case-2 Facilities Location and Renewable Power Plant Capacity (MW)

The model constructs 31 facilities with wind power plants capacity rage of 900 MW to 1,100 MW. Again, with the same reason in Case 1, PV power plants is not selected due to uncompetitive cost. Most of facility locations are located at the counties with high wind speed;

however, due to less demand of the model, southern region previously selected in Case 1 is no longer present in Case 2.

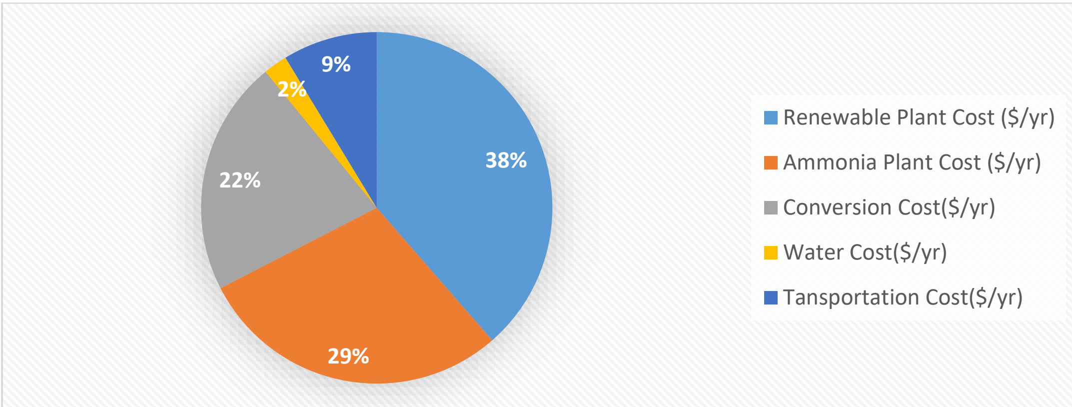

Figure 10 Case-2 Cost Breakdown for the Entire Energy Supply Chain Network

Portion of renewable power plant costs decreases from 42% to 38% slightly by avoiding locations with low wind speeds that are close to the demand sites. Transportation cost increases from 7% to 9%, and the rest remains almost the same. The reason for increase in transportation costs is due to transportation occurring between distant locations compared to Case 1. It is interpreted that cost increase from distant transportation has more advantages over facilities installed at location with low wind speeds, resulting in high wind plant capacity. Therefore, the model installs facilities at the northern Texas state at first as shown in figure 9.

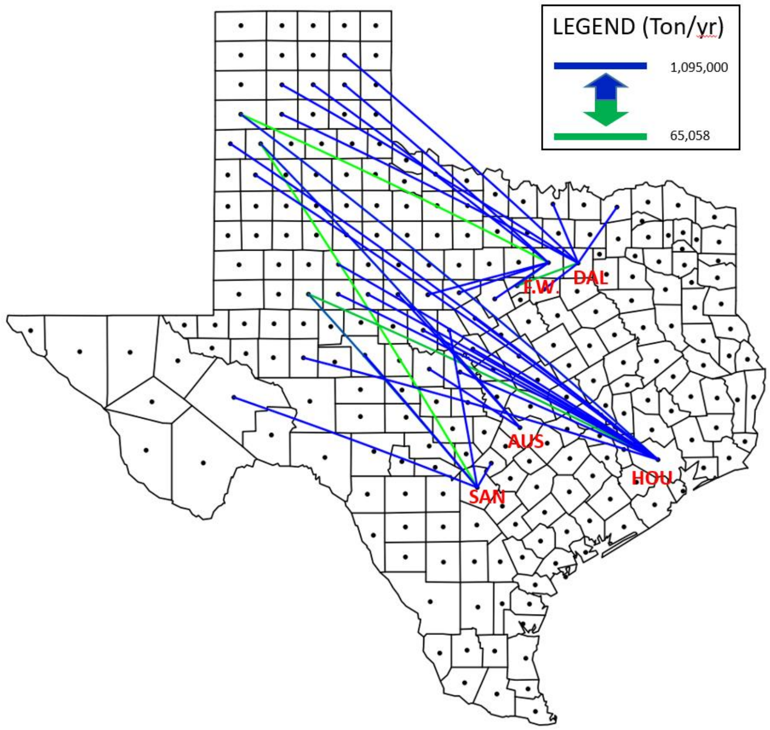

Figure 11 Case-2 Ammonia Flow from Location l to Demand Site c using Railroad Transportation

Case 2 model only selected to transport ammonia with railroad transportation due to the long travel distance. Parameters related to railroad transportation are favorable to long distance travel with respect to cost.

4.1.4. Case 3 Scenario

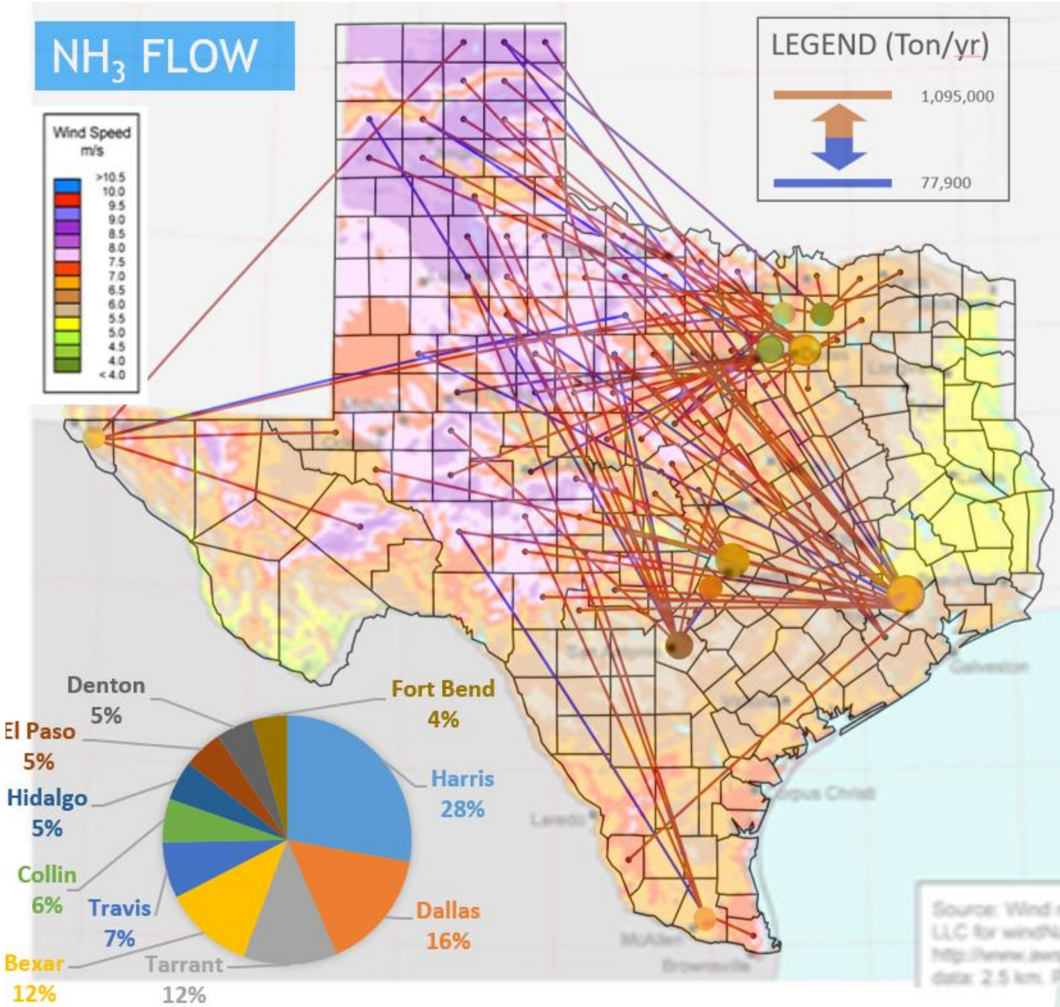

Figure 12 Case-3 Ammonia Flow from Location l to Demand Site c using Railroad Transportation

Case 3 considers 100% of top 10 electricity-consuming counties in the state of Texas, which accounts for 59.2% of entire Texas electricity consumption. The result shows annualized cost for the energy supply chain is \$ 38.0 / GJ and \$ 137.6 / MWh-yr. Though number of counties considered is twice to Case 1, annualized cost for the energy supply chain decreases as large portion of demand is still around top 5 counties, suburban area to large 5 cities in Texas, reducing transportation cost.

According to the results, 83 facilities are selected with wind power plants exclusively. Additional 22 facilities, compared to Case 1 61 facilities, are located at counties with the next highest wind potential available and the rest major portion of facilities are still located at the northern Texas. Accordingly, major portion of ammonia product flows from northern and western area with high wind potential. As renewable plant accounts for 43% of the cost, the largest portion in the energy supply chain as shown in Figure 13, the model aims to reduce them by reducing capacity of renewable power plants (ETR) with high wind potential.

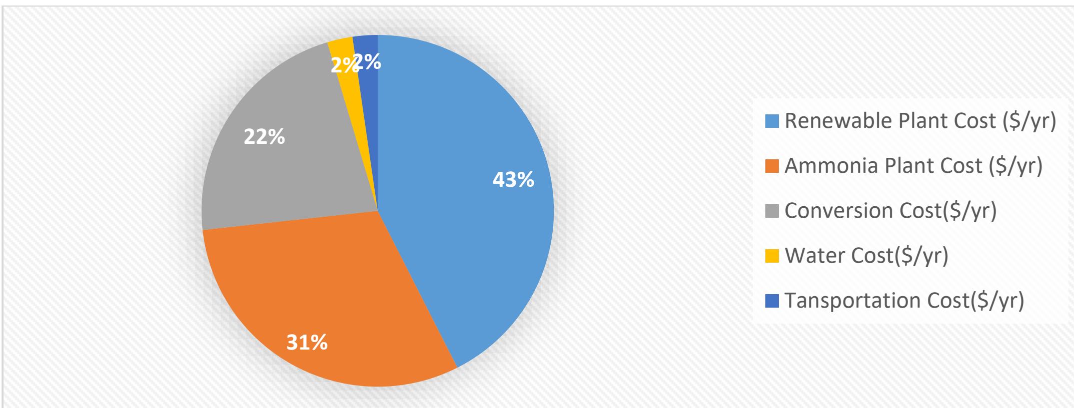

Figure 13 Case-3 Cost Breakdown for the Entire Energy Supply Chain Network

4.1.5. Case 4 Scenario

Case 4 considers all 254 counties and entire electricity demand in Texas. The result shows the annualized cost of $24.6 / GJ-yr. A number of facilities is 111 with wind power plants only. The results show the most competitive annualized cost among 4 case studies. Although the case covers entire Texas region and electricity demand sparsely spreads out, the results show that producing ammonia at locations with high renewable potential and transporting them to demand location are competitive in cost associated in energy supply chain, considering that transportation cost only accounts for 2% of the cost as shown in Figure 14.

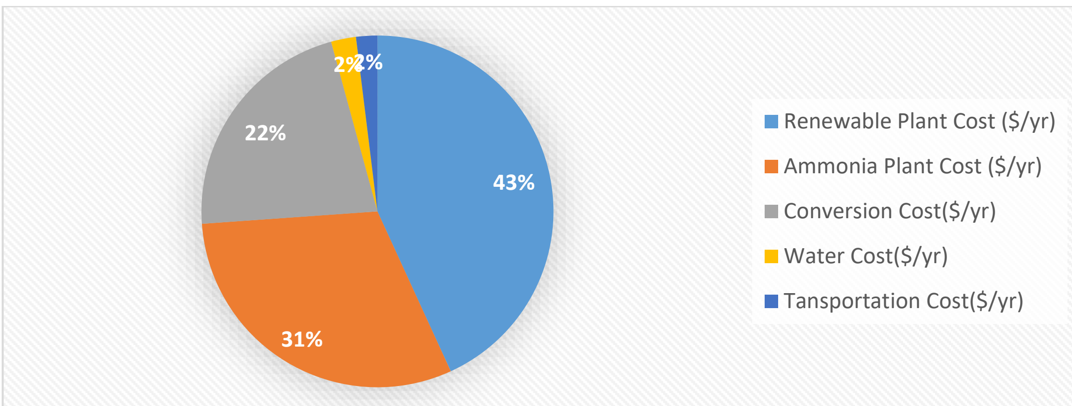

Figure 14 Case-4 Cost Breakdown for the Entire Energy Supply Chain Network

Similar results to Case 3, major portion of facilities is located at counties with high wind potential; in addition, the remaining facilities are located at the counties adjacent to the major demand sites shown in Figure 15.

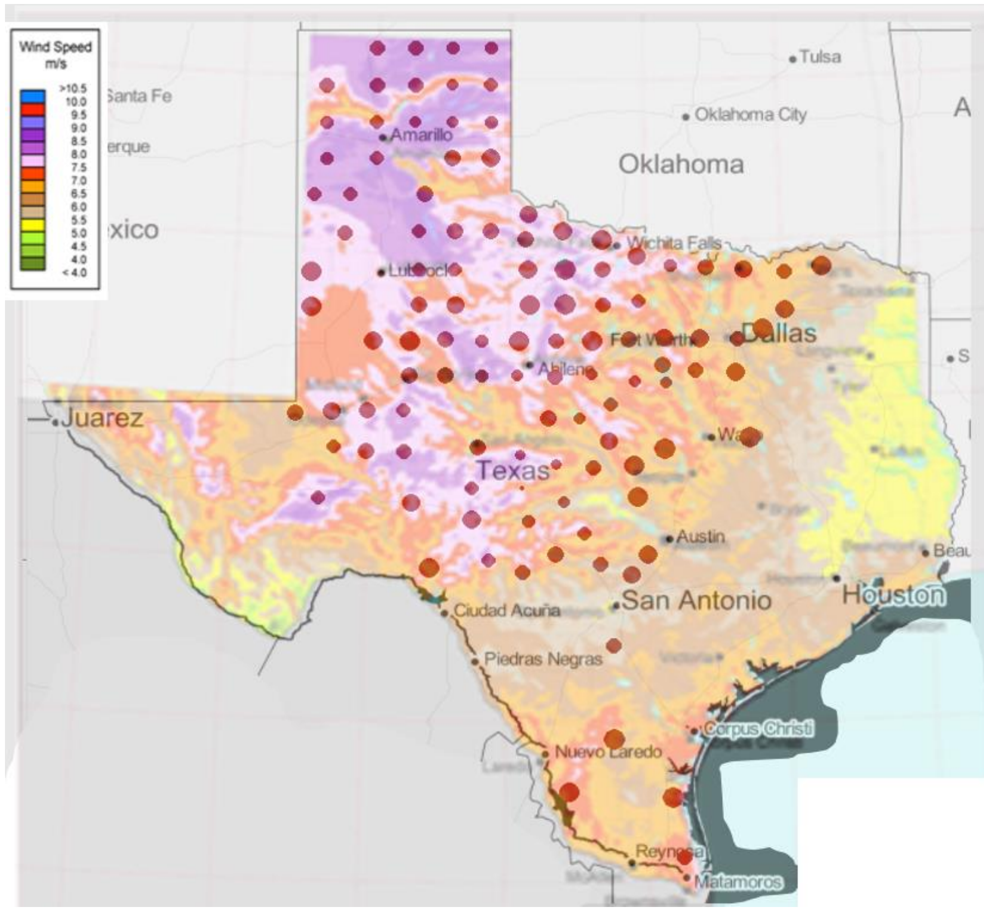

Figure 15 Case-4 Facilities Location and Renewable Power Plant Capacity (MW)

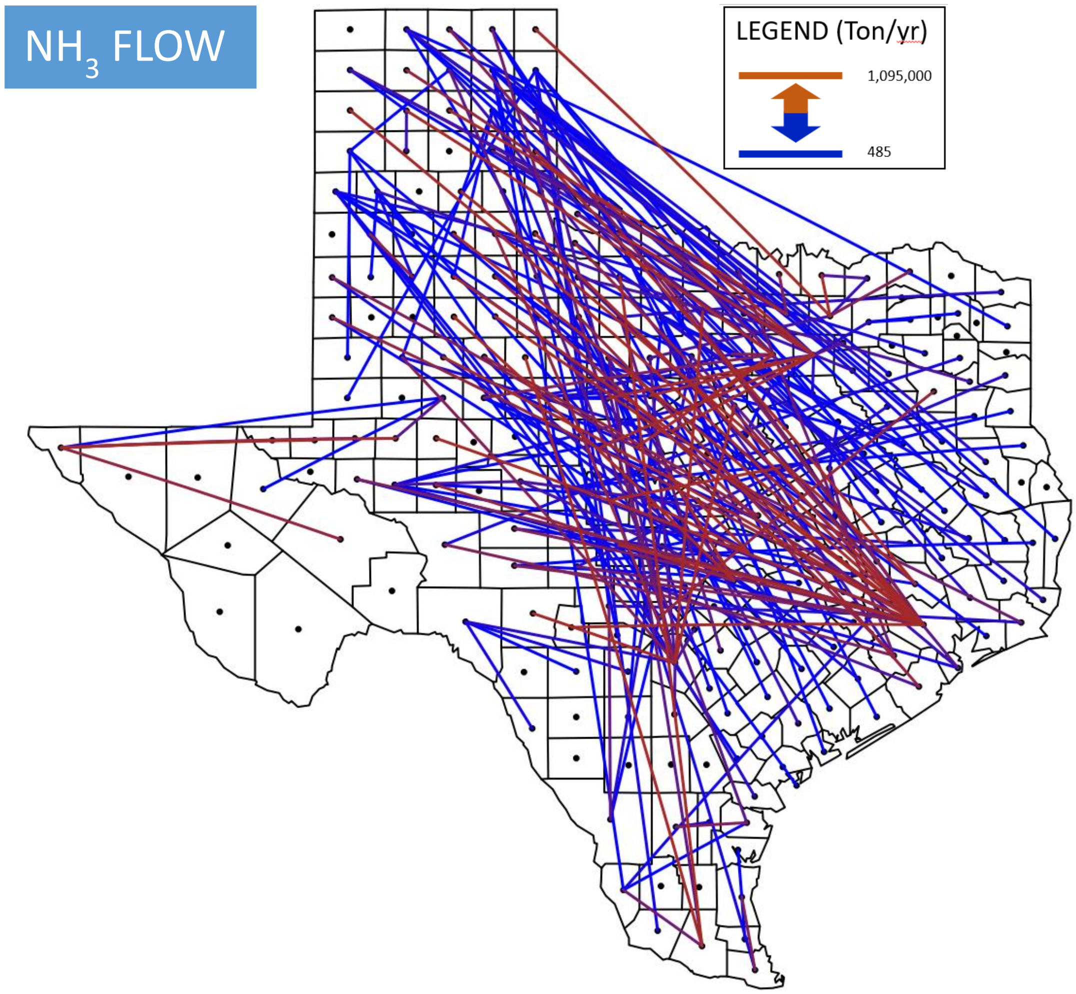

Figure 16 Case-4 Ammonia Flow from Location l to Demand Site c using Railroad Transportation

All flow is transported by railroad transportation regardless of locations. Major flows start from northern and central-western Texas.

4.1.6. Sensitivity Analysis

Sensitivity analysis based on Case 1 is to find the most effective parameters in the modeling. There are 7 parameter variations used for sensitivity analysis: i) Electrolyzer power factor, ii) years of operation, iii) discount rate, iv) wind and solar investment costs, v) maximum capacity for railroad transportation, vi) maximum water travel distance, and vii) ammonia heat of combustion. These parameters are selected avoiding any variation used in previous case studies. The amount of variation is from 60% to 140% of original values used in Case 1, except for oxygen sales and electrolyzer power factors. Oxygen sales is an additional parameter excluded in original case studies, so the value is given in above 100%. Also, original electrolyzer costs are calculated in cost function with power factor; therefore, power factors above 1 are not considered. Parameters calculated and used for sensitivity analyses are summarized in Table 15.

Table 15 Parameter Variation for Sensitivity Analysis

	Nomen.	unit	Base	A	B	C	D
		%	100	60	70	80	90
Electroyzer Power Factor	LC_t	-	0.85	0.51	0.595	0.68	0.765
Yrs of Operation	NP	years	25	15	18	20	23
Discount Rate	DR	%	7	4.2	4.9	5.6	6.3
Wind Investment	$RC_{r('WD')}$	$/MW/yr	1.7E+6	1.0E+6	1.2E+6	1.4E+6	1.5E+6
Solar Investment	$RC_{r('PV')}$	$/MW/yr	9.9E+5	5.9E+5	6.9E+5	7.9E+5	8.9E+5

# of Rail Cars	$TCap_{m('RR')}$	EA	5500	3300	3850	4400	4950
Water Distance	$DIWT_{h,l}$	mile	200	120	140	160	180
Heat of Combustion		MWH/ton	5.2	3.12	3.64	4.16	4.68
Oxygen Sell	$PR_{p('O2),t}$	%	-	-	-	-	-

	Nomen.	unit	Base	E	F	G	H
		%	100	110	120	130	140
Electroyzer Power Factor	LC_t	-	0.85	0.935	1.00	-	-
Yrs of Operation	NP	years	25	28	30	33	35
Discount Rate	DR	%	7	7.7	8.4	9.1	9.8
Wind Investment	$RC_{r('WD')}$	$/MW/yr	1.7E+6	1.9E+6	2.0E+6	2.2E+6	2.4E+6
Solar Investment	$RC_{r('PV')}$	$/MW/yr	9.9E+5	1.1E+6	1.2E+6	1.3E+6	1.4E+6
# of Rail Cars	$TCap_{m('RR')}$	EA	5500	6050	6600	7150	7700
Water Distance	$DIWT_{h,l}$	mile	200	220	240	260	280

Heat of Combustion		MWH/ton	5.2	5.72	6.24	6.76	7.28
Oxygen Sell	$PR_{p('O2),t}$	%	-	2	4	6	8

Sensitivity analyses are performed as many as iterations with parameter variations using GAMS and the result data are plotted using Microsoft Excel; accordingly, results are shown in Figure 17 and Table 16.

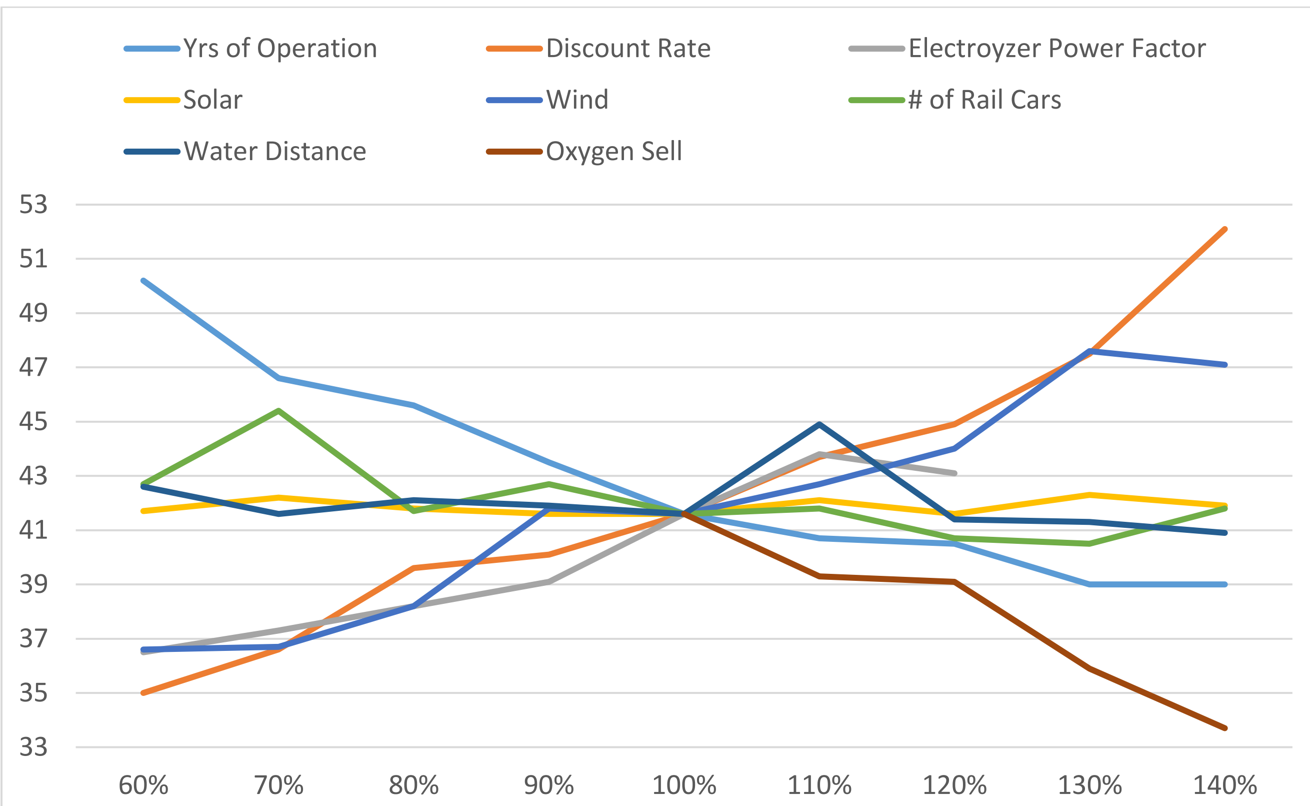

Figure 17 Sensitivity Analysis for Ammonia Energy Supply Chain with Respect to Parameter Variation

Parameters, such as electrolyzer power factors years of operation, discount rate, solar and wind investment costs, oxygen sales are significantly contributed the overall investment costs. Among those parameters, years of operation, water distance limit, oxygen sales are positive ones that reduces annualized total cost, whereas solar and wind investment costs, electrolyzer power factor are negative ones that increases annualized total cost.

Table 16 Summary of Annualized Total Cost in Sensitivity Analysis

Annalualized Total Cost ($/GJ-yr)	60%	70%	80%	90%	100 %	110 %	120 %	130 %	140 %
Electroyzer Power Factor	50.2	46.6	45.6	43.5	41.6	40.7	40.5	39	39
Years of Operation	35	36.6	39.6	40.1	41.6	43.7	44.9	47.5	52.1
Discount Rate	36.5	37.3	38.2	39.1	41.6	43.8	43.1	-	-
Investment Cost: Wind	41.7	42.2	41.8	41.6	41.6	42.1	41.6	42.3	41.9
Investment Cost: Solar	36.6	36.7	38.2	41.8	41.6	42.7	44.0	47.6	47.1
# of Rail Cars	42.7	45.4	41.7	42.7	41.6	41.8	40.7	40.5	41.8
Water Distance	42.6	41.6	42.1	41.9	41.6	44.9	41.4	41.3	40.9
Oxygen Sell	-	-	-	-	41.6	39.3	39.1	35.9	33.7

5. CONCLUSION

An optimization-based framework for the ammonia energy supply chain was proposed. Sets of renewable power plants, ammonia production plants, transportation means, and conversion power plants were modeled in MILP formulation. The model takes into account the location, capacity, and cost of facilities, transportation, and conversion power plants.

An MILP model was developed to identify strategic location of facilities (renewable power plants and ammonia production plants), the capacity of facilities, the topology for ammonia supply chain , costs associated within the supply chain, and sensitivity analysis for related variables and parameters. Constructed 4 cases were analyzed with comparison to each other, and sensitivity analysis was performed to understand how each parameters contribute to the overall cost in the model.

The resulting overall cost to replace Case 1 Top 5-electricity consuming counties in Texas \$41.6/GJ-yr and 150\$/MWH-yr and Case 4 Entire 254 counties in Texas \$24.6/GJ-yr and \$88.6/MWH-yr. Case 4 replacing entire fossil-fueled electricity in Texas shows the most favorable result, which is comparable to hardwood biomass to fuel-energy supply chain. Among parameters, it was found that oxygen sales, discount rate, electrolyzer cost, PV cost, and wind power plant cost are major sensitive parameters that would reduce the overall cost of energy supply chain.

Nontheless, the cost may not be competitive at the current market compared to fossil-fueled energy supply chain. However, with renewable energy credit (REC) and technology development of electrolyzer, wind turbines, and PV panels, the ammonia energy supply chain would be competitive in the future.

REFERENCES

[1] SIEMENS, 'GREEN' AMMONIA, SIEMENS, (2016).

[2] T. BROWN, AMMONIA PRODUCTION CAUSES 1% OF TOTAL GLOBAL GHG EMISSIONS, AMMONIA INDUSTRY, AMMONIA INDUSTRY, 2016.

[3] W.C.R.A.O. CENTER, WIND TO HYDROGEN TO AMMONIA PILOT PLANT, UNIVERSITY OF MINNESOTA, 2017.

[4] I.S. ANALYSIS, ELECTRICITY, U.S. ENERGY INFORMATION ADMINISTRATION, 2017.

[5] J. RHODES, WIND VS. COAL, THE UNVIERSITY OF TEXAS AT AUSTIN ENERGY INSTITUTE, THE UNVIERSITY OF TEXAS AT AUSTIN ENERGY INSTITUTE 2017.

[6] N. IKI, MICRO GAS TURBINE FIRING AMMONIA, PROCEEDINGS OF ASME TURBO EXPO 2016: TURBOMACHINERY TECHNICAL CONFERENCE AND EXPOSITION, (2016).

[7] D.K. MINET RG, COST-EFFECTIVE METHODS FOR HYDROGEN PRODUCTION, INT J HYDROGEN ENERGY, (1983).

[8] B. M., POTENTIAL IMPORTANCE OF HYDROGEN AS A FUTURE SOLUTION TO ENVIRONMENTAL AND TRANSPORTATION PROBLEMS, INT J HYDROGEN ENERGY, 33 (2008).

[9] M. BALAT, POTENTIAL IMPORTANCE OF HYDROGEN AS A FUTURE SOLUTION TO ENVIRONMENTAL AND TRANSPORTATION PROBLEMS, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY, 33 (2008) 4013-4029.

[10] E.R. MORGAN, J.F. MANWELL, J.G. MCGOWAN, SUSTAINABLE AMMONIA PRODUCTION FROM U.S. OFFSHORE WIND FARMS: A TECHNO-ECONOMIC REVIEW, ACS SUSTAINABLE CHEMISTRY & ENGINEERING, 5 (2017) 9554-9567.

[11] L.O.R. CENTER, LIST OF OFFSHORE WIND FARMS. AVAILABLE ONLINE, 2015.

[12] P.R. STATISTICS, NEW RECORD IN WORLDWIDE WIND INSTALLATIONS, WORLD WIND ENERGY ASSOCIATION, 2015.

[13] P. LIU, D.I. GEROGIORGIS, E.N. PISTIKOPOULOS, MODELING AND OPTIMIZATION OF POLYGENERATION ENERGY SYSTEMS, CATALYSIS TODAY, 127 (2007) 347-359.

[14] G.T.A.G. PARKS, POTENTIAL ROLES OF AMMONIA IN A HYDROGEN ECONOMY, U.S. DEPARTMENT OF ENERGY, U.S. DEPARTMENT OF ENERGY, 2006.

[15] A.A.P.D.D.T.S. KELLEY, A FRAMEWORK FOR AMMONIA SUPPLY CHAIN OPTIMIZATION INCORPORATING CONVENTIONAL AND RENEWABLE GENERATION, AICHE JOURNAL, 63 (2017).

[16] M.B.A.J.R. CHRISTOPHER MONE AND MAUREEN HAND, DONNA HEIMILLER AND JONATHAN HO, 2015 COST OF WIND ENERGY REVIEW, NATIONAL RENEWABLE ENERGY LABORATORY, 2017.

[17] R.E. CENTER, RURAL LAND PRICES FOR PANHANDLE - CENTRAL (LMA 2), 2017.

[18] A. ALMANSOORI, N. SHAH, DESIGN AND OPERATION OF A FUTURE HYDROGEN SUPPLY CHAIN: SNAPSHOT MODEL, CHEMICAL ENGINEERING RESEARCH AND DESIGN, 84 (2006) 423-438.

[19] J.A. ELIA, R.C. BALIBAN, C.A. FLOUDAS, B. GURAU, M.B. WEINGARTEN, S.D. KLOTZ, HARDWOOD BIOMASS TO GASOLINE, DIESEL, AND JET FUEL: 2. SUPPLY CHAIN OPTIMIZATION FRAMEWORK FOR A NETWORK OF THERMOCHEMICAL REFINERIES, ENERGY & FUELS, 27 (2013) 4325-4352.

[20] U.S.E.I. ADMINISTRATION, TEXAS ELECTRICITY PROFILE 2015, U.S. ENERGY INFORMATION ADMINISTRATION, STATE ELECTRICITY PROFILES, EIA, 2017.

[21] T.S.L.A.A. COMMISION, POPULATION, TEXAS COUNTIES, 2010-2016 U.S. CENSUS POPULATION ESTIMATESTEXAS STATE LIBRARY AND ARCHIVES COMMISSION, 2015.

[22] C.M.-H. DRAXL, BRI, WIND TOOLKIT POWER DATA SITE INDEX, NATIONAL RENEWABLE ENERGY LABORATORY, 2016.

[23] N.R.E. LABORATORY, DNI STATE STATE STATE FIPS ANNUAL AVERAGE (KWH/M2/DAY) ANNUAL AVERAGE MINIMUM, 2018.

[24] D. GREEN, SOLAR ENERGY FACTS – CONCENTRATED SOLAR POWER (CSP) VS PHOTOVOLTAIC PANELS (PV), RENEWABLE GREEN ENERGY POWER, (2012).

[25] J.S. MARK BOLINGER, KRISTINA HAMACHI LACOMMARE, UTILITY-SCALE SOLAR 2016, AN EMPIRICAL ANALYSIS OF PROJECT COST, PERFORMANCE, AND PRICING TRENDS IN THE UNITED STATES, LAWRENCE BERKELEY NATIONAL LABORATORY, LAWRENCE BERKELEY NATIONAL LABORATORY, 2017.

[26] H. HWANGBO, A.L. JOHNSON, Y. DING, SPLINE MODEL FOR WAKE EFFECT ANALYSIS: CHARACTERISTICS OF A SINGLE WAKE AND ITS IMPACTS ON WIND TURBINE POWER GENERATION, IISE TRANSACTIONS, 50 (2018) 112-125.

[27] L.B.E. AL, DEVELOPMENT OF WATER ELECTROLYSIS IN THE EUROPEAN UNION, FUEL CELLS AND HYDROGEN JOINT UNDERTAKING, 2014, PP. 160.

[28] T.K. WILHELM KUCKSHINRICHS, JAN CHRISTIAN KOJ, ECONOMIC ANALYSIS OF IMPROVED ALKALINE WATER ELECTROLYSIS, FORSCHUNGSZENTRUM JÜLICH, INSTITUTE OF ENERGY AND CLIMATE RESEARCH, (2016).

[29] D. BELLOTTI, M. RIVAROLO, L. MAGISTRI, A.F. MASSARDO, FEASIBILITY STUDY OF METHANOL PRODUCTION PLANT FROM HYDROGEN AND CAPTURED CARBON DIOXIDE, JOURNAL OF CO2 UTILIZATION, 21 (2017) 132-138.

[30] J. IVY, SUMMARY OF ELECTROLYTIC HYDROGEN PRODUCTION, MILESTONE COMPLETION REPORT NATIONAL RENEWABLE ENERGY LABORATORY, 2004.

[31] D.E.B. KRISTINE UHLMAN, MARK L. MCFARLAND, BRENT CLAYTON, AND JOHN W. SMITH, WELL OWNER'S GUIDE TO WATER SUPPLY, THE TEXAS A&M SYSTEM, TEXAS WELL OWNER NETWORK, 2012.

[32] L.E. APODACA, 2011 MINERALS YEARBOOK, NITROGEN [ADVANCE RELEASE]U.S. DEPARTMENT OF INTERIOR, 2011.

[33] I.S. ANALYSIS, CAPITAL COST ESTIMATES FOR UTILITY SCALE ELECTRICITY GENERATING PLANTS, U.S. ENERGY INFORMATION ADMINISTRATION, 2016.

[34] A.M. ROBERTO SCATAGLINI, A TOTAL COST OF OWNERSHIP MODEL FOR SOLID OXIDE FUEL CELLS IN COMBINED HEAT AND POWER AND POWER ONLY APPLICATIONS, ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY, 2015.

[35] E.I. CENTER, FUEL CELL TECHNOLOGIES PROGRAM, COMPARISON OF FUEL CELL TECHNOLOGIES, U.S. DEPARTMENT OF ENERGY, 2011.

[36] T.E.D. CORPORATION, INFRASTRUCTURE, GOBIG IN TEXAS, 2018.

[37] G.T.A.G. PARKS, POTENTIAL ROLES OF AMMONIA IN A HYDROGEN ECONOMY, A STUDY OF ISSUES RELATED TO THE USE AMMONIA FOR ON-BOARD VEHICULAR HYDROGEN STORAGE, U.S. DEPARTMENT OF ENERGY, 2006.

[38] T.D.O. TRANSPORTATION, RAILROAD MAP, TRANSPORTATION PLANNING/PROGRAMMING, 2016.

[39] C. BARKAN, REES 2012 MODULE #1 - INTRODUCTION TO RAIL TRANSPORTATION, IN: U.O.I.A. URBANA-CHAMPAIGN (ED.), 2012.

[40] D. TOLLIVER, P. LU, D. BENSON, COMPARING RAIL FUEL EFFICIENCY WITH TRUCK AND WATERWAY, TRANSPORTATION RESEARCH PART D: TRANSPORT AND ENVIRONMENT, 24 (2013) 69-75.

[41] T.H.D.A.M.A. HARRIS, WITHDRAWAL AND CONSUMPTION OF WATER BY THERMOELECTRIC POWER PLANTS IN THE UNITED STATES, SCIENTIFIC INVESTIGATIONS REPORT 2014–5184, U.S. DEPARTMENT OF THE INTERIOR, 2010.

APPENDIX A

[GAMS SIMULATION CODE]

```
option limrow = 100000;

option limcol = 100000;


Set

k /48201, 48113, 48439, 48029, 48453, 48085, 48215, 48141, 48121, 48157, 48339, 48491, 48061,

48355, 48039, 48027, 48167, 48303, 48479, 48245, 48309, 48423, 48041, 48209, 48139, 48251,

48329, 48135, 48187, 48441, 48091, 48381, 48485, 48367, 48181, 48183, 48375, 48451, 48257,

48397, 48037, 48469, 48231, 48005, 48361, 48021, 48291, 48213, 48099, 48471, 48409, 48203,

48347, 48497, 48427, 48001, 48323, 48221, 48199, 48467, 48401, 48073, 48265, 48473, 48277,

48325, 48465, 48013, 48349, 48493, 48373, 48053, 48499, 48259, 48481, 48143, 48055, 48249,

48459, 48071, 48097, 48049, 48321, 48227, 48223, 48241, 48217, 48477, 48189, 48147, 48025,

48449, 48273, 48067, 48015, 48363, 48407, 48185, 48463, 48171, 48007, 48419, 48149, 48331,

48365, 48293, 48219, 48225, 48179, 48341, 48057, 48489, 48019, 48233, 48457, 48089, 48177,

48123, 48281, 48165, 48299, 48253, 48285, 48161, 48337, 48163, 48117, 48133, 48503, 48035,

48003, 48051, 48415, 48289, 48145, 48287, 48395, 48371, 48255, 48353, 48389, 48239, 48455,

48505, 48351, 48313, 48059, 48093, 48279, 48115, 48487, 48063, 48445, 48343, 48387, 48297,

48507, 48475, 48131, 48031, 48379, 48127, 48159, 48399, 48357, 48403, 48077, 48315, 48429,

48369, 48043, 48425, 48237, 48335, 48009, 48501, 48083, 48405, 48193, 48307, 48495, 48069,

48283, 48175, 48437, 48391, 48047, 48017, 48111, 48075, 48377, 48169, 48065, 48107, 48411,

48153, 48205, 48317, 48305, 48207, 48483, 48195, 48119, 48247, 48333, 48103, 48267, 48095,
```

48211, 48319, 48229, 48197, 48435, 48151, 48275, 48023, 48105, 48461, 48383, 48271, 48295, 48129, 48385, 48417, 48081, 48191, 48421, 48413, 48087, 48079, 48243, 48109, 48125, 48327, 48359, 48137, 48011, 48235, 48447, 48045, 48433, 48101, 48431, 48173, 48155, 48345, 48393, 48443, 48311, 48263, 48033, 48261, 48269, 48301/

*Sets for all the states

s /States/

*Sets for all the counties (Demand Destination)

c /48439, 48113, 48201, 48029, 48453/

*Sets for Water Reservoir Counties

h /48201, 48113, 48439, 48029, 48453, 48215, 48141, 48121, 48157, 48339, 48355, 48167, 48303, 48309, 48139, 48251, 48135, 48187, 48375, 48257, 48361, 48213, 48409, 48203, 48497, 48221, 48401, 48073, 48277, 48481, 48071, 48147, 48449, 48185, 48149, 48293, 48299, 48161, 48503, 48395, 48279, 48487, 48475, 48315, 48175 /

*Sets for Facility Locations (Porudction Location)

l /48201, 48113, 48439, 48029, 48453, 48085, 48215, 48141, 48121, 48157, 48339, 48491, 48061, 48355, 48039, 48027, 48167, 48303, 48479, 48245, 48309, 48423, 48041, 48209, 48139, 48251, 48329, 48135, 48187, 48441, 48091, 48381, 48485, 48367, 48181, 48183, 48375, 48451, 48257, 48397, 48037, 48469, 48231, 48005, 48361, 48021, 48291, 48213, 48099, 48471, 48409, 48203, 48347, 48497, 48427, 48001, 48323, 48221, 48199, 48467, 48401, 48073, 48265, 48473, 48277, 48325, 48465, 48013, 48349, 48493, 48373, 48053, 48499, 48259, 48481, 48143, 48055, 48249, 48459, 48071, 48097, 48049, 48321, 48227, 48223, 48241, 48217, 48477, 48189, 48147, 48025, 48449, 48273, 48067, 48015, 48363, 48407, 48185, 48463, 48171, 48007, 48419, 48149, 48331, 48365, 48293, 48219, 48225, 48179, 48341, 48057, 48489, 48019, 48233, 48457, 48089, 48177,

```
48123, 48281, 48165, 48299, 48253, 48285, 48161, 48337, 48163, 48117, 48133, 48503, 48035,

48003, 48051, 48415, 48289, 48145, 48287, 48395, 48371, 48255, 48353, 48389, 48239, 48455,

48505, 48351, 48313, 48059, 48093, 48279, 48115, 48487, 48063, 48445, 48343, 48387, 48297,

48507, 48475, 48131, 48031, 48379, 48127, 48159, 48399, 48357, 48403, 48077, 48315, 48429,

48369, 48043, 48425, 48237, 48335, 48009, 48501, 48083, 48405, 48193, 48307, 48495, 48069,

48283, 48175, 48437, 48391, 48047, 48017, 48111, 48075, 48377, 48169, 48065, 48107, 48411,

48153, 48205, 48317, 48305, 48207, 48483, 48195, 48119, 48247, 48333, 48103, 48267, 48095,

48211, 48319, 48229, 48197, 48435, 48151, 48275, 48023, 48105, 48461, 48383, 48271, 48295,

48129, 48385, 48417, 48081, 48191, 48421, 48413, 48087, 48079, 48243, 48109, 48125, 48327,

48359, 48137, 48011, 48235, 48447, 48045, 48433, 48101, 48431, 48173, 48155, 48345, 48393,

48443, 48311, 48263, 48033, 48261, 48269, 48301/


*Sets for Transportation Means

m /TR, RR/

*Sets for Product

p /NH3, O2, H2/

*Sets for Renewable Energies

r /WD, PV/

*Sets for Conversion Technologies

j /CT, ACT, FUC/

*Sets for Plant Sizes

t /300, 1200, 2100, 3000/;
```

```
Binary Variable

* Facility Binary

y(r,t,l)

* conversion plant binary

x(c,j)

;


Parameter

N /1/

NTMAX /200/

NTMIN /1/

B Maximum Number of Conversion Plant in US /100/

ATR Present Value of Annuity Factor

DR Discount Rate(%) /0.07/

NP Number of Periods(YRS) /25/


RC(r)  **LINA EAC Renewable Plant Investment Cost /PV 985093, WD 1690000/

RLR(r) land requirement for renewable power plant for renewable technology r /PV 0.03, WD
0.345/

RLC(r) **LINA Renewable Plant land unit cost at location l /PV 30000, WD 8000/

RLM(l) Land Price Multiplier /48201 2.008, 48113 1.458, 48439 2.043, 48029 1.711, 48453 1.718,
48085 1.458, 48215 1.437, 48141 6.564, 48121 1.458, 48157 2.008, 48339 2.008, 48491 1.718,
48061 1.437, 48355 1.031, 48039 2.008, 48027 0.983, 48167 2.008, 48303 0.372, 48479 0.676,
```

48245 2.008, 48309 0.983, 48423 1.013, 48041 1.865, 48209 1.718, 48139 1.458, 48251 2.043,

48329 0.308, 48135 0.308, 48187 1.711, 48441 0.396, 48091 1.711, 48381 0.326, 48485 0.511,

48367 2.043, 48181 1.402, 48183 1.013, 48375 0.369, 48451 0.508, 48257 1.458, 48397 1.458,

48037 0.883, 48469 1.115, 48231 1.458, 48005 0.961, 48361 2.008, 48021 1.718, 48291 2.008,

48213 1.013, 48099 0.983, 48471 2.008, 48409 1.031, 48203 1.013, 48347 1.013, 48497 2.043,

48427 0.676, 48001 1.013, 48323 1.217, 48221 2.043, 48199 2.008, 48467 1.458, 48401 1.013,

48073 1.013, 48265 2.716, 48473 2.008, 48277 0.883, 48325 1.217, 48465 0.508, 48013 1.711,

48349 0.983, 48493 1.711, 48373 0.961, 48053 2.009, 48499 0.883, 48259 2.716, 48481 1.115,

48143 0.837, 48055 1.718, 48249 1.031, 48459 0.883, 48071 2.008, 48097 1.402, 48049 0.837,

48321 1.115, 48227 0.308, 48223 0.883, 48241 0.961, 48217 0.983, 48477 1.865, 48189 0.372,

48147 1.402, 48025 1.031, 48449 0.883, 48273 1.031, 48067 0.883, 48015 2.008, 48363 2.043,

48407 2.008, 48185 1.865, 48463 1.217, 48171 2.009, 48007 1.031, 48419 1.013, 48149 1.954,

48331 1.718, 48365 1.013, 48293 0.983, 48219 0.308, 48225 1.013, 48179 0.326, 48341 0.543,

48057 1.115, 48489 1.437, 48019 2.716, 48233 0.369, 48457 0.961, 48089 1.954, 48177 1.954,

48123 1.954, 48281 0.986, 48165 0.308, 48299 2.009, 48253 0.396, 48285 1.954, 48161 0.983,

48337 1.402, 48163 1.217, 48117 0.326, 48133 0.837, 48503 0.511, 48035 0.983, 48003 0.308,

48051 1.865, 48415 0.396, 48289 1.865, 48145 0.983, 48287 1.718, 48395 1.865, 48371 0.214,

48255 1.711, 48353 0.396, 48389 0.214, 48239 1.115, 48455 0.961, 48505 0.676, 48351 0.961,

48313 1.865, 48059 0.837, 48093 0.837, 48279 0.308, 48115 0.372, 48487 0.511, 48063 0.883,

48445 0.308, 48343 0.883, 48387 0.883, 48297 1.031, 48507 1.217, 48475 0.214, 48131 0.676,

48031 2.716, 48379 1.458, 48127 0.676, 48159 0.883, 48399 0.396, 48357 0.543, 48403 0.961,

48077 0.511, 48315 0.883, 48429 0.511, 48369 0.326, 48043 0.214, 48425 2.043, 48237 0.511,

48335 0.396, 48009 0.511, 48501 0.308, 48083 0.837, 48405 0.961, 48193 0.986, 48307 0.986, 48495 0.214, 48069 0.326, 48283 0.676, 48175 1.031, 48437 0.326, 48391 1.031, 48047 0.676, 48017 0.308, 48111 0.543, 48075 0.31, 48377 0.214, 48169 0.372, 48065 0.326, 48107 0.372, 48411 0.986, 48153 0.372, 48205 0.543, 48317 0.308, 48305 0.372, 48207 0.511, 48483 0.31, 48195 0.543, 48119 0.883, 48247 0.676, 48333 0.986, 48103 0.214, 48267 1.019, 48095 0.508, 48211 0.369, 48319 2.009, 48229 0.214, 48197 0.511, 48435 0.508, 48151 0.396, 48275 0.511, 48023 0.511, 48105 0.508, 48461 0.508, 48383 0.508, 48271 0.508, 48295 0.369, 48129 0.31, 48385 1.019, 48417 0.511, 48081 0.508, 48191 0.31, 48421 0.543, 48413 0.508, 48087 0.31, 48079 0.308, 48243 0.214, 48109 0.214, 48125 0.31, 48327 1.019, 48359 0.369, 48137 0.508, 48011 0.326, 48235 0.508, 48447 0.511, 48045 0.326, 48433 0.31, 48101 0.31, 48431 0.508, 48173 0.508, 48155 0.511, 48345 0.31, 48393 0.369, 48443 0.214, 48311 0.676, 48263 0.31, 48033 0.372, 48261 0.676, 48269 0.31, 48301 0.214/

RLA(l) Land availability at location l /48201 1773.49474, 48113 907.69279, 48439 897.6493, 48029 1256.12293, 48453 1023.70464, 48085 886.22372, 48215 1582.57893, 48141 1014.66408, 48121 958.17136, 48157 884.82548, 48339 1076.71202, 48491 1133.90708, 48061 943.54942, 48355 841.30654, 48039 1442.45298, 48027 1088.3069, 48167 403.34793, 48303 900.68912, 48479 3375.52611, 48245 990.30342, 48309 1060.22528, 48423 949.85218, 48041 590.74836, 48209 678.9033, 48139 951.85865, 48251 733.82752, 48329 901.9744, 48135 901.6912, 48187 714.5658, 48441 919.2524, 48091 574.74852, 48381 922.39456, 48485 633.02683, 48367 909.49378, 48181 978.57528, 48183 276.31306, 48375 921.98564, 48451 1540.53686, 48257 806.42169, 48397 148.75771, 48037 922.77203, 48469 888.89203, 48231 881.76672, 48005 864.45076, 48361 379.54064, 48021 895.94583, 48291 1176.44947, 48213 949.09999, 48099 1056.72981, 48471 801.4357, 48409 704.25872, 48203 915.09158, 48347 981.32873, 48497 922.72646, 48427 1229.25075, 48001 1077.94486, 48323 1291.73656, 48221 437.01796, 48199

897.38283, 48467 859.35422, 48401 938.57483, 48073 1061.98916, 48265 1107.66085, 48473
518.75411, 48277 932.46803, 48325 1334.49909, 48465 3232.37828, 48013 1235.62863, 48349
1086.32318, 48493 808.51515, 48373 1109.81603, 48053 1021.40986, 48499 695.81731, 48259
663.07084, 48481 1094.36121, 48143 1089.79202, 48055 546.8637, 48249 868.34465, 48459
592.7588, 48071 629.43908, 48097 898.73849, 48049 956.93501, 48321 1144.91755, 48227
904.1949, 48223 793.11351, 48241 969.61989, 48217 986.28579, 48477 621.53008, 48189
1004.76967, 48147 899.22139, 48025 880.37196, 48449 425.689, 48273 886.51821, 48067
960.34456, 48015 656.57166, 48363 985.83432, 48407 627.89885, 48185 800.97806, 48463
1558.61071, 48171 1061.80209, 48007 242.62836, 48419 834.53333, 48149 959.47373, 48331
1021.82478, 48365 821.34071, 48293 933.15271, 48219 908.55998, 48225 1236.83898, 48179
929.27128, 48341 909.61779, 48057 530.90825, 48489 600.19341, 48019 797.52845, 48233
894.936, 48457 935.71065, 48089 973.22014, 48177 1069.84874, 48123 910.61173, 48281
713.53638, 48165 1502.83973, 48299 965.55271, 48253 937.12873, 48285 970.59177, 48161
892.13336, 48337 938.44389, 48163 1134.28044, 48117 1498.2907, 48133 931.90378, 48503
930.8458, 48035 1002.58308, 48003 1500.99525, 48051 677.78405, 48415 907.52933, 48289
1080.37651, 48145 773.80356, 48287 633.54051, 48395 865.64563, 48371 4764.73833, 48255
753.71763, 48353 913.92886, 48389 2641.95333, 48239 852.45977, 48455 714.00198, 48505
1058.10252, 48351 939.50057, 48313 472.44112, 48059 901.25932, 48093 947.66975, 48279
1017.73091, 48115 902.12152, 48487 978.09101, 48063 203.19798, 48445 890.92394, 48343
258.63934, 48387 1057.61477, 48297 1078.85508, 48507 1301.7022, 48475 835.74011, 48131
1795.58602, 48031 713.35892, 48379 258.951, 48127 1334.47888, 48159 294.77275, 48399
1057.12879, 48357 918.0707, 48403 576.61049, 48077 1116.16705, 48315 420.35919, 48429
921.47164, 48369 885.16761, 48043 6192.77226, 48425 192.03068, 48237 920.11363, 48335

915.897, 48009 925.78532, 48501 799.76433, 48083 1281.5525, 48405 592.21675, 48193 836.37511, 48307 1073.35182, 48495 841.23432, 48069 899.31916, 48283 1494.22553, 48175 859.06954, 48437 900.67699, 48391 778.54687, 48047 943.61856, 48017 827.37969, 48111 1505.25449, 48075 713.6113, 48377 3856.24436, 48169 896.18907, 48065 924.088, 48107 901.69238, 48411 1138.77192, 48153 992.50568, 48205 1463.18718, 48317 915.62136, 48305 893.45805, 48207 910.25281, 48483 915.3391, 48195 920.40306, 48119 277.91962, 48247 1136.17014, 48333 749.88439, 48103 785.58491, 48267 1250.92225, 48095 993.58651, 48211 912.05822, 48319 932.46068, 48229 4571.92792, 48197 696.99963, 48435 1454.3998, 48151 901.74094, 48275 855.43664, 48023 901.01468, 48105 2807.43195, 48461 1241.83322, 48383 1175.98378, 48271 1365.29466, 48295 932.22184, 48129 933.04358, 48385 700.04642, 48417 915.54441, 48081 927.97829, 48191 904.07493, 48421 923.19753, 48413 1310.65368, 48087 919.43872, 48079 775.30692, 48243 2264.59964, 48109 3812.68754, 48125 905.21364, 48327 902.24954, 48359 1501.42537, 48137 2119.94361, 48011 913.81133, 48235 1051.58851, 48447 915.46905, 48045 901.58858, 48433 920.22927, 48101 901.59419, 48431 923.49182, 48173 900.92847, 48155 707.68812, 48345 989.81152, 48393 924.18169, 48443 2357.74538, 48311 1142.6582, 48263 902.90767, 48033 906.04182, 48261 1416.87824, 48269 913.32893, 48301 676.85033/

ROM(r) Renewable Plant O&M Cost /PV 18500, WD 39560/

NTU Number of Transportation Unit

TCC Transportation Capital Cost

*LC(t) Production Plant Investment unit Cost (PF:0.85)   /300 142500000, 1200 415522174, 2100 644544027, 3000 854290734/

*LC(t) PF(1) /300 142500000, 1200 485082661, 2100 808678031, 3000 1124805951/

LC(t) PF(0.85) for ELEC and PF(0.6) for the Rest /300 142500000, 1200 462983866, 2100 744986149, 3000 1008822743/

LO(t) Production Plant O&M Cost

CC(j) EAC Conversion Plant Investment Unit Cost /CT 1101, ACT 678, FUC 1600/

CFO(j) Conversion Plant Fixed O&M Cost   /CT 17.5, ACT 6.8, FUC 16/

CVO(j) Conversion Plant Variable O&M Cost   /CT 3.5, ACT 10.7, FUC 30/

CA(j)   Conversion Plant Availability per year   /CT 0.913, ACT 0.913, FUC 0.98/

ETHA(j) Conversion Plant Electrical Efficiency   /CT 0.4,   ACT 0.4,   FUC 0.59/

ERC(r) EAC RC

ELC(t) EAC LC

ECC(j) EAC CC

WD Water Constant for Partaility

PD Demand Constant for Partiality /0.5/

DM(c) Top 5 Demand Location /48201 74101871, 48113 41571705, 48439 32561293, 48029 31137481, 48453 19362412/

WA(h) Water Availability /48201 10659964, 48113 8121877, 48439 169206, 48029 1692058, 48453 169206, 48215 7952672, 48141 846029, 48121 169206, 48157 14382491, 48339 3384116, 48355 5076173, 48167 2199675, 48303 5922202, 48309 1353646, 48139 1522852, 48251 1353646, 48135 1692058, 48187 8121877, 48375 21996751, 48257 7783466, 48361 9983141, 48213 1692058, 48409 1184440, 48203 4568556, 48497 4399350, 48221 507617, 48401 39086535, 48073 846029, 48277 3384116, 48481 846029, 48071 676823, 48147 507617, 48449 34348773, 48185 13028845, 48149 107276465, 48293 31810687, 48299 3553321, 48161 20135488, 48503 1015235, 48395 26565307, 48279 20304694, 48487 1015235, 48475 17935813, 48315 169206, 48175 1522852/

FW(t) **Ammonia production water requirement for capacity t /300 173740, 1200 694960, 2100 1216180, 3000 1737400/

ELT(t) **Electricity Required at Capacity t /300 1270200, 1200 5080800, 2100 8891400, 3000 12702000/

DC Distance Curvature /1.1/

TCap(m) Transportation Capacity /TR 43.5, RR 5500/

TMC(m) **Total Cost /TR 39643, RR 75305/

FE(m) Fuel Economy /TR 262.3,RR 457/

*FE(m) Fuel Economy /TR 160,RR 27/

SP(m) Average Speed /TR 34.4, RR 28.1/

```
TMA(m) Availability of Transportation/TR 18, RR 12/

LUT(m) Loading and Unloading Time /TR 2, RR 12/

DW(m)  Driver Wage  /TR 23,RR 23/

FP(m)  Fuel Price   /TR 4.38,RR 1.06/

ME(m)  Maintenance Expense /TR 0.16,RR 0.1/

GE(m)  General Expense /TR 8.22,RR 6.85/


DFC overton           /3/

DVC overton-mi        /0.005/


PC(p) **Price of Product /NH3 100, O2 1000, H2 100/

EAC Equivalent Annual Cost /11.65/


COSTWP **Water Cost /2.4/


ZUP Upper bound for Continuous variable Z /5000000/


OS Oxygen Sales /0.00/

;


* RF(l,r) Renewable energy scaling factor

$include "C:\Users\songeol5\Desktop\PARAMETER\FINAL5\RF.txt";

* GMMA(l,r) Capacity Factor for Renewable Plant
```

```
$include "C:\Users\songeol5\Desktop\PARAMETER\FINAL5\GMMA.txt"

* DI(l,c,m);

$include "C:\Users\songeol5\Desktop\PARAMETER\FINAL5\DI.txt"

* DIWT(h,l);

$include "C:\Users\songeol5\Desktop\PARAMETER\FINAL5\WT.txt"


*$ontext

Set MAX_TR_DIST(l,c,m);

   MAX_TR_DIST(l,c,m) = YES;

loop((l,c,m)$(DI(l,c,'TR') ge 300), MAX_TR_DIST(l,c,'TR') = NO;);


Set MAX_TR_DISTWT(h,l);

   MAX_TR_DISTWT(h,l) = YES;

loop((h,l)$(DIWT(h,l) ge 200), MAX_TR_DISTWT(h,l) = NO;);

*$offtext


* Ammonia Transportation Cost *

Parameter FC(l,c,m), LA(l,c,m), MC(l,c,m), GC(l,c,m), COSTPT(l,c,m), COSTWT(h,l);


*NTU = 1/(TMA(m)*TCap(m)*SP(m))+LUT(m)/(TMA(m)+TCap(m));

*TCC =


WD = sum(c, DM(c))/449826336;
```

```
FC(l,c,m) = FP(m)*2/FE(m);

LA(l,c,m) = DW(m)/TCap(m)*2/SP(m)+LUT(m)*(DW(m)/TCap(m));

MC(l,c,m) = ME(m)*2/TCap(m);

GC(l,c,m) = GE(m)/(TMA(m)*TCap(m))*(2/SP(m))+LUT(m)*GE(m)/(TMA(m)*TCap(m));

COSTPT(l,c,m) = DC*2*DI(l,c,m)*(FC(l,c,m)+LA(l,c,m)+MC(l,c,m)+GC(l,c,m));

COSTWT(h,l) = DFC + DVC*DIWT(h,l)*DC;

ATR = (1-1/power((1+DR),NP))/DR;

LO(t) = 0.03*LC(t);

ERC(r) = RC(r) / ATR;

ELC(t) = LC(t) / ATR;

ECC(j) = CC(j) / ATR;


Display COSTPT, COSTWT;


Table PR(p,t) Product Ratio Tonyr

    300     1200    2100    3000

NH3 109500  438000  766500  1095000

O2  15637   62548   109459  156370

H2  123355  493420  863485  1233550;



Positive Variable
```

* Investment and O&MN cost for facility including renewable and production plant *

COSTIF(l)

COSTOMF(l)

INVEST

* Investment and O&MN cost for conversion power plant *

COSTCV(c)

CONVERS

* Electricity variable *

ELR(r,l)

* Water Flow Variable *

WF(l)

w(h,l)

* Conversion Plant Variable *

CV(c,j)

* Product Flow Variable *

z(p,l,c,m)   Product flow

u(r,t,l)

```
e(c,j) Linearization Variable


INVR

INVA

INVF

ONMR

ONMA

ONMF

WTCO

TRPT

TRPTA

LCOA


LOBJGJ

LOBJMWH


OXY

;


variable

obj

;
```

Equation   FCBIN *FCN **FCNMAX(t) **FCNMIN(t) *LANDRE ELCNSP *ELFLOW PRFLOW CCBIN CVFLOW LIN1 LIN2 LIN3 LIN4

LIN5

LIN6

DEMAND(c)

FCINV(l)

FCONM(l)

WTR1(l)

WTR2(l)

WTR3(h)

CCCOST

INVES1

INVES2

INVES3

ONM1

ONM2

ONM3

CONVE

WTRCT

TRANS

```
LVLCOA

LVOBJ1

LVOBJ2


OXYS


**TRDI


Objective;


  LIN1(r,t,l).. u(r,t,l) =l= 10000*y(r,t,l);

  LIN2(r,t,l).. u(r,t,l) =l= ELR(r,l);

  LIN3(r,t,l).. u(r,t,l) =g= ELR(r,l)-(1-y(r,t,l))*10000;

* Linearization of Continuous CV(c,j) and Binary Variable x(c,j) **

  LIN4(c,j).. e(c,j) =l= ZUP*x(c,j);

  LIN5(c,j).. e(c,j) =l= CV(c,j);

  LIN6(c,j).. e(c,j) =g= CV(c,j)-(1-x(c,j))*ZUP;


*                              $(MAX_TR_DIST(l,c,m) and MIN_RR_DIST(l,c,m))



* Facility Constraints *

FCBIN(l)..    1   =g= sum((r,t), y(r,t,l));
```

```
*FCN(r)..      1   =l= sum((t,l), y(r,t,l));

**FCNMAX(t).. NTMAX =g= sum((r,l), y(r,t,l));

**FCNMIN(t).. NTMIN =l= sum((r,l), y(r,t,l));


* Electricity Consumption *

ELCNSP(r,l).. sum(t, 8760*GMMA(l,r)*RF(l,r)*u(r,t,l)) =e= sum((t), y(r,t,l)*ELT(t));


* Land Requirement for Renewable Technologies *

*LANDRE(l).. RLA(l) =g= sum((r,t), RLR(r)*u(r,t,l));


* Production Plant Flow *

PRFLOW(l)..  sum((p('NH3'),r,t), y(r,t,l)*PR(p,t)) =e= sum((p('NH3'),c,m), z(p,l,c,m));


* Conversion Plant Flow *

CCBIN(c)..  sum(j, x(c,j)) =l= 1;

CVFLOW(c).. sum(j, e(c,j)*8760) =e= sum((p('NH3'),l,m), 5.2*z(p,l,c,m));


* Demand Satisfaction *

DEMAND(c)..   sum((j), e(c,j)*8760*CA(j)*ETHA(j)) =g= DM(c)*PD;


* Facility Cost (Renewable Power Plant + Ammonia Production Plant) *

FCINV(l).. sum((r,t), u(r,t,l)*ERC(r)+y(r,t,l)*ELC(t)) =e= COSTIF(l);
```

```
FCONM(l).. sum((r,t), u(r,t,l)*(ROM(r)+RLC(r)*RLM(l)))+sum((r,t), y(r,t,l)*LO(t)) =e=
COSTOMF(l);


* Conversion Technology Cost (Inv+O&M) *
CCCOST(c).. sum(j, e(c,j)*(ECC(j)+CFO(j)+CVO(j))) =e= COSTCV(c);


* Water Requirement, Flow, Availaibilty *
WTR1(l).. sum((r,t), y(r,t,l)*FW(t)) =e= WF(l);
WTR2(l).. WF(l) =e= sum(h$MAX_TR_DISTWT(h,l), w(h,l));
WTR3(h).. sum(l, w(h,l)) =l= WD*WA(h);


* Transportation
TRANS..  TRPT =e= sum((p('NH3'),l,c,m), z(p,l,c,m)*COSTPT(l,c,m)) ;


* Oxygen Sales *
OXYS..   OXY  =e= sum((p('O2'),r,t,l), OS*y(r,t,l)*PR(p,t)*PC(p));


* OBJECTIVE *
Objective..
obj =e= sum(l, COSTIF(l)+COSTOMF(l)) + sum(c, COSTCV(c)) - OXY + WTCO + TRPT;



* ------------------------------------------------------------- *
```

```
INVES1..    INVR =e= sum((r,l,t), u(r,t,l)*ERC(r))+sum((r,t,l), y(r,t,l)*LO(t));

INVES2..    INVA =e= sum((r,l,t), y(r,t,l)*ELC(t))+sum((r,t,l),
u(r,t,l)*(ROM(r)+RLC(r)*RLM(l)));

INVES3..    INVF =e= sum(l, COSTIF(l)+COSTOMF(l));


ONM1(l)..   ONMR(l) =e= sum((r,t), u(r,t,l)*(ROM(r)+RLC(r)*RLM(l)));

ONM2(l)..   ONMA(l) =e= sum((r,t), y(r,t,l)*LO(t));

ONM3(l)..ONMF(l) =e= COSTOMF(l);


CONVE..  CONVERS =e= sum(c, COSTCV(c));


WTRCT..  WTCO =e= sum((h,l), w(h,l)*(COSTWP+COSTWT(h,l)));


LVLCOA.. LCOA =e= sum(l,(COSTIF(l)+COSTOMF(l))) / (6.68E+07*PD);


LVOBJ1..  LOBJGJ  =e= obj/(715445142.8*PD);

LVOBJ2..  LOBJMWH =e= obj/(198734762*PD);

* ---------------------------------------------------------------- *


model supply /all/;
```

```
Solve supply using MIP minimizing obj;


Display y.l;

Display ELR.l;

Display z.l ;

Display CV.l, e.l ;

Display x.l, ATR, ERC, ELC, ECC;


file Results /Final_Case2.csv/;

Results.pw=32767;

Results.nr=6;

Results.nd=6;

Results.pc=5;

put Results;


$include "C:\Users\songeol5\Desktop\PARAMETER\FINAL5\ExportExcel.txt";
```

APPENDIX B

[RESULT DATA CASE-1]

Facility Selection Results - y(r,t,l)				
Renewable Source	Ammonia Capacity	Plant Location	Binary Variable	Renewable Capacity
	TPD			MW
WD	3,000	48113	1	1,520
WD	3,000	48439	1	1,330
WD	3,000	48121	1	1,830
WD	3,000	48491	1	1,520
WD	3,000	48209	1	1,350
WD	3,000	48139	1	1,340
WD	3,000	48251	1	1,090
WD	3,000	48441	1	888
WD	3,000	48091	1	1,180
WD	3,000	48381	1	1,010
WD	3,000	48485	1	1,430
WD	3,000	48367	1	1,200
WD	3,000	48181	1	1,240
WD	3,000	48375	1	977
WD	3,000	48451	1	1,160
WD	3,000	48397	1	1,420

WD	3,000	48231	1	1,350
WD	3,000	48497	1	1,470
WD	3,000	48221	1	1,130
WD	3,000	48277	1	1,370
WD	3,000	48465	1	1,410
WD	3,000	48013	1	1,490
WD	3,000	48053	1	1,400
WD	3,000	48259	1	1,070
WD	3,000	48143	1	852
WD	3,000	48097	1	1,120
WD	3,000	48049	1	876
WD	3,000	48147	1	1,060
WD	3,000	48067	1	1,950
WD	3,000	48293	1	1,480
WD	3,000	48179	1	864
WD	3,000	48281	1	1,400
WD	3,000	48117	1	943
WD	3,000	48133	1	874
WD	3,000	48035	1	1,540
WD	3,000	48415	1	1,110
WD	3,000	48289	1	1,840
WD	3,000	48145	1	1,590
WD	3,000	48371	1	1,010

WD	3,000	48353	1	917
WD	3,000	48059	1	1,090
WD	3,000	48093	1	987
WD	3,000	48279	1	1,070
WD	3,000	48487	1	1,330
WD	3,000	48131	1	1,490
WD	3,000	48077	1	1,260
WD	3,000	48369	1	1,010
WD	3,000	48237	1	957
WD	3,000	48335	1	1,130
WD	3,000	48083	1	1,140
WD	3,000	48307	1	828
WD	3,000	48495	1	1,170
WD	3,000	48069	1	1,010
WD	3,000	48169	1	1,170
WD	3,000	48065	1	858
WD	3,000	48411	1	1,090
WD	3,000	48333	1	1,180
WD	3,000	48197	1	1,230
WD	3,000	48461	1	1,120
WD	3,000	48383	1	1,050
WD	3,000	48129	1	1,140
WD	3,000	48421	1	1,020

WD	3,000	48393	1	882
WD	3,000	48261	1	1,470

Product Flow - z(p,l,c,m)					
Product	Mode of Transportation	Plant Location	Demand Location	Product Flow	Distance
				Ton/yr	miles
NH3	RR	48113	48113	1,100,000	0
NH3	RR	48439	48113	1,100,000	30
NH3	RR	48121	48113	1,100,000	36
NH3	RR	48491	48453	1,100,000	24
NH3	RR	48209	48029	1,100,000	52
NH3	RR	48139	48201	1,100,000	193
NH3	RR	48251	48201	1,100,000	226
NH3	RR	48441	48029	501,000	298
NH3	RR	48441	48453	594,000	222
NH3	RR	48091	48029	1,100,000	29
NH3	RR	48381	48453	1,100,000	470
NH3	RR	48485	48113	1,100,000	149
NH3	RR	48367	48113	1,100,000	60
NH3	RR	48181	48113	1,100,000	63
NH3	RR	48375	48113	687,000	376
NH3	RR	48375	48439	408,000	346

NH3	RR	48451	48201	724,000	366
NH3	RR	48451	48453	371,000	258
NH3	RR	48397	48113	1,100,000	23
NH3	RR	48231	48113	1,100,000	48
NH3	RR	48497	48439	1,100,000	37
NH3	RR	48221	48201	927,000	254
NH3	RR	48221	48439	168,000	39
NH3	RR	48277	48113	1,100,000	112
NH3	RR	48465	48029	1,100,000	167
NH3	RR	48013	48029	1,100,000	38
NH3	RR	48053	48453	1,100,000	40
NH3	TR	48259	48029	1,100,000	36
NH3	RR	48143	48439	1,100,000	66
NH3	RR	48097	48113	1,100,000	67
NH3	RR	48049	48201	1,100,000	267
NH3	RR	48147	48113	1,100,000	80
NH3	TR	48067	48113	1,100,000	143
NH3	RR	48293	48201	1,100,000	148
NH3	RR	48179	48439	1,100,000	407
NH3	RR	48281	48201	1,100,000	207
NH3	RR	48117	48201	1,100,000	618
NH3	RR	48133	48439	1,100,000	97
NH3	RR	48035	48201	1,100,000	221

NH3	RR	48415	48201	1,100,000	403
NH3	TR	48289	48201	1,100,000	106
NH3	RR	48145	48201	1,100,000	140
NH3	RR	48371	48029	1,100,000	377
NH3	RR	48353	48201	1,100,000	360
NH3	RR	48059	48439	1,100,000	129
NH3	RR	48093	48453	1,100,000	187
NH3	RR	48279	48201	1,100,000	527
NH3	RR	48487	48439	1,100,000	151
NH3	RR	48131	48029	1,100,000	191
NH3	RR	48077	48439	1,100,000	88
NH3	RR	48369	48201	1,100,000	586
NH3	TR	48237	48439	1,100,000	60
NH3	RR	48335	48201	1,100,000	391
NH3	RR	48083	48453	1,100,000	185
NH3	RR	48307	48201	1,100,000	273
NH3	RR	48495	48201	1,100,000	576
NH3	RR	48069	48201	1,100,000	555
NH3	RR	48169	48201	1,100,000	440
NH3	RR	48065	48439	1,100,000	376
NH3	RR	48411	48201	1,100,000	241
NH3	RR	48333	48201	1,100,000	236
NH3	RR	48197	48439	1,100,000	183

NH3	RR	48461	48029	1,100,000	428
NH3	RR	48383	48201	1,100,000	429
NH3	RR	48129	48439	1,100,000	272
NH3	RR	48421	48439	1,100,000	407
NH3	RR	48393	48439	1,100,000	437
NH3	RR	48261	48029	1,100,000	193

Conversion Plant COST - e(c,j)			
Demand Location	Technology	Capacity	COST
		MW	$
48201	FUC	14,600	2,680,000
48113	FUC	8,210	1,500,000
48439	FUC	8,790	1,610,000
48029	FUC	6,150	1,130,000
48453	FUC	3,820	701,000

Water Flow - w(h,l)			
Water Source Location	Plant Location	Transported Water Flow	Distance
		Ton/yr	Miles
48113	48113	1,740,000	-
48113	48485	571,000	139

48113	48487	1,280,000	169
48439	48441	74,800	155
48029	48465	748,000	161
48453	48441	74,800	184
48215	48261	1,740,000	48
48141	48495	374,000	187
48121	48121	74,800	-
48355	48013	505,000	98
48355	48131	1,740,000	55
48303	48415	593,000	79
48303	48169	1,740,000	42
48303	48129	286,000	110
48309	48441	317,000	166
48309	48353	281,000	195
48139	48441	673,000	181
48251	48441	598,000	148
48135	48415	472,000	113
48135	48335	276,000	100
48187	48091	825,000	25
48187	48451	1,740,000	196
48187	48465	990,000	194
48187	48013	36,000	59
48375	48375	1,740,000	-

48375	48179	1,740,000	61
48375	48065	1,740,000	30
48375	48129	1,030,000	68
48375	48421	1,740,000	61
48375	48393	1,740,000	68
48257	48121	1,660,000	64
48257	48485	786,000	169
48257	48397	990,000	22
48213	48397	748,000	57
48409	48013	523,000	87
48203	48067	1,660,000	37
48497	48497	61,400	-
48497	48487	145,000	109
48497	48197	1,740,000	141
48221	48415	224,000	181
48277	48485	156,000	181
48277	48277	1,340,000	0
48147	48485	224,000	152
48449	48181	1,740,000	103
48449	48231	1,740,000	65
48449	48277	398,000	47
48449	48097	1,740,000	133
48449	48147	1,740,000	71

48449	48077	1,740,000	191
48149	48491	1,740,000	67
48149	48209	1,740,000	68
48149	48091	912,000	82
48149	48053	1,740,000	98
48149	48259	1,740,000	108
48149	48307	1,740,000	171
48293	48251	1,740,000	74
48293	48367	155,000	111
48293	48221	1,740,000	96
48293	48143	1,740,000	107
48293	48293	1,740,000	-
48293	48133	1,740,000	143
48293	48035	1,740,000	67
48293	48059	1,740,000	172
48293	48093	1,740,000	120
48299	48353	1,460,000	150
48299	48335	113,000	172
48161	48439	1,740,000	100
48161	48139	1,740,000	58
48161	48367	1,580,000	122
48161	48497	1,680,000	137
48161	48289	425,000	30

48161	48237	1,740,000	158
48503	48415	449,000	133
48395	48049	1,740,000	156
48395	48281	1,740,000	103
48395	48289	1,310,000	36
48395	48145	1,740,000	30
48395	48083	1,740,000	181
48395	48411	1,740,000	137
48395	48333	1,740,000	127
48279	48381	1,740,000	67
48279	48117	1,740,000	64
48279	48279	1,740,000	-
48279	48369	1,740,000	40
48279	48069	1,740,000	32
48279	48129	284,000	107
48487	48487	312,000	-
48487	48129	136,000	109
48475	48371	1,740,000	55
48475	48335	1,350,000	139
48475	48495	1,360,000	24
48475	48461	1,740,000	63
48475	48383	1,740,000	94
48315	48067	74,800	19

48175	48013	673,000	69

APPENDIX C

[RESULT DATA CASE-2]

Facility Selection Results - y(r,t,l)				
Renewable Source	Ammonia Capacity	Plant Location	Binary Variable	Renewable Capacity
				MW
WD	3,000	48251	1	1,094
WD	3,000	48441	1	888
WD	3,000	48091	1	1,178
WD	3,000	48381	1	1,009
WD	3,000	48375	1	977
WD	3,000	48451	1	1,156
WD	3,000	48221	1	1,126
WD	3,000	48143	1	852
WD	3,000	48097	1	1,123
WD	3,000	48049	1	876
WD	3,000	48227	1	1,109
WD	3,000	48147	1	1,062
WD	3,000	48179	1	864
WD	3,000	48117	1	943
WD	3,000	48133	1	874
WD	3,000	48415	1	1,109

WD	3,000	48371	1	1,013
WD	3,000	48353	1	917
WD	3,000	48059	1	1,090
WD	3,000	48093	1	987
WD	3,000	48279	1	1,069
WD	3,000	48369	1	1,005
WD	3,000	48335	1	1,131
WD	3,000	48083	1	1,138
WD	3,000	48307	1	828
WD	3,000	48069	1	1,009
WD	3,000	48065	1	858
WD	3,000	48411	1	1,094
WD	3,000	48333	1	1,183
WD	3,000	48383	1	1,054
WD	3,000	48393	1	882

Product Flow - z(p,l,c,m)					
Product	Plant Location	Mode of Transportation	Demand Location	Product Flow	Distance
				Ton/yr	miles
NH3	RR	48251	48113	1,095,000	44

NH3	RR	48441	48453	1,095,000	222
NH3	RR	48091	48029	1,095,000	29
NH3	RR	48381	48113	1,095,000	406
NH3	RR	48375	48113	1,095,000	376
NH3	RR	48451	48029	1,095,000	333
NH3	RR	48221	48113	343,316	69
NH3	RR	48221	48439	751,684	39
NH3	RR	48143	48439	1,095,000	66
NH3	RR	48097	48113	1,095,000	67
NH3	RR	48049	48029	1,095,000	235
NH3	RR	48227	48201	361,939	421
NH3	RR	48227	48029	733,061	388
NH3	RR	48147	48113	1,095,000	80
NH3	RR	48179	48439	1,095,000	407
NH3	RR	48117	48201	1,011,100	618
NH3	RR	48117	48439	83,902	416
NH3	RR	48133	48439	1,095,000	97
NH3	RR	48415	48201	1,095,000	403
NH3	RR	48371	48029	1,095,000	377
NH3	RR	48353	48201	1,095,000	360
NH3	RR	48059	48439	1,095,000	129
NH3	RR	48093	48201	1,095,000	296
NH3	RR	48279	48201	1,095,000	527

NH3	RR	48369	48201	1,095,000	586
NH3	RR	48335	48201	1,095,000	391
NH3	RR	48083	48201	1,095,000	294
NH3	RR	48307	48453	1,095,000	164
NH3	RR	48069	48029	65,058	523
NH3	RR	48069	48453	1,029,940	447
NH3	RR	48065	48439	1,095,000	376
NH3	RR	48411	48201	1,095,000	241
NH3	RR	48333	48201	1,095,000	236
NH3	RR	48383	48201	1,095,000	429
NH3	RR	48393	48113	1,095,000	467

Conversion Plant COST - e(c,j)			
Demand Location	Technology	Capacity	COST
	j	MW	$
48201	FUC	7,315	1,340,820
48113	FUC	4,104	752,213
48439	FUC	3,746	686,632
48029	FUC	3,074	563,412
48453	FUC	1,911	350,350

Water Flow - w(h,l)			
Water Source Location	Plant Location	Transported Water Flow	Distance
		Ton/yr	miles
48113	48251	412,495	44
48113	48221	1,513,130	66
48113	48097	1,662,640	65
48439	48133	74,756	95
48029	48307	747,557	131
48453	48411	74,756	84
48121	48097	74,756	30
48303	48415	879,048	79
48303	48353	1,737,400	122
48309	48333	598,045	82
48139	48251	672,801	33
48251	48251	598,045	0
48135	48227	747,557	72
48187	48091	1,737,400	25
48187	48307	989,843	140
48187	48411	92,775	121
48375	48381	1,737,400	30
48375	48375	1,737,400	0

48375	48179	1,737,400	61
48375	48117	1,031,240	50
48375	48065	1,737,400	30
48375	48393	1,737,400	68
48257	48251	54,059	65
48257	48147	18,020	70
48497	48133	654,782	92
48497	48059	1,288,870	118
48221	48221	224,267	0
48277	48147	1,495,110	31
48147	48147	224,267	0
48293	48143	1,737,400	107
48293	48049	1,737,400	143
48293	48133	1,007,860	143
48293	48093	1,737,400	120
48293	48083	1,737,400	170
48293	48333	1,139,350	119
48299	48411	1,569,870	32
48503	48059	448,534	73
48279	48441	1,288,870	188
48279	48117	706,163	64
48279	48415	858,352	123
48279	48279	1,737,400	0

48279	48369	1,737,400	40
48279	48335	15,342	147
48279	48069	1,737,400	32
48487	48441	448,534	129
48475	48451	1,737,400	156
48475	48227	989,843	112
48475	48371	1,737,400	55
48475	48335	1,722,060	139
48475	48383	1,737,400	94

APPENDIX D

[RESULT DATA CASE-3]

Facility Selection Results - y(r,t,l)				
Renewable Source	Ammonia Capacity	Plant Location	Binary Variable	Renewable Capacity
WD	1200	48451	1.00E+00	4.62E+02
WD	1200	48359	1.00E+00	3.75E+02
WD	2100	48439	1.00E+00	9.31E+02
WD	2100	48227	1.00E+00	7.76E+02
WD	2100	48295	1.00E+00	6.40E+02
WD	3000	48061	1.00E+00	1.53E+03
WD	3000	48209	1.00E+00	1.35E+03
WD	3000	48139	1.00E+00	1.34E+03
WD	3000	48251	1.00E+00	1.09E+03
WD	3000	48441	1.00E+00	8.88E+02
WD	3000	48091	1.00E+00	1.18E+03
WD	3000	48381	1.00E+00	1.01E+03
WD	3000	48367	1.00E+00	1.20E+03
WD	3000	48181	1.00E+00	1.24E+03
WD	3000	48375	1.00E+00	9.77E+02
WD	3000	48397	1.00E+00	1.42E+03
WD	3000	48231	1.00E+00	1.35E+03

WD	3000	48099	1.00E+00	1.47E+03
WD	3000	48221	1.00E+00	1.13E+03
WD	3000	48265	1.00E+00	1.16E+03
WD	3000	48277	1.00E+00	1.37E+03
WD	3000	48053	1.00E+00	1.40E+03
WD	3000	48259	1.00E+00	1.07E+03
WD	3000	48143	1.00E+00	8.52E+02
WD	3000	48097	1.00E+00	1.12E+03
WD	3000	48049	1.00E+00	8.76E+02
WD	3000	48147	1.00E+00	1.06E+03
WD	3000	48363	1.00E+00	1.15E+03
WD	3000	48171	1.00E+00	9.62E+02
WD	3000	48179	1.00E+00	8.64E+02
WD	3000	48233	1.00E+00	1.09E+03
WD	3000	48281	1.00E+00	1.40E+03
WD	3000	48337	1.00E+00	1.31E+03
WD	3000	48117	1.00E+00	9.43E+02
WD	3000	48133	1.00E+00	8.74E+02
WD	3000	48503	1.00E+00	1.08E+03
WD	3000	48371	1.00E+00	1.01E+03
WD	3000	48353	1.00E+00	9.17E+02
WD	3000	48505	1.00E+00	1.39E+03
WD	3000	48059	1.00E+00	1.09E+03

WD	3000	48093	1.00E+00	9.87E+02
WD	3000	48115	1.00E+00	1.29E+03
WD	3000	48487	1.00E+00	1.33E+03
WD	3000	48357	1.00E+00	9.40E+02
WD	3000	48077	1.00E+00	1.26E+03
WD	3000	48429	1.00E+00	1.37E+03
WD	3000	48425	1.00E+00	8.58E+02
WD	3000	48237	1.00E+00	9.57E+02
WD	3000	48009	1.00E+00	1.17E+03
WD	3000	48083	1.00E+00	1.14E+03
WD	3000	48307	1.00E+00	8.28E+02
WD	3000	48495	1.00E+00	1.17E+03
WD	3000	48065	1.00E+00	8.58E+02
WD	3000	48107	1.00E+00	1.01E+03
WD	3000	48411	1.00E+00	1.09E+03
WD	3000	48153	1.00E+00	1.01E+03
WD	3000	48483	1.00E+00	9.43E+02
WD	3000	48195	1.00E+00	1.04E+03
WD	3000	48333	1.00E+00	1.18E+03
WD	3000	48103	1.00E+00	9.91E+02
WD	3000	48267	1.00E+00	9.51E+02
WD	3000	48095	1.00E+00	8.16E+02
WD	3000	48319	1.00E+00	8.80E+02

WD	3000	48435	1.00E+00	1.35E+03
WD	3000	48151	1.00E+00	9.24E+02
WD	3000	48275	1.00E+00	1.34E+03
WD	3000	48023	1.00E+00	1.48E+03
WD	3000	48105	1.00E+00	1.18E+03
WD	3000	48383	1.00E+00	1.05E+03
WD	3000	48385	1.00E+00	1.02E+03
WD	3000	48417	1.00E+00	1.04E+03
WD	3000	48413	1.00E+00	9.87E+02
WD	3000	48125	1.00E+00	1.01E+03
WD	3000	48327	1.00E+00	7.18E+02
WD	3000	48137	1.00E+00	9.60E+02
WD	3000	48447	1.00E+00	1.52E+03
WD	3000	48045	1.00E+00	1.14E+03
WD	3000	48101	1.00E+00	1.11E+03
WD	3000	48173	1.00E+00	9.88E+02
WD	3000	48155	1.00E+00	1.14E+03
WD	3000	48345	1.00E+00	1.11E+03
WD	3000	48393	1.00E+00	8.82E+02
WD	3000	48263	1.00E+00	1.21E+03

Product Flow - z(p,l,c,m)			

Product	Plant Location	Mode of Transportation	Demand Location	Product Flow (Ton/yr)	Distance (miles)
NH3	RR	48439	48439	7.67E+05	0.00E+00
NH3	RR	48061	48215	1.10E+06	4.50E+01
NH3	RR	48209	48029	1.30E+05	5.15E+01
NH3	RR	48209	48453	9.65E+05	2.42E+01
NH3	RR	48139	48113	1.10E+06	2.89E+01
NH3	RR	48251	48113	1.10E+06	4.36E+01
NH3	RR	48441	48439	1.10E+06	1.59E+02
NH3	RR	48091	48029	1.10E+06	2.88E+01
NH3	RR	48381	48439	1.10E+06	3.76E+02
NH3	RR	48367	48439	1.10E+06	2.99E+01
NH3	RR	48181	48085	1.10E+06	3.10E+01
NH3	RR	48375	48113	1.02E+06	3.76E+02
NH3	RR	48375	48439	7.99E+04	3.46E+02
NH3	RR	48451	48439	4.38E+05	2.21E+02
NH3	RR	48397	48113	1.10E+06	2.33E+01
NH3	RR	48231	48113	1.10E+06	4.77E+01
NH3	RR	48099	48201	1.10E+06	0.00E+00
NH3	RR	48221	48439	1.10E+06	3.94E+01
NH3	RR	48265	48201	1.10E+06	0.00E+00
NH3	RR	48277	48085	1.10E+06	9.52E+01
NH3	RR	48053	48453	1.10E+06	3.95E+01

NH3	RR	48259	48201	1.10E+06	0.00E+00
NH3	RR	48143	48113	1.10E+06	9.54E+01
NH3	RR	48097	48121	1.10E+06	3.05E+01
NH3	RR	48049	48121	1.10E+06	1.54E+02
NH3	RR	48227	48113	7.67E+05	3.06E+02
NH3	RR	48147	48085	1.10E+06	6.39E+01
NH3	RR	48363	48201	1.10E+06	0.00E+00
NH3	RR	48171	48201	1.10E+06	0.00E+00
NH3	RR	48179	48439	1.10E+06	4.07E+02
NH3	RR	48233	48201	1.10E+06	0.00E+00
NH3	RR	48281	48453	1.10E+06	9.87E+01
NH3	RR	48337	48201	1.10E+06	0.00E+00
NH3	RR	48117	48113	1.10E+06	4.46E+02
NH3	RR	48133	48439	1.10E+06	9.74E+01
NH3	RR	48503	48201	1.10E+06	0.00E+00
NH3	RR	48371	48141	1.10E+06	3.11E+02
NH3	RR	48353	48113	1.10E+06	2.46E+02
NH3	RR	48505	48201	1.10E+06	0.00E+00
NH3	RR	48059	48113	1.10E+06	1.59E+02
NH3	RR	48093	48439	8.56E+05	9.38E+01
NH3	RR	48093	48121	2.40E+05	1.25E+02
NH3	RR	48115	48201	2.91E+05	0.00E+00
NH3	RR	48115	48121	8.04E+05	0.00E+00

NH3	RR	48487	48121	1.10E+06	1.83E+02
NH3	RR	48357	48201	4.30E+05	0.00E+00
NH3	RR	48357	48085	6.65E+05	0.00E+00
NH3	RR	48077	48113	1.10E+06	1.18E+02
NH3	RR	48429	48157	1.10E+06	0.00E+00
NH3	RR	48425	48029	1.10E+06	0.00E+00
NH3	RR	48237	48141	1.10E+06	0.00E+00
NH3	RR	48009	48157	1.10E+06	0.00E+00
NH3	RR	48083	48439	1.10E+06	1.49E+02
NH3	RR	48307	48453	1.10E+06	1.64E+02
NH3	RR	48495	48141	1.10E+06	2.16E+02
NH3	RR	48065	48113	1.10E+06	4.06E+02
NH3	RR	48107	48215	1.10E+06	0.00E+00
NH3	RR	48411	48453	1.10E+06	1.33E+02
NH3	RR	48153	48029	1.10E+06	0.00E+00
NH3	RR	48483	48029	1.10E+06	0.00E+00
NH3	RR	48195	48141	1.10E+06	0.00E+00
NH3	RR	48333	48453	1.10E+06	1.28E+02
NH3	RR	48103	48201	1.10E+06	0.00E+00
NH3	RR	48267	48215	1.10E+06	0.00E+00
NH3	RR	48095	48201	1.10E+06	0.00E+00
NH3	RR	48319	48201	1.10E+06	0.00E+00
NH3	RR	48435	48201	1.10E+06	0.00E+00

NH3	RR	48151	48201	1.10E+06	0.00E+00
NH3	RR	48275	48085	1.10E+06	0.00E+00
NH3	RR	48023	48201	1.10E+06	0.00E+00
NH3	RR	48105	48201	9.12E+05	0.00E+00
NH3	RR	48105	48215	1.83E+05	0.00E+00
NH3	RR	48383	48439	1.10E+06	2.85E+02
NH3	RR	48295	48201	7.67E+05	0.00E+00
NH3	RR	48385	48201	1.10E+06	0.00E+00
NH3	RR	48417	48029	2.81E+05	0.00E+00
NH3	RR	48417	48157	8.14E+05	0.00E+00
NH3	RR	48413	48215	1.10E+06	0.00E+00
NH3	RR	48125	48201	1.10E+06	0.00E+00
NH3	RR	48327	48201	1.10E+06	0.00E+00
NH3	RR	48359	48029	4.38E+05	0.00E+00
NH3	RR	48137	48201	1.10E+06	0.00E+00
NH3	RR	48447	48141	1.19E+05	0.00E+00
NH3	RR	48447	48157	9.76E+05	0.00E+00
NH3	RR	48045	48029	1.10E+06	0.00E+00
NH3	RR	48101	48029	1.10E+06	0.00E+00
NH3	RR	48173	48029	1.10E+06	0.00E+00
NH3	RR	48155	48201	1.10E+06	0.00E+00
NH3	RR	48345	48029	1.10E+06	0.00E+00
NH3	RR	48393	48113	1.10E+06	4.67E+02

NH3	RR	48263	48201	3.47E+05	0.00E+00
NH3	RR	48263	48029	7.48E+05	0.00E+00

Conversion Plant COST - e(c,j)			
Demand Location	Technology	Capacity (MW)	COST ($)
48201	FUC	1.46E+04	2.24E+09
48113	FUC	8.21E+03	1.26E+09
48439	FUC	6.47E+03	9.92E+08
48029	FUC	6.15E+03	9.43E+08
48453	FUC	3.82E+03	5.86E+08
48085	FUC	2.99E+03	4.59E+08
48215	FUC	2.71E+03	4.15E+08
48141	FUC	2.67E+03	4.10E+08
48121	FUC	2.57E+03	3.94E+08
48157	FUC	2.36E+03	3.62E+08

Water Flow - w(h,l)			
Water Source Location	Plant Location	Transported Water Flow (kg/h)	Distance(miles)
48113	48441	3.56E+04	1.84E+02
48113	48275	1.74E+06	1.81E+02
48113	48023	1.65E+06	1.53E+02

48113	48155	1.39E+06	1.92E+02
48439	48151	1.00E+05	1.81E+02
48029	48105	1.00E+06	1.94E+02
48453	48451	1.00E+05	1.75E+02
48215	48061	1.74E+06	4.50E+01
48215	48505	1.74E+06	7.40E+01
48141	48495	5.01E+05	1.87E+02
48121	48337	1.00E+05	4.78E+01
48303	48107	1.74E+06	3.00E+01
48303	48125	6.07E+05	6.00E+01
48303	48263	1.16E+06	6.70E+01
48309	48441	8.01E+05	1.66E+02
48139	48441	9.01E+05	1.81E+02
48251	48151	8.01E+05	1.79E+02
48135	48227	1.00E+06	7.16E+01
48187	48451	4.94E+05	1.96E+02
48187	48435	1.74E+06	1.67E+02
48187	48413	1.74E+06	1.79E+02
48187	48137	8.37E+05	1.44E+02
48375	48375	1.74E+06	0.00E+00
48375	48179	1.37E+06	6.10E+01
48375	48233	1.74E+06	4.29E+01
48375	48357	1.74E+06	8.57E+01

48375	48065	1.74E+06	3.04E+01
48375	48195	1.74E+06	6.77E+01
48375	48295	1.22E+06	1.09E+02
48375	48393	1.74E+06	6.79E+01
48257	48397	7.36E+05	2.18E+01
48257	48337	1.64E+06	1.12E+02
48257	48487	1.74E+06	1.99E+02
48257	48077	4.03E+05	1.38E+02
48257	48023	9.06E+04	1.84E+02
48213	48397	1.00E+06	5.74E+01
48497	48151	5.13E+05	1.63E+02
48497	48101	1.74E+06	1.62E+02
48497	48155	3.52E+05	1.33E+02
48221	48151	3.00E+05	1.51E+02
48277	48277	1.74E+06	1.00E-04
48277	48147	2.65E+05	3.13E+01
48147	48147	3.00E+05	0.00E+00
48449	48181	1.74E+06	1.03E+02
48449	48231	1.74E+06	6.52E+01
48449	48097	1.74E+06	1.33E+02
48449	48147	1.17E+06	7.09E+01
48149	48209	1.74E+06	6.78E+01
48149	48091	1.74E+06	8.16E+01

48149	48265	1.74E+06	1.46E+02
48149	48053	1.74E+06	9.83E+01
48149	48259	1.74E+06	1.08E+02
48149	48171	1.74E+06	1.25E+02
48149	48267	1.74E+06	1.74E+02
48149	48319	1.74E+06	1.50E+02
48149	48385	1.74E+06	1.74E+02
48149	48327	1.74E+06	1.87E+02
48293	48221	1.74E+06	9.57E+01
48293	48143	1.74E+06	1.07E+02
48293	48363	1.74E+06	1.31E+02
48293	48133	1.74E+06	1.43E+02
48293	48503	1.45E+06	1.67E+02
48293	48059	1.74E+06	1.72E+02
48293	48093	1.74E+06	1.20E+02
48293	48429	1.74E+06	1.56E+02
48293	48425	1.74E+06	8.43E+01
48293	48417	1.74E+06	1.82E+02
48293	48447	1.74E+06	1.91E+02
48299	48451	1.01E+05	1.16E+02
48299	48353	1.74E+06	1.50E+02
48299	48105	2.64E+05	1.62E+02
48161	48439	1.22E+06	9.95E+01

48161	48139	1.74E+06	5.84E+01
48161	48251	1.74E+06	8.53E+01
48161	48367	1.74E+06	1.22E+02
48161	48503	2.91E+05	1.80E+02
48161	48077	1.33E+06	1.87E+02
48161	48237	1.74E+06	1.58E+02
48161	48009	1.74E+06	1.98E+02
48503	48151	2.27E+04	1.04E+02
48503	48263	5.78E+05	1.21E+02
48395	48099	1.74E+06	8.02E+01
48395	48049	1.74E+06	1.56E+02
48395	48281	1.74E+06	1.03E+02
48395	48083	1.74E+06	1.81E+02
48395	48307	1.74E+06	1.68E+02
48395	48411	1.74E+06	1.37E+02
48395	48333	1.74E+06	1.27E+02
48395	48095	1.74E+06	1.99E+02
48279	48381	1.74E+06	6.73E+01
48279	48179	3.64E+05	1.27E+02
48279	48117	1.74E+06	6.37E+01
48279	48153	1.74E+06	6.01E+01
48279	48483	1.14E+06	1.50E+02
48279	48125	1.13E+06	9.56E+01

48279	48359	6.95E+05	9.35E+01
48279	48045	1.74E+06	7.27E+01
48279	48345	1.74E+06	9.01E+01
48487	48483	6.01E+05	1.08E+02
48475	48227	2.15E+05	1.12E+02
48475	48371	1.74E+06	5.52E+01
48475	48115	1.74E+06	1.09E+02
48475	48495	1.24E+06	2.38E+01
48475	48103	1.74E+06	3.51E+01
48475	48105	4.73E+05	1.14E+02
48475	48383	1.74E+06	9.37E+01
48475	48173	1.74E+06	9.64E+01
48175	48385	2.33E+02	1.66E+02
48175	48137	9.01E+05	1.96E+02

APPENDIX E

[RESULT DATA CASE-4]

Facility Selection Results - y(r,t,l)				
Renewable Source	Ammonia Capacity	Plant Location	Binary Variable	Renewable Capacity
WD	2100	48113	1.00E+00	1.06E+03
WD	2100	48061	1.00E+00	1.07E+03
WD	2100	48013	1.00E+00	1.04E+03
WD	2100	48337	1.00E+00	9.17E+02
WD	3000	48439	1.00E+00	1.33E+03
WD	3000	48209	1.00E+00	1.35E+03
WD	3000	48139	1.00E+00	1.34E+03
WD	3000	48251	1.00E+00	1.09E+03
WD	3000	48329	1.00E+00	1.16E+03
WD	3000	48135	1.00E+00	1.20E+03
WD	3000	48441	1.00E+00	8.88E+02
WD	3000	48091	1.00E+00	1.18E+03
WD	3000	48381	1.00E+00	1.01E+03
WD	3000	48485	1.00E+00	1.43E+03
WD	3000	48367	1.00E+00	1.20E+03
WD	3000	48181	1.00E+00	1.24E+03
WD	3000	48375	1.00E+00	9.77E+02

WD	3000	48451	1.00E+00	1.16E+03
WD	3000	48397	1.00E+00	1.42E+03
WD	3000	48231	1.00E+00	1.35E+03
WD	3000	48099	1.00E+00	1.47E+03
WD	3000	48221	1.00E+00	1.13E+03
WD	3000	48265	1.00E+00	1.16E+03
WD	3000	48277	1.00E+00	1.37E+03
WD	3000	48465	1.00E+00	1.41E+03
WD	3000	48053	1.00E+00	1.40E+03
WD	3000	48259	1.00E+00	1.07E+03
WD	3000	48143	1.00E+00	8.52E+02
WD	3000	48097	1.00E+00	1.12E+03
WD	3000	48049	1.00E+00	8.76E+02
WD	3000	48227	1.00E+00	1.11E+03
WD	3000	48147	1.00E+00	1.06E+03
WD	3000	48363	1.00E+00	1.15E+03
WD	3000	48171	1.00E+00	9.62E+02
WD	3000	48293	1.00E+00	1.48E+03
WD	3000	48179	1.00E+00	8.64E+02
WD	3000	48341	1.00E+00	1.09E+03
WD	3000	48233	1.00E+00	1.09E+03
WD	3000	48281	1.00E+00	1.40E+03
WD	3000	48253	1.00E+00	1.43E+03

WD	3000	48117	1.00E+00	9.43E+02
WD	3000	48133	1.00E+00	8.74E+02
WD	3000	48503	1.00E+00	1.08E+03
WD	3000	48415	1.00E+00	1.11E+03
WD	3000	48371	1.00E+00	1.01E+03
WD	3000	48353	1.00E+00	9.17E+02
WD	3000	48505	1.00E+00	1.39E+03
WD	3000	48059	1.00E+00	1.09E+03
WD	3000	48093	1.00E+00	9.87E+02
WD	3000	48279	1.00E+00	1.07E+03
WD	3000	48115	1.00E+00	1.29E+03
WD	3000	48487	1.00E+00	1.33E+03
WD	3000	48131	1.00E+00	1.49E+03
WD	3000	48357	1.00E+00	9.40E+02
WD	3000	48077	1.00E+00	1.26E+03
WD	3000	48429	1.00E+00	1.37E+03
WD	3000	48369	1.00E+00	1.01E+03
WD	3000	48425	1.00E+00	8.58E+02
WD	3000	48237	1.00E+00	9.57E+02
WD	3000	48335	1.00E+00	1.13E+03
WD	3000	48009	1.00E+00	1.17E+03
WD	3000	48501	1.00E+00	1.37E+03
WD	3000	48083	1.00E+00	1.14E+03

WD	3000	48307	1.00E+00	8.28E+02
WD	3000	48495	1.00E+00	1.17E+03
WD	3000	48069	1.00E+00	1.01E+03
WD	3000	48169	1.00E+00	1.17E+03
WD	3000	48065	1.00E+00	8.58E+02
WD	3000	48107	1.00E+00	1.01E+03
WD	3000	48411	1.00E+00	1.09E+03
WD	3000	48153	1.00E+00	1.01E+03
WD	3000	48205	1.00E+00	1.07E+03
WD	3000	48207	1.00E+00	1.45E+03
WD	3000	48483	1.00E+00	9.43E+02
WD	3000	48195	1.00E+00	1.04E+03
WD	3000	48333	1.00E+00	1.18E+03
WD	3000	48103	1.00E+00	9.91E+02
WD	3000	48267	1.00E+00	9.51E+02
WD	3000	48095	1.00E+00	8.16E+02
WD	3000	48211	1.00E+00	1.01E+03
WD	3000	48319	1.00E+00	8.80E+02
WD	3000	48197	1.00E+00	1.23E+03
WD	3000	48435	1.00E+00	1.35E+03
WD	3000	48151	1.00E+00	9.24E+02
WD	3000	48275	1.00E+00	1.34E+03
WD	3000	48023	1.00E+00	1.48E+03

WD	3000	48105	1.00E+00	1.18E+03
WD	3000	48461	1.00E+00	1.12E+03
WD	3000	48383	1.00E+00	1.05E+03
WD	3000	48295	1.00E+00	9.14E+02
WD	3000	48129	1.00E+00	1.14E+03
WD	3000	48385	1.00E+00	1.02E+03
WD	3000	48417	1.00E+00	1.04E+03
WD	3000	48421	1.00E+00	1.02E+03
WD	3000	48413	1.00E+00	9.87E+02
WD	3000	48087	1.00E+00	1.33E+03
WD	3000	48079	1.00E+00	1.37E+03
WD	3000	48125	1.00E+00	1.01E+03
WD	3000	48327	1.00E+00	7.18E+02
WD	3000	48359	1.00E+00	9.38E+02
WD	3000	48137	1.00E+00	9.60E+02
WD	3000	48447	1.00E+00	1.52E+03
WD	3000	48045	1.00E+00	1.14E+03
WD	3000	48101	1.00E+00	1.11E+03
WD	3000	48173	1.00E+00	9.88E+02
WD	3000	48155	1.00E+00	1.14E+03
WD	3000	48345	1.00E+00	1.11E+03
WD	3000	48393	1.00E+00	8.82E+02
WD	3000	48263	1.00E+00	1.21E+03

WD	3000	48033	1.00E+00	1.38E+03
WD	3000	48261	1.00E+00	1.47E+03

Product Flow - z(p,l,c,m)					
Product	Plant Location	Mode of Transportation	Demand Location	Product Flow (Ton/yr)	Distance (miles)
NH3	TR	48113	48113	7.67E+05	0.00E+00
NH3	TR	48439	48439	1.10E+06	0.00E+00
NH3	TR	48061	48061	7.67E+05	0.00E+00
NH3	RR	48209	48453	3.98E+04	2.42E+01
NH3	TR	48209	48209	8.78E+05	0.00E+00
NH3	RR	48209	48055	1.77E+05	2.90E+01
NH3	RR	48139	48113	3.71E+05	2.89E+01
NH3	TR	48139	48139	7.24E+05	0.00E+00
NH3	RR	48251	48113	1.65E+05	4.36E+01
NH3	RR	48251	48251	7.01E+05	0.00E+00
NH3	RR	48251	48217	1.51E+05	3.02E+01
NH3	RR	48251	48035	7.77E+04	3.66E+01
NH3	RR	48329	48141	1.10E+06	2.64E+02
NH3	RR	48135	48141	3.69E+05	2.34E+02
NH3	TR	48135	48135	6.76E+05	0.00E+00
NH3	RR	48135	48475	4.98E+04	4.13E+01
NH3	RR	48441	48441	5.87E+05	0.00E+00

NH3	RR	48441	48367	3.71E+05	1.29E+02
NH3	RR	48441	48133	7.85E+04	6.19E+01
NH3	RR	48441	48059	5.94E+04	3.02E+01
NH3	RR	48091	48029	5.16E+05	2.88E+01
NH3	TR	48091	48091	5.79E+05	0.00E+00
NH3	RR	48381	48381	5.69E+05	0.00E+00
NH3	RR	48381	48375	4.50E+05	3.01E+01
NH3	RR	48381	48077	4.38E+04	2.88E+02
NH3	RR	48381	48437	3.21E+04	3.15E+01
NH3	RR	48485	48439	8.18E+05	1.19E+02
NH3	RR	48485	48497	2.77E+05	8.22E+01
NH3	RR	48367	48439	9.10E+05	2.99E+01
NH3	RR	48367	48367	1.85E+05	0.00E+00
NH3	RR	48181	48085	1.10E+06	3.10E+01
NH3	RR	48375	48439	1.10E+06	3.46E+02
NH3	RR	48451	48453	5.44E+05	2.58E+02
NH3	RR	48451	48027	5.06E+05	2.05E+02
NH3	RR	48451	48399	4.49E+04	4.11E+01
NH3	RR	48397	48113	6.91E+05	2.33E+01
NH3	RR	48397	48397	4.04E+05	0.00E+00
NH3	RR	48231	48113	3.41E+05	4.77E+01
NH3	RR	48231	48231	3.96E+05	0.00E+00
NH3	RR	48231	48223	1.56E+05	3.03E+01

NH3	RR	48231	48449	1.40E+05	6.53E+01
NH3	RR	48231	48063	1.65E+04	6.63E+01
NH3	RR	48231	48159	4.56E+04	5.04E+01
NH3	RR	48099	48245	7.25E+05	0.00E+00
NH3	RR	48099	48041	2.33E+05	0.00E+00
NH3	RR	48099	48365	1.01E+05	0.00E+00
NH3	RR	48099	48405	3.57E+04	0.00E+00
NH3	RR	48221	48439	1.10E+06	3.94E+01
NH3	RR	48265	48479	6.95E+05	0.00E+00
NH3	RR	48265	48245	3.69E+05	0.00E+00
NH3	RR	48265	48391	3.14E+04	0.00E+00
NH3	RR	48277	48085	8.81E+05	9.52E+01
NH3	RR	48277	48277	2.14E+05	0.00E+00
NH3	RR	48465	48029	3.08E+05	1.67E+02
NH3	RR	48465	48323	2.48E+05	9.42E+01
NH3	RR	48465	48325	2.12E+05	1.31E+02
NH3	RR	48465	48465	2.10E+05	0.00E+00
NH3	RR	48465	48463	1.17E+05	9.14E+01
NH3	RR	48013	48029	5.57E+05	3.84E+01
NH3	RR	48013	48013	2.10E+05	0.00E+00
NH3	RR	48053	48453	8.09E+05	3.95E+01
NH3	RR	48053	48053	1.99E+05	0.00E+00
NH3	RR	48053	48299	8.75E+04	3.04E+01

NH3	RR	48259	48479	1.27E+05	0.00E+00
NH3	RR	48259	48423	9.68E+05	0.00E+00
NH3	RR	48143	48439	1.10E+06	6.56E+01
NH3	RR	48097	48121	9.26E+05	3.05E+01
NH3	TR	48097	48097	1.69E+05	0.00E+00
NH3	RR	48049	48439	1.09E+06	1.22E+02
NH3	RR	48049	48309	5.15E+03	1.46E+02
NH3	RR	48227	48141	1.21E+05	3.24E+02
NH3	RR	48227	48329	6.98E+05	6.07E+01
NH3	RR	48227	48227	1.58E+05	0.00E+00
NH3	RR	48227	48331	2.39E+03	2.95E+02
NH3	RR	48227	48389	6.41E+04	1.69E+02
NH3	RR	48227	48317	2.46E+04	3.02E+01
NH3	RR	48227	48229	1.74E+04	2.70E+02
NH3	RR	48227	48109	9.44E+03	2.19E+02
NH3	RR	48147	48085	3.98E+05	6.39E+01
NH3	RR	48147	48181	5.51E+05	3.30E+01
NH3	TR	48147	48147	1.46E+05	0.00E+00
NH3	RR	48363	48167	7.13E+05	0.00E+00
NH3	RR	48363	48479	3.43E+05	0.00E+00
NH3	RR	48363	48037	3.90E+04	0.00E+00
NH3	RR	48171	48039	5.16E+05	0.00E+00
NH3	RR	48171	48167	2.36E+05	0.00E+00

NH3	RR	48171	48213	3.43E+05	0.00E+00
NH3	RR	48293	48041	7.14E+05	6.34E+01
NH3	RR	48293	48349	2.08E+05	3.53E+01
NH3	RR	48293	48293	1.01E+05	0.00E+00
NH3	RR	48293	48395	7.20E+04	3.61E+01
NH3	RR	48179	48493	2.08E+05	0.00E+00
NH3	RR	48179	48071	3.91E+04	0.00E+00
NH3	RR	48179	48185	1.19E+05	0.00E+00
NH3	TR	48179	48179	9.76E+04	0.00E+00
NH3	RR	48179	48115	5.63E+04	0.00E+00
NH3	RR	48179	48387	5.24E+04	0.00E+00
NH3	RR	48179	48127	4.64E+04	0.00E+00
NH3	RR	48179	48403	4.43E+04	0.00E+00
NH3	RR	48179	48425	3.77E+04	0.00E+00
NH3	RR	48179	48237	3.76E+04	0.00E+00
NH3	RR	48179	48193	3.57E+04	0.00E+00
NH3	RR	48179	48175	3.23E+04	0.00E+00
NH3	RR	48179	48047	3.10E+04	0.00E+00
NH3	RR	48179	48107	8.23E+04	0.00E+00
NH3	RR	48179	48305	2.45E+04	0.00E+00
NH3	RR	48179	48207	2.44E+04	0.00E+00
NH3	RR	48179	48483	2.38E+04	0.00E+00
NH3	RR	48179	48119	2.24E+04	0.00E+00

NH3	RR	48179	48103	2.07E+04	0.00E+00
NH3	RR	48179	48295	1.50E+04	0.00E+00
NH3	RR	48179	48417	1.42E+04	0.00E+00
NH3	RR	48179	48413	1.31E+04	0.00E+00
NH3	RR	48179	48045	6.33E+03	0.00E+00
NH3	RR	48179	48173	5.64E+03	0.00E+00
NH3	RR	48179	48155	5.08E+03	0.00E+00
NH3	RR	48341	48113	9.47E+05	4.06E+02
NH3	RR	48341	48341	9.50E+04	0.00E+00
NH3	RR	48341	48197	1.68E+04	1.93E+02
NH3	RR	48341	48129	1.46E+04	1.04E+02
NH3	RR	48341	48191	1.35E+04	1.35E+02
NH3	RR	48341	48011	8.06E+03	7.30E+01
NH3	RR	48233	48157	4.78E+05	0.00E+00
NH3	RR	48233	48355	6.17E+05	0.00E+00
NH3	RR	48281	48491	1.10E+06	7.44E+01
NH3	RR	48253	48061	1.83E+05	0.00E+00
NH3	RR	48253	48167	4.66E+05	0.00E+00
NH3	RR	48253	48021	3.55E+05	0.00E+00
NH3	RR	48253	48001	8.98E+04	0.00E+00
NH3	RR	48337	48157	7.67E+05	0.00E+00
NH3	RR	48117	48099	1.06E+05	0.00E+00
NH3	RR	48117	48171	1.14E+05	0.00E+00

NH3	RR	48117	48233	9.24E+04	0.00E+00
NH3	RR	48117	48165	8.80E+04	0.00E+00
NH3	RR	48117	48117	5.21E+05	0.00E+00
NH3	RR	48117	48031	4.89E+04	0.00E+00
NH3	RR	48117	48429	4.26E+04	0.00E+00
NH3	RR	48117	48153	2.54E+04	0.00E+00
NH3	RR	48117	48081	1.40E+04	0.00E+00
NH3	RR	48117	48079	1.24E+04	0.00E+00
NH3	RR	48117	48243	9.45E+03	0.00E+00
NH3	RR	48117	48137	8.21E+03	0.00E+00
NH3	RR	48117	48433	6.13E+03	0.00E+00
NH3	RR	48117	48101	6.02E+03	0.00E+00
NH3	RR	48133	48113	1.10E+06	1.27E+02
NH3	RR	48503	48005	2.04E+05	0.00E+00
NH3	RR	48503	48361	3.65E+05	0.00E+00
NH3	RR	48503	48199	2.42E+05	0.00E+00
NH3	RR	48503	48149	1.08E+05	0.00E+00
NH3	RR	48503	48057	9.44E+04	0.00E+00
NH3	RR	48503	48163	8.14E+04	0.00E+00
NH3	RR	48415	48027	9.56E+05	2.43E+02
NH3	RR	48415	48415	7.45E+04	0.00E+00
NH3	RR	48415	48353	6.44E+04	4.28E+01
NH3	RR	48371	48141	9.54E+05	3.11E+02

NH3	RR	48371	48371	6.86E+04	0.00E+00
NH3	RR	48371	48043	3.95E+04	7.41E+01
NH3	RR	48371	48377	2.99E+04	1.35E+02
NH3	RR	48371	48443	3.49E+03	1.50E+02
NH3	RR	48353	48113	2.73E+05	2.46E+02
NH3	RR	48353	48453	4.13E+05	2.52E+02
NH3	RR	48353	48221	2.44E+05	1.76E+02
NH3	RR	48353	48049	1.64E+05	9.35E+01
NH3	RR	48505	48215	7.59E+05	0.00E+00
NH3	RR	48505	48355	8.80E+04	0.00E+00
NH3	RR	48505	48473	2.05E+05	0.00E+00
NH3	RR	48505	48315	4.36E+04	0.00E+00
NH3	RR	48059	48113	1.10E+06	1.59E+02
NH3	RR	48093	48113	1.10E+06	1.24E+02
NH3	RR	48279	48303	1.04E+06	4.40E+01
NH3	TR	48279	48279	5.70E+04	0.00E+00
NH3	RR	48115	48029	8.35E+05	0.00E+00
NH3	RR	48115	48373	2.06E+05	0.00E+00
NH3	RR	48115	48343	5.41E+04	0.00E+00
NH3	RR	48487	48113	1.10E+06	1.81E+02
NH3	RR	48131	48355	8.47E+05	5.48E+01
NH3	RR	48131	48249	1.77E+05	2.59E+01
NH3	TR	48131	48131	4.91E+04	0.00E+00

NH3	RR	48131	48247	2.21E+04	4.56E+01
NH3	RR	48357	48029	7.29E+05	0.00E+00
NH3	RR	48357	48469	4.19E+03	0.00E+00
NH3	RR	48357	48321	1.60E+05	0.00E+00
NH3	RR	48357	48477	1.51E+05	0.00E+00
NH3	RR	48357	48297	5.18E+04	0.00E+00
NH3	RR	48077	48113	1.10E+06	1.18E+02
NH3	RR	48429	48029	5.28E+05	0.00E+00
NH3	RR	48429	48085	5.67E+05	0.00E+00
NH3	RR	48369	48499	1.90E+05	0.00E+00
NH3	RR	48369	48259	1.83E+05	0.00E+00
NH3	RR	48369	48071	1.32E+05	0.00E+00
NH3	RR	48369	48025	1.41E+05	0.00E+00
NH3	RR	48369	48363	1.21E+05	0.00E+00
NH3	RR	48369	48007	1.10E+05	0.00E+00
NH3	RR	48369	48253	8.60E+04	0.00E+00
NH3	TR	48369	48369	4.20E+04	0.00E+00
NH3	RR	48369	48017	3.08E+04	3.20E+01
NH3	RR	48369	48267	1.90E+04	0.00E+00
NH3	RR	48369	48271	1.54E+04	0.00E+00
NH3	RR	48369	48087	1.30E+04	0.00E+00
NH3	RR	48369	48125	9.38E+03	0.00E+00
NH3	RR	48369	48033	2.72E+03	0.00E+00

NH3	RR	48425	48029	1.10E+06	0.00E+00
NH3	RR	48237	48029	1.10E+06	0.00E+00
NH3	RR	48335	48439	8.46E+05	2.46E+02
NH3	RR	48335	48491	1.07E+05	2.58E+02
NH3	RR	48335	48331	1.04E+05	2.65E+02
NH3	RR	48335	48335	3.75E+04	0.00E+00
NH3	RR	48009	48201	7.44E+05	0.00E+00
NH3	RR	48009	48291	3.51E+05	0.00E+00
NH3	RR	48501	48201	1.00E+06	0.00E+00
NH3	RR	48501	48089	9.03E+04	0.00E+00
NH3	RR	48083	48113	1.10E+06	1.79E+02
NH3	RR	48307	48309	1.06E+06	1.51E+02
NH3	RR	48307	48307	3.51E+04	0.00E+00
NH3	RR	48495	48141	1.06E+06	2.16E+02
NH3	TR	48495	48495	3.39E+04	0.00E+00
NH3	RR	48069	48303	2.64E+05	7.22E+01
NH3	RR	48069	48257	3.95E+05	0.00E+00
NH3	RR	48069	48189	1.47E+05	4.03E+01
NH3	RR	48069	48219	1.00E+05	1.02E+02
NH3	RR	48069	48285	8.51E+04	0.00E+00
NH3	RR	48069	48445	5.50E+04	1.15E+02
NH3	RR	48069	48069	3.29E+04	0.00E+00
NH3	RR	48069	48105	1.58E+04	0.00E+00

NH3	RR	48169	48453	1.07E+06	3.32E+02
NH3	RR	48169	48169	2.77E+04	0.00E+00
NH3	RR	48065	48121	1.07E+06	4.08E+02
NH3	RR	48065	48065	2.60E+04	0.00E+00
NH3	RR	48107	48201	1.10E+06	0.00E+00
NH3	RR	48411	48491	1.07E+06	1.09E+02
NH3	RR	48411	48411	2.55E+04	0.00E+00
NH3	RR	48153	48201	1.10E+06	0.00E+00
NH3	RR	48205	48121	3.49E+05	4.28E+02
NH3	RR	48205	48485	5.66E+05	2.77E+02
NH3	RR	48205	48375	6.91E+04	5.01E+01
NH3	RR	48205	48487	5.54E+04	2.45E+02
NH3	RR	48205	48075	3.03E+04	1.82E+02
NH3	RR	48205	48205	2.47E+04	0.00E+00
NH3	RR	48207	48039	1.01E+06	0.00E+00
NH3	RR	48207	48123	8.96E+04	0.00E+00
NH3	RR	48483	48029	5.90E+05	0.00E+00
NH3	RR	48483	48347	2.83E+05	0.00E+00
NH3	RR	48483	48073	2.22E+05	0.00E+00
NH3	RR	48195	48201	9.22E+05	0.00E+00
NH3	RR	48195	48005	1.73E+05	0.00E+00
NH3	RR	48333	48453	1.10E+06	1.28E+02
NH3	RR	48103	48201	9.28E+05	0.00E+00

NH3	RR	48103	48015	1.28E+05	0.00E+00
NH3	RR	48103	48063	3.88E+04	0.00E+00
NH3	RR	48267	48201	7.99E+05	0.00E+00
NH3	RR	48267	48203	2.86E+05	0.00E+00
NH3	RR	48267	48473	1.05E+04	0.00E+00
NH3	RR	48095	48201	4.35E+05	0.00E+00
NH3	RR	48095	48409	2.91E+05	0.00E+00
NH3	RR	48095	48401	2.27E+05	0.00E+00
NH3	RR	48095	48419	1.10E+05	0.00E+00
NH3	RR	48095	48283	3.27E+04	0.00E+00
NH3	RR	48211	48099	2.15E+05	0.00E+00
NH3	RR	48211	48427	2.75E+05	0.00E+00
NH3	RR	48211	48265	2.21E+05	0.00E+00
NH3	RR	48211	48407	1.19E+05	0.00E+00
NH3	RR	48211	48503	5.49E+04	0.00E+00
NH3	RR	48211	48003	7.63E+04	0.00E+00
NH3	RR	48211	48313	6.01E+04	0.00E+00
NH3	RR	48211	48009	3.74E+04	0.00E+00
NH3	RR	48211	48095	1.84E+04	0.00E+00
NH3	RR	48211	48211	1.77E+04	0.00E+00
NH3	RR	48319	48201	1.10E+06	0.00E+00
NH3	RR	48197	48113	4.75E+05	2.13E+02
NH3	RR	48197	48439	6.20E+05	1.83E+02

NH3	RR	48435	48201	8.69E+05	0.00E+00
NH3	RR	48435	48241	1.53E+05	0.00E+00
NH3	RR	48435	48287	7.33E+04	0.00E+00
NH3	RR	48151	48215	1.10E+06	0.00E+00
NH3	RR	48275	48201	5.63E+05	0.00E+00
NH3	RR	48275	48183	5.32E+05	0.00E+00
NH3	RR	48023	48215	1.10E+06	0.00E+00
NH3	RR	48105	48157	9.19E+05	0.00E+00
NH3	RR	48105	48459	1.76E+05	0.00E+00
NH3	RR	48461	48453	1.78E+05	3.52E+02
NH3	RR	48461	48451	5.09E+05	9.45E+01
NH3	RR	48461	48143	1.79E+05	2.50E+02
NH3	RR	48461	48051	7.63E+04	3.64E+02
NH3	RR	48461	48093	5.79E+04	2.22E+02
NH3	RR	48461	48083	3.62E+04	1.67E+02
NH3	RR	48461	48333	2.11E+04	2.24E+02
NH3	RR	48461	48461	1.58E+04	0.00E+00
NH3	RR	48461	48383	1.55E+04	3.07E+01
NH3	RR	48461	48235	6.69E+03	6.29E+01
NH3	RR	48383	48453	1.01E+06	3.21E+02
NH3	RR	48383	48281	8.92E+04	2.23E+02
NH3	RR	48295	48085	1.10E+06	0.00E+00
NH3	RR	48129	48113	4.61E+05	3.02E+02

NH3	RR	48129	48121	6.34E+05	3.04E+02
NH3	RR	48385	48201	1.10E+06	0.00E+00
NH3	RR	48417	48215	7.02E+05	0.00E+00
NH3	RR	48417	48469	3.93E+05	0.00E+00
NH3	RR	48421	48121	4.84E+05	4.38E+02
NH3	RR	48421	48257	1.14E+05	0.00E+00
NH3	RR	48421	48067	1.30E+05	0.00E+00
NH3	RR	48421	48177	8.97E+04	0.00E+00
NH3	RR	48421	48503	2.31E+04	0.00E+00
NH3	RR	48421	48289	7.43E+04	0.00E+00
NH3	RR	48421	48455	6.20E+04	0.00E+00
NH3	RR	48421	48501	3.65E+04	0.00E+00
NH3	RR	48421	48111	3.03E+04	3.95E+01
NH3	RR	48421	48275	1.63E+04	0.00E+00
NH3	RR	48421	48421	1.32E+04	0.00E+00
NH3	RR	48421	48447	6.59E+03	0.00E+00
NH3	RR	48421	48431	5.87E+03	0.00E+00
NH3	RR	48421	48345	4.98E+03	0.00E+00
NH3	RR	48421	48311	3.45E+03	0.00E+00
NH3	RR	48421	48301	4.85E+02	0.00E+00
NH3	RR	48413	48201	8.96E+05	0.00E+00
NH3	RR	48413	48339	1.99E+05	0.00E+00
NH3	RR	48087	48339	1.10E+06	0.00E+00

NH3	RR	48079	48201	9.16E+05	0.00E+00
NH3	RR	48079	48481	1.79E+05	0.00E+00
NH3	RR	48125	48157	1.02E+06	0.00E+00
NH3	RR	48125	48145	7.42E+04	0.00E+00
NH3	RR	48327	48201	7.88E+05	0.00E+00
NH3	RR	48327	48471	3.07E+05	0.00E+00
NH3	RR	48359	48201	1.10E+06	0.00E+00
NH3	RR	48137	48029	1.10E+06	0.00E+00
NH3	RR	48447	48187	6.67E+05	0.00E+00
NH3	RR	48447	48037	3.64E+05	0.00E+00
NH3	RR	48447	48239	6.39E+04	0.00E+00
NH3	RR	48045	48339	1.10E+06	0.00E+00
NH3	RR	48101	48201	1.10E+06	0.00E+00
NH3	RR	48173	48201	1.10E+06	0.00E+00
NH3	RR	48155	48201	9.97E+05	0.00E+00
NH3	RR	48155	48225	9.77E+04	0.00E+00
NH3	RR	48345	48029	9.37E+05	0.00E+00
NH3	RR	48345	48001	1.58E+05	0.00E+00
NH3	RR	48393	48467	2.33E+05	0.00E+00
NH3	RR	48393	48019	9.35E+04	0.00E+00
NH3	RR	48393	48457	9.16E+04	0.00E+00
NH3	RR	48393	48161	8.43E+04	0.00E+00
NH3	RR	48393	48337	8.34E+04	0.00E+00

NH3	RR	48393	48255	6.55E+04	0.00E+00
NH3	RR	48393	48505	6.16E+04	0.00E+00
NH3	RR	48393	48351	6.02E+04	0.00E+00
NH3	RR	48393	48507	5.16E+04	0.00E+00
NH3	RR	48393	48379	4.86E+04	0.00E+00
NH3	RR	48393	48357	4.43E+04	0.00E+00
NH3	RR	48393	48195	2.38E+04	0.00E+00
NH3	RR	48393	48319	1.77E+04	0.00E+00
NH3	RR	48393	48435	1.66E+04	0.00E+00
NH3	RR	48393	48151	1.66E+04	0.00E+00
NH3	RR	48393	48023	1.59E+04	0.00E+00
NH3	RR	48393	48385	1.46E+04	0.00E+00
NH3	RR	48393	48327	9.12E+03	0.00E+00
NH3	RR	48393	48359	8.92E+03	0.00E+00
NH3	RR	48393	48393	3.93E+03	0.00E+00
NH3	RR	48393	48263	3.30E+03	0.00E+00
NH3	RR	48393	48269	4.65E+04	0.00E+00
NH3	RR	48263	48201	1.10E+06	0.00E+00
NH3	RR	48033	48201	1.10E+06	0.00E+00
NH3	RR	48261	48061	8.63E+05	5.58E+01
NH3	RR	48261	48273	1.36E+05	3.53E+01
NH3	RR	48261	48489	9.37E+04	3.14E+01
NH3	RR	48261	48261	1.74E+03	0.00E+00

Conversion Plant COST - e(c,j)			
Demand Location	Technology	Capacity (MW)	COST ($)
48201	FUC	1.17E+04	1.79E+09
48113	FUC	6.57E+03	1.01E+09
48439	FUC	5.14E+03	7.89E+08
48029	FUC	4.92E+03	7.54E+08
48453	FUC	3.06E+03	4.69E+08
48085	FUC	2.40E+03	3.67E+08
48215	FUC	2.17E+03	3.32E+08
48141	FUC	2.14E+03	3.28E+08
48121	FUC	2.06E+03	3.15E+08
48157	FUC	1.89E+03	2.90E+08
48339	FUC	1.42E+03	2.17E+08
48491	FUC	1.35E+03	2.07E+08
48061	FUC	1.08E+03	1.65E+08
48355	FUC	9.21E+02	1.41E+08
48039	FUC	9.03E+02	1.38E+08
48027	FUC	8.68E+02	1.33E+08
48167	FUC	8.40E+02	1.29E+08
48303	FUC	7.73E+02	1.19E+08
48479	FUC	6.92E+02	1.06E+08

48245	FUC	6.49E+02	9.96E+07
48309	FUC	6.32E+02	9.69E+07
48423	FUC	5.74E+02	8.81E+07
48041	FUC	5.62E+02	8.62E+07
48209	FUC	5.21E+02	7.99E+07
48139	FUC	4.30E+02	6.59E+07
48251	FUC	4.16E+02	6.38E+07
48329	FUC	4.15E+02	6.36E+07
48135	FUC	4.02E+02	6.16E+07
48187	FUC	3.96E+02	6.07E+07
48441	FUC	3.48E+02	5.34E+07
48091	FUC	3.44E+02	5.27E+07
48381	FUC	3.38E+02	5.18E+07
48485	FUC	3.36E+02	5.15E+07
48367	FUC	3.30E+02	5.06E+07
48181	FUC	3.27E+02	5.01E+07
48183	FUC	3.16E+02	4.84E+07
48375	FUC	3.08E+02	4.72E+07
48451	FUC	3.02E+02	4.63E+07
48257	FUC	3.02E+02	4.63E+07
48397	FUC	2.40E+02	3.67E+07
48037	FUC	2.39E+02	3.67E+07
48469	FUC	2.36E+02	3.62E+07

48231	FUC	2.35E+02	3.60E+07
48005	FUC	2.24E+02	3.43E+07
48361	FUC	2.17E+02	3.32E+07
48021	FUC	2.11E+02	3.23E+07
48291	FUC	2.08E+02	3.19E+07
48213	FUC	2.04E+02	3.12E+07
48099	FUC	1.90E+02	2.92E+07
48471	FUC	1.82E+02	2.79E+07
48409	FUC	1.73E+02	2.65E+07
48203	FUC	1.70E+02	2.60E+07
48347	FUC	1.68E+02	2.57E+07
48497	FUC	1.64E+02	2.52E+07
48427	FUC	1.64E+02	2.51E+07
48001	FUC	1.47E+02	2.26E+07
48323	FUC	1.47E+02	2.26E+07
48221	FUC	1.45E+02	2.22E+07
48199	FUC	1.44E+02	2.20E+07
48467	FUC	1.39E+02	2.13E+07
48401	FUC	1.34E+02	2.06E+07
48073	FUC	1.32E+02	2.02E+07
48265	FUC	1.31E+02	2.01E+07
48473	FUC	1.28E+02	1.96E+07
48277	FUC	1.27E+02	1.95E+07

48325	FUC	1.26E+02	1.93E+07
48465	FUC	1.25E+02	1.91E+07
48013	FUC	1.24E+02	1.91E+07
48349	FUC	1.24E+02	1.90E+07
48493	FUC	1.24E+02	1.90E+07
48373	FUC	1.22E+02	1.87E+07
48053	FUC	1.18E+02	1.81E+07
48499	FUC	1.13E+02	1.73E+07
48259	FUC	1.08E+02	1.66E+07
48481	FUC	1.06E+02	1.63E+07
48143	FUC	1.06E+02	1.63E+07
48055	FUC	1.05E+02	1.61E+07
48249	FUC	1.05E+02	1.61E+07
48459	FUC	1.04E+02	1.60E+07
48071	FUC	1.02E+02	1.56E+07
48097	FUC	1.00E+02	1.54E+07
48049	FUC	9.76E+01	1.50E+07
48321	FUC	9.48E+01	1.45E+07
48227	FUC	9.36E+01	1.44E+07
48223	FUC	9.28E+01	1.42E+07
48241	FUC	9.09E+01	1.39E+07
48217	FUC	8.94E+01	1.37E+07
48477	FUC	8.94E+01	1.37E+07

48189	FUC	8.74E+01	1.34E+07
48147	FUC	8.68E+01	1.33E+07
48025	FUC	8.35E+01	1.28E+07
48449	FUC	8.31E+01	1.27E+07
48273	FUC	8.08E+01	1.24E+07
48067	FUC	7.75E+01	1.19E+07
48015	FUC	7.59E+01	1.16E+07
48363	FUC	7.15E+01	1.10E+07
48407	FUC	7.07E+01	1.08E+07
48185	FUC	7.06E+01	1.08E+07
48463	FUC	6.96E+01	1.07E+07
48171	FUC	6.76E+01	1.04E+07
48007	FUC	6.56E+01	1.01E+07
48419	FUC	6.52E+01	1.00E+07
48149	FUC	6.41E+01	9.83E+06
48331	FUC	6.34E+01	9.72E+06
48365	FUC	5.99E+01	9.18E+06
48293	FUC	5.98E+01	9.18E+06
48219	FUC	5.94E+01	9.10E+06
48225	FUC	5.80E+01	8.90E+06
48179	FUC	5.79E+01	8.88E+06
48341	FUC	5.64E+01	8.65E+06
48057	FUC	5.60E+01	8.59E+06

48489	FUC	5.56E+01	8.53E+06
48019	FUC	5.55E+01	8.51E+06
48233	FUC	5.49E+01	8.41E+06
48457	FUC	5.44E+01	8.34E+06
48089	FUC	5.36E+01	8.22E+06
48177	FUC	5.32E+01	8.16E+06
48123	FUC	5.32E+01	8.16E+06
48281	FUC	5.29E+01	8.12E+06
48165	FUC	5.22E+01	8.01E+06
48299	FUC	5.19E+01	7.96E+06
48253	FUC	5.10E+01	7.82E+06
48285	FUC	5.05E+01	7.74E+06
48161	FUC	5.00E+01	7.67E+06
48337	FUC	4.95E+01	7.59E+06
48163	FUC	4.83E+01	7.41E+06
48117	FUC	3.09E+02	4.74E+07
48133	FUC	4.66E+01	7.14E+06
48503	FUC	4.63E+01	7.10E+06
48035	FUC	4.61E+01	7.08E+06
48003	FUC	4.53E+01	6.94E+06
48051	FUC	4.53E+01	6.94E+06
48415	FUC	4.42E+01	6.78E+06
48289	FUC	4.41E+01	6.76E+06

48145	FUC	4.40E+01	6.75E+06
48287	FUC	4.35E+01	6.67E+06
48395	FUC	4.27E+01	6.55E+06
48371	FUC	4.07E+01	6.24E+06
48255	FUC	3.89E+01	5.96E+06
48353	FUC	3.82E+01	5.86E+06
48389	FUC	3.80E+01	5.83E+06
48239	FUC	3.79E+01	5.81E+06
48455	FUC	3.68E+01	5.65E+06
48505	FUC	3.66E+01	5.61E+06
48351	FUC	3.57E+01	5.47E+06
48313	FUC	3.57E+01	5.47E+06
48059	FUC	3.52E+01	5.40E+06
48093	FUC	3.44E+01	5.27E+06
48279	FUC	3.39E+01	5.19E+06
48115	FUC	3.34E+01	5.13E+06
48487	FUC	3.29E+01	5.04E+06
48063	FUC	3.28E+01	5.03E+06
48445	FUC	3.26E+01	5.00E+06
48343	FUC	3.21E+01	4.92E+06
48387	FUC	3.11E+01	4.77E+06
48297	FUC	3.07E+01	4.71E+06
48507	FUC	3.07E+01	4.70E+06

48475	FUC	2.96E+01	4.54E+06
48131	FUC	2.91E+01	4.47E+06
48031	FUC	2.90E+01	4.45E+06
48379	FUC	2.89E+01	4.42E+06
48127	FUC	2.75E+01	4.22E+06
48159	FUC	2.70E+01	4.15E+06
48399	FUC	2.66E+01	4.08E+06
48357	FUC	2.63E+01	4.03E+06
48403	FUC	2.63E+01	4.03E+06
48077	FUC	2.60E+01	3.99E+06
48315	FUC	2.59E+01	3.97E+06
48429	FUC	2.53E+01	3.87E+06
48369	FUC	2.49E+01	3.82E+06
48043	FUC	2.35E+01	3.60E+06
48425	FUC	2.24E+01	3.43E+06
48237	FUC	2.23E+01	3.42E+06
48335	FUC	2.22E+01	3.41E+06
48009	FUC	2.22E+01	3.40E+06
48501	FUC	2.16E+01	3.32E+06
48083	FUC	2.15E+01	3.29E+06
48405	FUC	2.12E+01	3.25E+06
48193	FUC	2.12E+01	3.25E+06
48307	FUC	2.08E+01	3.20E+06

48495	FUC	2.01E+01	3.09E+06
48069	FUC	1.96E+01	3.00E+06
48283	FUC	1.94E+01	2.98E+06
48175	FUC	1.92E+01	2.94E+06
48437	FUC	1.90E+01	2.92E+06
48391	FUC	1.87E+01	2.86E+06
48047	FUC	1.84E+01	2.82E+06
48017	FUC	1.83E+01	2.81E+06
48111	FUC	1.80E+01	2.76E+06
48075	FUC	1.80E+01	2.76E+06
48377	FUC	1.77E+01	2.72E+06
48169	FUC	1.64E+01	2.52E+06
48065	FUC	1.54E+01	2.37E+06
48107	FUC	4.88E+01	7.49E+06
48411	FUC	1.52E+01	2.32E+06
48153	FUC	1.51E+01	2.31E+06
48205	FUC	1.47E+01	2.25E+06
48317	FUC	1.46E+01	2.24E+06
48305	FUC	1.46E+01	2.23E+06
48207	FUC	1.45E+01	2.22E+06
48483	FUC	1.41E+01	2.17E+06
48195	FUC	1.41E+01	2.17E+06
48119	FUC	1.33E+01	2.04E+06

48247	FUC	1.31E+01	2.01E+06
48333	FUC	1.25E+01	1.92E+06
48103	FUC	1.23E+01	1.89E+06
48267	FUC	1.13E+01	1.73E+06
48095	FUC	1.09E+01	1.67E+06
48211	FUC	1.05E+01	1.61E+06
48319	FUC	1.05E+01	1.61E+06
48229	FUC	1.03E+01	1.58E+06
48197	FUC	9.96E+00	1.53E+06
48435	FUC	9.87E+00	1.51E+06
48151	FUC	9.83E+00	1.51E+06
48275	FUC	9.71E+00	1.49E+06
48023	FUC	9.43E+00	1.45E+06
48105	FUC	9.37E+00	1.44E+06
48461	FUC	9.37E+00	1.44E+06
48383	FUC	9.20E+00	1.41E+06
48271	FUC	9.15E+00	1.40E+06
48295	FUC	8.89E+00	1.36E+06
48129	FUC	8.68E+00	1.33E+06
48385	FUC	8.64E+00	1.33E+06
48417	FUC	8.45E+00	1.30E+06
48081	FUC	8.32E+00	1.28E+06
48191	FUC	8.00E+00	1.23E+06

48421	FUC	7.82E+00	1.20E+06
48413	FUC	7.79E+00	1.19E+06
48087	FUC	7.69E+00	1.18E+06
48079	FUC	7.35E+00	1.13E+06
48243	FUC	5.61E+00	8.60E+05
48109	FUC	5.60E+00	8.59E+05
48125	FUC	5.57E+00	8.54E+05
48327	FUC	5.41E+00	8.30E+05
48359	FUC	5.29E+00	8.12E+05
48137	FUC	4.87E+00	7.47E+05
48011	FUC	4.78E+00	7.33E+05
48235	FUC	3.97E+00	6.09E+05
48447	FUC	3.91E+00	5.99E+05
48045	FUC	3.76E+00	5.76E+05
48433	FUC	3.64E+00	5.58E+05
48101	FUC	3.58E+00	5.48E+05
48431	FUC	3.49E+00	5.34E+05
48173	FUC	3.35E+00	5.14E+05
48155	FUC	3.02E+00	4.63E+05
48345	FUC	2.96E+00	4.54E+05
48393	FUC	2.34E+00	3.58E+05
48443	FUC	2.07E+00	3.17E+05
48311	FUC	2.05E+00	3.14E+05

48263	FUC	1.96E+00	3.01E+05
48033	FUC	1.61E+00	2.47E+05
48261	FUC	1.03E+00	1.58E+05
48269	FUC	2.76E+01	4.23E+06
48301	FUC	2.88E-01	4.42E+04

Water Flow - w(h,l)			
Water Source Location	Plant Location	Transported Water Flow (kg/h)	Distance(miles)
48113	48253	1.74E+06	1.80E+02
48113	48207	1.74E+06	1.74E+02
48113	48275	1.74E+06	1.81E+02
48113	48023	1.17E+06	1.53E+02
48113	48155	1.74E+06	1.92E+02
48439	48101	1.69E+05	1.95E+02
48029	48105	1.69E+06	1.94E+02
48453	48451	1.69E+05	1.75E+02
48215	48061	1.22E+06	4.50E+01
48215	48505	1.74E+06	7.40E+01
48215	48261	1.74E+06	4.78E+01
48141	48495	8.46E+05	1.87E+02
48121	48197	1.69E+05	1.69E+02
48355	48131	1.74E+06	5.47E+01

48303	48169	1.74E+06	4.24E+01
48303	48107	1.74E+06	3.00E+01
48303	48125	1.68E+06	6.00E+01
48303	48263	7.71E+05	6.70E+01
48309	48441	2.15E+05	1.66E+02
48309	48353	1.14E+06	1.95E+02
48139	48441	1.52E+06	1.81E+02
48251	48151	1.35E+06	1.79E+02
48135	48135	1.69E+06	0.00E+00
48187	48451	1.25E+06	1.96E+02
48187	48465	1.74E+06	1.94E+02
48187	48435	1.74E+06	1.67E+02
48187	48413	1.74E+06	1.79E+02
48187	48137	1.66E+06	1.44E+02
48375	48375	1.74E+06	0.00E+00
48375	48179	1.74E+06	6.10E+01
48375	48341	1.74E+06	3.02E+01
48375	48233	1.74E+06	4.29E+01
48375	48357	1.74E+06	8.57E+01
48375	48065	1.74E+06	3.04E+01
48375	48205	1.74E+06	5.01E+01
48375	48483	1.15E+06	9.16E+01
48375	48195	1.74E+06	6.77E+01

48375	48211	1.74E+06	9.61E+01
48375	48295	1.74E+06	1.09E+02
48375	48421	1.74E+06	6.06E+01
48375	48393	1.74E+06	6.79E+01
48257	48485	1.74E+06	1.69E+02
48257	48397	1.26E+06	2.18E+01
48257	48337	1.22E+06	1.12E+02
48257	48487	1.74E+06	1.99E+02
48257	48077	1.27E+06	1.38E+02
48257	48023	5.65E+05	1.84E+02
48213	48113	1.22E+06	6.62E+01
48213	48397	4.76E+05	5.74E+01
48497	48197	1.14E+06	1.41E+02
48497	48087	1.74E+06	1.93E+02
48497	48101	1.52E+06	1.62E+02
48221	48415	1.24E+05	1.81E+02
48221	48151	3.84E+05	1.51E+02
48277	48181	4.17E+05	6.38E+01
48277	48277	1.74E+06	1.00E-04
48277	48147	1.23E+06	3.13E+01
48147	48147	5.08E+05	0.00E+00
48449	48181	1.32E+06	1.03E+02
48449	48231	1.74E+06	6.52E+01

48449	48097	1.74E+06	1.33E+02
48149	48209	1.74E+06	6.78E+01
48149	48091	1.74E+06	8.16E+01
48149	48265	1.74E+06	1.46E+02
48149	48053	1.74E+06	9.83E+01
48149	48259	1.74E+06	1.08E+02
48149	48171	1.74E+06	1.25E+02
48149	48267	1.74E+06	1.74E+02
48149	48319	1.74E+06	1.50E+02
48149	48385	1.51E+06	1.74E+02
48149	48327	1.74E+06	1.87E+02
48293	48251	1.74E+06	7.38E+01
48293	48367	1.74E+06	1.11E+02
48293	48221	1.74E+06	9.57E+01
48293	48143	1.74E+06	1.07E+02
48293	48049	1.74E+06	1.43E+02
48293	48363	1.74E+06	1.31E+02
48293	48293	1.74E+06	0.00E+00
48293	48133	1.74E+06	1.43E+02
48293	48503	1.74E+06	1.67E+02
48293	48059	1.74E+06	1.72E+02
48293	48093	1.74E+06	1.20E+02
48293	48429	1.74E+06	1.56E+02

48293	48425	1.74E+06	8.43E+01
48293	48237	1.74E+06	1.49E+02
48293	48009	1.74E+06	1.89E+02
48293	48083	1.74E+06	1.70E+02
48293	48333	5.37E+05	1.19E+02
48293	48417	1.74E+06	1.82E+02
48293	48447	1.74E+06	1.91E+02
48299	48451	3.16E+05	1.16E+02
48299	48415	9.01E+05	1.93E+02
48299	48353	5.98E+05	1.50E+02
48299	48335	1.74E+06	1.72E+02
48161	48439	1.74E+06	9.95E+01
48161	48139	1.74E+06	5.84E+01
48161	48077	4.72E+05	1.87E+02
48503	48101	4.87E+04	1.11E+02
48503	48263	9.67E+05	1.21E+02
48395	48099	1.74E+06	8.02E+01
48395	48281	1.74E+06	1.03E+02
48395	48307	1.74E+06	1.68E+02
48395	48411	1.74E+06	1.37E+02
48395	48333	1.20E+06	1.27E+02
48395	48095	1.74E+06	1.99E+02
48279	48381	1.74E+06	6.73E+01

48279	48117	1.74E+06	6.37E+01
48279	48279	1.74E+06	0.00E+00
48279	48369	1.74E+06	4.04E+01
48279	48501	1.13E+06	6.78E+01
48279	48069	1.74E+06	3.23E+01
48279	48153	1.74E+06	6.01E+01
48279	48129	1.74E+06	1.07E+02
48279	48079	1.74E+06	4.22E+01
48279	48125	6.08E+04	9.56E+01
48279	48359	1.74E+06	9.35E+01
48279	48045	1.74E+06	7.27E+01
48279	48345	1.74E+06	9.01E+01
48487	48483	5.89E+05	1.08E+02
48487	48197	4.26E+05	3.23E+01
48475	48329	1.74E+06	6.78E+01
48475	48135	4.53E+04	4.13E+01
48475	48227	1.74E+06	1.12E+02
48475	48415	7.12E+05	1.54E+02
48475	48371	1.74E+06	5.52E+01
48475	48115	1.74E+06	1.09E+02
48475	48501	6.05E+05	1.16E+02
48475	48495	8.91E+05	2.38E+01
48475	48103	1.74E+06	3.51E+01

48475	48105	4.53E+04	1.14E+02
48475	48461	1.74E+06	6.33E+01
48475	48383	1.74E+06	9.37E+01
48475	48173	1.74E+06	9.64E+01
48475	48033	1.74E+06	1.30E+02
48175	48013	1.22E+06	6.87E+01
48175	48385	2.27E+05	1.66E+02
48175	48137	7.96E+04	1.96E+02