INTEGRATING MICROGRID POWER FOR NET-ZERO ENERGY SUPPLY CHAIN OPERATIONS: A BIG DATA ANALYTICS APPROACH

by

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A thesis submitted to the Graduate Council
of Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science with a Major in
Industrial Engineering
August 2018

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ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. Tongdan Jin in the Ingram School of Engineering at Texas State University for all his endless support in guiding me in my research and giving me valuable life advice. He has always been there to support and give helpful guidance whenever I needed his help.

I would also like to thank Dr. Clara Novoa in the Ingram School of Engineering at Texas State University who is always there to provide insightful help and support. I would like to extend my gratitude to her for advising me in enhancing my research capabilities.

I would also like to thank Dr. Cecilia Temponi in the McCoy School of Business at Texas State University who is always there to guide the research from a business perspective. I would like to extend my gratitude to her for encouraging me to pursue a Ph.D.

I would like to thank Dr. Zong in the Computer Science Department at Texas State University for providing research fund support and technical assistance to my research.

I would also like to thank all the professors and staff of the Ingram School of Engineering at Texas State University in extending their guidance throughout my school years. Last but not least, I would express my appreciation to the US Department of Agriculture for funding my thesis project under the B-GREEN Grant (#2011-38422-30803), and to the National Science Foundation for partly supporting me with under the NSF Grant (# 1522318).

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I. LITERATURE REVIEW

Since the industrial revolution, there is a rise in temperature and sea level, as well as worsening heat waves and extreme weather conditions including hurricanes and tornadoes. Seasons like spring arrive earlier and ice sheets are melting while the oceans are acidifying. "In January, weather researchers confirmed that 2015 was the hottest year worldwide since record keeping began in the 19^{th} century, eclipsing 2014, which previously held the record. The vast majority of scientists say human activities are to blame," (Smith, 2016). According to the book Renewable Energy and Climate Change (2009), in 2003 Europe experienced the most extreme heat wave which killed 70,000 people and caused 13 billion euros losses. In 2005, hurricane Katrina devastated the US gulf coast laying waste to the city of New Orleans consequently killing 1322 people and causing $125 billion dollars in damage. Four weeks after Katrina, Hurricane Rita caused $14.7 billion dollars in damage and the evacuation of three million people. Currently, "in Bangladesh, rising sea levels have forced millions to leave coastal villages along the Bay of Bengal. In Mali, an impoverished African country, drought is making the local farming increasingly difficult. And in the northwestern U.S., the Pacific Ocean is encroaching upon lands the Quinault Indian Nation has lived on for thousands of years" (Smith, 2016). Earth's temperature has remained steady for the course of western civilization much as a human's body temperature remains steady through the course of life. However, since the 19^{th} century Earth's average temperature rose $1.4^{o}F$. Albeit it is a small change, it can be viewed in the same way one views a $1.4^{O}F$ fever in a small child; this rise in Earth's temperature is a concern for human society. The difference between now and the last ice age, when North America was covered in a half mile thick ice sheet, was only 9^{O}F. However, where the warming between then and now took thousands of years the warming of 1.4^{O}F took only 100 years. In fact, "the projected rate of temperature change for this century is greater than that of any extended global warming period over the past 65 million years. The Intergovernmental Panel on Climate Change stated that continuing on a path of rapid increase in atmospheric CO_2 could cause another 4 to 8^{O}F warming before the year 2100" (McKibben, 2012).

Key climate processes involve long lags, and important greenhouses gases remain in the atmosphere for many years after they are emitted (Richard, 2016). Among all the heat trapping gases in the atmosphere, carbon dioxide (CO_2) is the most significant contributor to the climate change. CO_2 is mainly produced from human activities and remains the longest in the atmosphere. It takes about a decade for methane (CH_4) emissions to leave the atmosphere (it converts into CO_2) and about a century for nitrous oxide (N_2O) (EPA, 2016). In the case of CO_2, much of today's emissions will be gone in a century, but about 20 percent will still exist in the atmosphere approximately for 800 years from now (Forster, 2007). In 2013, CO_2 accounted for about 82% of all U.S. greenhouse gas emissions from human activities (EPA, 2016). The most popular activities of humankind that emit CO_2 are using fossil fuel for energy and transportation usage. Emission from burning fossil fuels are the primary cause of rapid and accelerating growth in CO_2. The combustion of fossil fuels to generate electricity is the largest single source of CO_2 emissions in the nation, accounting for about 37% of total U.S. CO_2 emissions were 31% of total U.S. greenhouse gas emissions in 2013 (EPA, 2016). The combustion of fossil fuels such as gasoline and diesel for transporting people and goods is the second largest source of CO_2 emissions, accounting for about 31% of total U.S.

"Based on well-established evidence, about 97% of climate scientists conclude that humans are changing the climate" (EPA, 2016).

The International Energy Agency projects that by 2030, about 42% electricity will need to be supplied by renewables, increasing to 57% in 2050, to stay within a 2-degree Celsius average global warming threshold (RE100, 2016). There is a necessity for renewable energy to be increased by 200% between now and 2030. In December 2015 a conference was held in Paris where political leaders as well as business executives could make critical decisions to keep world average temperature rise between a 1.5 to 2 ^{O}C. According to the IPCC a limit of 1,000 giga-tons of CO_2 cannot be emitted by human being in order to stay within this limit, however at the current rate of emission limit will be reached by the year 2040 (Greenpeace, 2015).

1.1 Energy Efficiency

Due to the growing energy issue which developed between 1970 and 1980 and even after the 1986 counter oil shocks, energy efficiency has grown to become a big attraction for sustainable economic growth. This is noticed within the context of climate change and global warming. These two controversial subjects have given energy efficiency a new outlook. With top issues like the increase in the price of crude oil during the 2000s as well as the 1993 energy crisis, energy efficiency has been placed on the top list of priorities for many countries in political agendas.

With this urgency to reduce CO_2 emissions and the carbon budget running low, it is reasonable for public policy to be enacted in order to curtail the current rate of carbon emissions. Many governments are aware of the numerous benefits that are brought by increasing energy efficiency for their country. This include environmental benefits such as reductions in greenhouse gases as well as pollution that contaminates air, water, and soil. Aside from this are the reduction in investments for infrastructure, improved consumer welfare, as well as lowering of fossil fuel dependency, and increased competitiveness.

Makidou et al. (2015) studies the energy efficiency in EU using data from 2000 to 2010. In this paper, two methodologies that were used to analyze the data include data envelopment analysis (DEU) and multicriteria evaluation model. The results show more improvement need to be addressed to increase the energy efficiency in EU. It suggests the policy makers to "consider a much wider range of impacts of energy efficiency programs, instead of focusing solely on an input-output energy economic production framework.

According to National Energy Independence Strategy, energy efficiency will increase yearly by 1.5 percent up to 2020. It predicts that the total power consumption during the period of 2014 to 2020 will increase up to 1.5 percent where 1.3 percent is from natural sources. About 37 percent of total energy use in the world came from industrial sector which use more energy than any other sector. Abdelaziz et al. (2010) provide a review of energy saving methods in industrial fields. The review paper is divided into three categories which include energy saving by management, by technologies, and by policies. The use of energy saving technologies is found to be cost effective using the equipment in the facilities to reduce the total consumptions. Together with the public policies, the efficiency and energy saving strategies are proved to be economically viable in most cases.

The USA consumes 25% of the world's energy. Nevertheless, the most significant growth of energy consumption is currently taking place in China, which has been growing at 5.5% per year (International energy outlook 2009). An evaluation of the effectiveness of China's energy saving and emission reduction policies (ESER) in 15 energy intensive industries is conducted by Yang and Yang (2016). The data envelopment analysis (DEA) is used to analyze the energy productivity of the selected industries in the 10th and 11th Five-Year Plan (FYPs). The study shows that four out of fifteen industries have significantly improved energy productivity, and the whole nation has reduced 20 percent of energy intensity during the 11th FYPs.

Mouzon et al. (2014) developed a multi-objective optimization model which aims to minimize the total energy consumption with the shortest completion time. The authors consider the non-bottleneck machines to consume the large amount of energy and develop the methodology to reduce the total energy consumption by optimizing the production schedule. The proposed dispatching rules show to have a potential to effectively reduce energy consumption.

Li et al. (2015) study the energy efficiency of biofuel feedstock and its related processing improvement. The authors optimize the energy consumption of the feedstock processing with production constraints based on the improving scenario. They consider two different dryer structures of particle separation after grinding stage. Different scenarios are demonstrated by applying the proposed method which includes: material flow with no particle separation, material flow with adoption of particle separation, and applied proposed scheduling model.

1.2 Carbon Tax, Cap and Trade

Currently there exist two main branches of policy that have been implemented globally for the reduction of greenhouse gases, these are the carbon tax system, and the carbon cap and trade system. A carbon tax is simply an excise tax imposed on carbon emitted per ton of CO_2. It can be implemented in upstream of the production as well as downstream of the energy consumption chain. However, it is considered a tax in its name and purpose. Hence it carries a negative connotation among policy makers in the United States. Where a large majority of them try to amend for a more tax neutral policy such as the cap and trade system. Under this system, Green House Gas emitters receive allowances which they are allowed to emit. It becomes their choice to improve their facilities to greener methods of emissions, generate less emissions, do nothing, or purchase allowances from the emissions market. "Because emissions trading uses markets to determine how to deal with the problem of pollution, cap and trade is often touted as an example of effective free market environmentalism" (Tracey et al., 2010). This produces an advantageous flexibility that is expanded upon by the U.S. policy makers. However, cap and trade has a few underlying problems that undermine its efficacy. At the top of the list is its complexity in terms of policy and in its ability to actually curtail climate change and the greenhouse effect. In the U.S., the only type of emissions market that existed was the Sulfur Dioxide market used to prevent acid rain but it eventually collapsed in 2008. In the European Union, there is a system of cap and trade that is being implemented, but is not considered a success due to its overwhelming complexity.

According to the report in (Sewalk, 2013), for the foreseeable future in the United States there exists a time span by which a cap and trade system will take to be actually implemented as well as for a full emission regulation market to be developed. This time span may be longer than preferable for the greenhouse gas emissions allowance will allow for. With regards to a federally imposed carbon tax, there exists also precarious problems that may undermine its effectiveness. States may choose to impose their own CO_2 tax or Renewable Portfolio Standards regardless of the existence of national climate policy or federal CO_2 tax. With a national emissions tax, there will be overlapping at state level. However, "the maximum feasible reduction in national emissions… is higher for a state-level Renewable Portfolio Standard compared to a state level CO_2 tax," (Accordino and Rajagopal, 2015).

Hammami et al. (2014) introduce a mathematical model to control carbon emission in a multi-echelon production inventory framework. The main decision is to minimize the total system cost considering the carbon tax and carbon cap with the constraints of lead time. The study demonstrates the "effect of individual emissions caps on each facility with comparison to a global cap on the entire supply chain."

Krass et al. (2013) develop different models to study the influence of environment tax on reducing environmental pollution process. They consider to maximize the firm's profit with technology choices of greener technology and regular production technology. Both technologies affect the production costs, the amount of pollutant generated, and product selling price by considering that the consumers may not want to pay for additional green product cost. They also study the scenario where the regulators work with the firm to agree on the level of taxes, fixed costs, subsidies, and consumer rebates to maximize the benefit of the social welfare,

Marti et al. (2015) introduce the mathematical approach of supply chain network design that focuses on carbon footprint and operation trade-offs as well as on the impacts of carbon policies and their cost effectiveness. The paper shows that the design and signature of the products can heavily influence the network design, the cost, the carbon emission control, and carbon abatement. In conclusion, the market carbon footprint cap (MCFC) is more applicable because it has an important impact on the supply chain network design. Furthermore, the total cost of the cap policy is lower than the tax policy.

1.3 Power Purchase Agreement

Numerous companies have committed to achieve 100% renewable energy through Power Purchase Agreement (PPA) in combination with other methods to reduce carbon and greenhouse gas emissions. A power purchase agreement is a solar power contract where a developer goes on site and designs, finances, and permits the installation of a solar energy system on the client's site. The client is committed to a 10 to 25-year contract which upon fulfillment he/she can expand, cancel , or purchase the system from the developer. During the life of the contract, the developer not the client is responsible for maintenance and upkeep of the system. According to Edge (Edge, 2015), Power Purchase Agreements have no/low up-front cost, ability for the tax-exempt entity to enjoy lower electricity price thanks to savings passed on from federal tax incentives, predictable cost of electricity over 15-25 years, no need to deal with complex system design and permits, and lastly no operating and maintenance responsibilities. There exist some potential constraints that are inherent to Power Purchase Agreements due to municipal laws such as debt limitations, restrictions on contracting power, budgeting issues, public purpose and credit lending issues, public utility rules, and authority to interests and buying electricity. The solar powered system installed by the Independent Power Producer (or contractor) should contain a spinning reserve capable of having a spare generation capacity in the event of power imbalance such as in the case of power loss. The loading scheme on the reserve system should be arranged in such a way that the backup should cover a preset fraction of the largest infeed on the system. "If a system event occurs and insufficient generation reserve is available to cover the required power demand, then load shedding will occur" (Proctor and Flynn, 2000). Therefore, in order to have a risk-averse Power Purchase Agreement, the IPP should have a system capable of providing partial backup to the system in contingency.

Many companies have chosen to go with Power Purchase Agreements to achieve their goal of being supplied by 100% renewable energy to their facilities. Recently in order to achieve the 100% renewable energy target, "Walmart went into contract to buy 58% of the estimated output from Pattern Energy Group's new Logan's Gap Wind farm in Texas under a 10-year Power Purchase Agreement" (Lozanova, 2015).Walmart, the world giant retailer, is considered the world leader in renewable energy. From 2005 to present, the company has more than 300 renewable projects which are under development or in operation. Its target is to procure 7,000 GWh of renewable energy per year by 2020. In 2005, the company successfully reduced Green House Gases (GHGs) by 20% from all of its stores, distribution centers and clubs which resulted in about 3 million metric tons of GHGs. In the Approach to Renewable Energy, Walmart reported that even though its "square footage increased by 45% and sales grew 51%, emission grew only about 12%" (Walmart, 2015). At present, the company has 26% of its power coming from renewable energy sources. By purchasing Power Purchase Agreements (PPAs), Walmart is taking a significant step in achieving its long-term goal of getting 7 billion kilowatt-hours of renewable energy by 2020.

Microsoft is one of the major tech companies that “took a big step toward transforming the energy supply chain with its biggest power purchase agreement to date with the Pilot Hill Wind project near Chicago, Illinois, a 175-megawatt wind farm” (Verge, 2014). Microsoft will purchase approximately 675 GWh of renewable energy from Pilot Hill Wind which is equivalent to powering 70,000 homes. The company has also signed two PPAs for wind generation projects with Keechi Wind Projects in Texas which is generating up to 110 MW yearly. Microsoft made a commitment to achieving carbon neutral in 2025. As of today, “roughly 44 percent of the electricity used by our datacenter comes from these sources. Our goal is to pass the 50 percent milestone by the end of 2018, top 60 percent early in the next decade, and then to keep improving from there,” wrote Brad SmithPresident and Chief Legal Officer of Microsoft (Smith, 2016).

Davidson et al. (2015) evaluate the overall impact on the cost of systems for customers under third party ownership. Analysis is done on contract data from 2010-2012 consisting of 1113 contracts in that timeframe. Implication is made regarding the timing of payment and the structure of the contract such as the higher average cost of power purchase contracts over leases. Second it is seen that the cost of pre-paid contracts is less than no money down contracts. Lastly power purchase agreements and leases both cost more if they include escalator clauses within them.

Jenkins and Lim (1999) propose to look at different scenarios with various perspectives regarding a power purchase agreement. They take an overall look at PPA effects on the country’s economy. Central to the evaluation are sensitivity and risk analysis which identify the most critical values that allow the model to show a probability distribution of values rather than single predicted value. The paper then identifies those who are to gain and lose from the contract. Should it be undertaken using a distributive or stakeholder analysis allowing the partners to test the contract under various circumstances for sustainability? This is to show the benefits of a financial or economic stakeholder, and the analysis can be made from both PPA and Build-Operate-Transfer (BOT) agreements.

Ferrey (2004) describes the development of small power producer initiative among five Asian countries. These countries include Thailand, Indonesia, India, Sri Lanka, and Vietnam. A common feature of all these nations is that they are in need of increase in long term power generation. Most of these countries have been approached by private developers in the deployment of small power production projects. Cost concepts are applied in various ways for each nation. For example the payment in Vietnam will be done based on “needed” demand regardless of whether that demand is actually used or not.

Zeng and Yang et al. (2015) investigate the development of prices of green energy. The article describes the detriment that a non-market guided price has done to the development of the green energy market in several provinces of China. The paper goes on to describe the importance of Direct Power Purchase for Large Users (DPLU) on the reform of the electricity market. It shows that DPLU will be a critical factor that allows the users to decide the price of electricity with the chosen generators so as to improving the market.

In their paper, Binkley and Harsh et al. (2013) describe the different types of electricity purchase agreements involved with anaerobic digesters on dairy farms. They show that even possessing larger electricity production capacity, net metering’s Net present value was only 6% more than the buy-all sell-all agreement on average. Also, the limitations implicated from net metering constrain the generator size which is a detriment, especially when larger herd size is involved. Repealing size limitations with net metering purchase agreements will allow for high net present value.

1.4 Onsite renewable energy generation

Onsite generation, also known as distribute generation, produces electricity through the installation of distributed energy resources (DER) locally. Typical DER units include wind turbine, solar PV, and geothermal systems that are placed close to end consumers. Due to its long-term contact and public policy restriction to large energy users, large companies are working on developing onsite renewable energy generation to supply its own power. This is an increasingly popular way of reducing GHG that is used by many industry facilities, commercial/government building, distribution warehouses as well as educational institutions through on-site renewable energy. Minimizing fossil fuel emissions like carbon dioxide can be achieved with onsite wind and solar generation which can supply partial power to a facility while reducing CO_2. Aside generating public publicity for the sites entity, it also allows for the facility to become energy independent while reducing costs and becoming a visible demonstration of civic commitment to environmental commitment. Another benefit is net metering which can provide positive dividends for the facility and become a variable source of income for the entity.

IKEA, the retailer of home furnishing products, has made its pledge to power its stores entirely by renewable energy by 2020. The company has installed solar systems on 90 percent of its stores, over 700,000 solar panels, in the U.S. locations. By 2015, the company has spent $1.9 billion to invest in renewable energy by owning and operating its own solar system. The company also operates a total of 279 wind turbines located in Canada, Ireland, and the US.

Telsa Motors, the electric car company, targets to operate a Gigafactory in Storey County, Nevada entirely by 100% onsite renewable energy. The renewable energy used for the plant will be solar panels, wind farm, and geothermal electricity plant. The factory manufacture batteries for 500,000 vehicles per year. The company plans to lower the sell price for its car battery pack to $3000 due to the reduction of operating cost driving by the self-supply green energy (Armstrong, 2015).

Much research has been done focusing on optimizing the onsite renewable energy system. Roy et al. (2009) proposed a design space for different reliability levels using chance constrained programming. The system is modeled using a probabilistic mathematical approach which takes into consideration a wind turbine and transmission system as well as an electrical generator. With this method, it was possible to account for uncertainty in resource availability.

Shafer et al. (2009) discuss different types of renewable energy projects that can benefit manufacturing companies such as net metering, selling intermittent surplus generation, and behind-the-meter-project (i.e. onsite wind generation) in the cement industry. It is recommended that the energy-intensive industry considers balancing the onsite natural wind resources and avoids getting in the wind business by signing a long term PPA for 25 years. Considering that the power demand of a cement facility is in a range between 100 to 300MW, the paper concludes that onsite wind generation projects benefits the heavy manufacture by creating a long-term investment in reducing the risk of price changing for 35% of electricity needed.

Shigenobu et al. (2016) proposes a method of protecting a distribution system and attaining reduction in distribution loss using cooperative controlled PVs, battery energy storage system (BESS) and EVs. An optimization problem is formulated and solved using Particle Swarm Optimization where the objective function is to minimize the distribution loss and to guarantee the power quality.

Rogelj et al. (2015) makes a discussion in clarifying concepts like carbon neutrality, climate neutrality, full decarbonization, and net zero carbon or net zero greenhouse gas emissions (GHG). They express the confidence that with current global pledge, there is a 66% chance to stay below the target of $2^{O}C$ and achievement of net negative CO_2 emissions after 2070.

Pechmann et al. (2015) consider the financial benefit of self-supply renewable energy grid using a case study approach. The study shows that partially self-supply renewable energy is very promising and attractive alternative in financial terms, especially for onsite photovoltaic system. Furthermore, the optimization in dimension of virtual power plan can achieve further cost benefits.

1.5 Microgrid Systems

Unlike onsite or multi-node distributed generation (DG), a microgrid system technically is an independent and self-sufficient power system which may or may not be connected to the utility grid. For grid-interconnected microgrid, the user can choose to operate the system in islanding mode if the supply of the main grid is interrupted or in a failure state. In this case, new considerations must be taken for reliability design as the islanding model essentially benefits the reliable power supply of local consumers, especially in a contingent event. In addition, a microgrid system is considered as a viable energy solution in remote areas where long distance transmission or distribution lines are too costly to be constructed. Architecturally, both onsite generation and microgrid systems adopt one or multiple distributed energy resource (DER) units to supply the electricity to meet the local needs. The main difference is that the microgrid is capable of maintaining independent and sustainable supply while onsite generation usually co-supplies the power along with the main grid. Last, but not the least, microgrid systems possess the unique capability of ensuring power resilience by forming an islanding model against extreme events, including hurricane, tornados, earthquake and man-made attacks.

1.6 Research Objectives

Though carbon tax, cap and trade have their benefits in curtailing GHG, their inherent drawbacks include the penalty mechanism and market complexity. Namely they would permit for the day to day business of carbon emissions to continue by simply letting companies pay their way. Although the idea of a carbon tax is to spur the curtailing of carbon emissions, companies whose profits are large enough could inherently continue to emit GHG as usual. While smaller companies with less profit margin would attempt at avoiding the tax and going green by lowering their carbon emissions, the larger companies would pursue to just pay the tax and continue polluting. Similarly, while cap and trade poses a large obstacle for polluting firms, it would still leave a way for companies to continue their production processes as they were before by the acquisition of permits on the market. Although the incentive is there to cut back on emissions by generating innovation in their market and making gains through these breakthroughs as well as by selling and making profit from the trading of permits, the simple logic of the cap and trade system is inherent on companies making purchase to continue their production without changing their processes. Lohman (2006) argues that carbon trading "encourages the industries most addicted to coal, oil, and gas to carry on much as before". Since the company can purchase cheap carbon credits, they will continue using fossil fuel rather than renewable energy. Leonard (2009) believes that carbon offsets reassure the companies to do unfair practices and allow firms to continue pollution as normal practices which essentially detract from the bigger picture of global climate change impacts.

Power purchase agreements (PPA) offer monetary as well as operational benefits, and there are various aspects that might be looked at as negative parts of a PPA. Among is the lack of ownership that goes with entering into a PPA. This apparent benefit with regards to maintenance cost could leave the consumer vulnerable to drastic prices changes in the future especially if the price costs are lower. Also, from the lack of control in the setup of the equipment lies the project completion risk which can leave the consumer at setback regarding projects and schedules. Furthermore, entering into PPA will mean the loss of financial incentive programs such as grants, rebates, and carbon tax credits.

Despite the apparent disadvantages of PPA, Carbon tax, and cap and trade, the development of on-site renewable energy generation is very promising. Among the top benefits that on-site generation has is although it has a higher initial investment it leaves the consumer safe from varying price costs as well as allowing them to have ownership and control of the electricity generation technology. Furthermore, beyond the breakeven point the company's utility cost, if optimized, will be at a minimum if not zero. Adding to this the company through net metering can be able to turn a profit by selling excess energy back to the grid as well as alleviate peak energy demand costs.

This thesis proposes a mathematical method to approach net zero carbon emission in supply chain. To achieve net-zero carbon emission performance, a production-distribution system is designed requiring the total energy consumed by transportation network as well as the production network. This includes consumption from renewable energy sources such as wind turbines, photovoltaic sources, and among others hydro generators. Due to the output of hydro systems, PV, and WT being intermittent, at sometimes power generation will be less than the demand of the production-distribution system. In those cases, the energy gap is fulfilled using energy from fossil fuel power plants. In order to attain net zero-carbon criteria this “borrowed” conventional energy should be “balanced” later on. This can be achieved through the use of net-metering which is done when there exists a surplus of power generated by the renewable energy sources such as WT and PV units. This net metering, unlike traditional energy sources, allows for two-way flow between the main grid and the manufacturing facility. For instance, when there are strong wind profiles or particularly sunny days the renewable energy sources would produce surplus energy exceeding the power demand of the facility. In this case, through net metering the excess energy is fed to the main grid achieving the net-zero carbon goal through the production and logistic network if energy consumption is balanced with the aggregate energy supplied by the renewable energy supply drive the course of a year.

The thesis is organized as follows. In Chapter 2, we review the practice of renewable energy in both manufacturing and service industry. In Chapter 3, we introduce the methodology to calculate WT and PV capacitor factor as well as electric vehicle energy intensity. In Chapter 4, we propose a mathematical approach to achieve net zero carbon for single facility and warehouse setting with onsite generation and deterministic production demand. In Chapter 5, we propose the mathematical approach to achieve the propose model considering demand uncertainty. In Chapter 6, we introduce approach to achieve net zero carbon for a whole supply chain with both deterministic and stochastic demand. In Chapter 7 concludes the paper and discus future work.

II. INDUSTRY PRACTICE OF RENEWABLE INTEGRATION

2.1 Manufacturing Industries

2.1.1 Manufacturing in US.

a. Apple. Apple Inc. is a global technology company with headquarter located at Cupertino, California. It was founded by Steve Jobs, Steve Wozniak, and Ronald Wayne in 1976. The company specializes in electronic devices, computer software, and online service. Apple was the first US Company that has value over $700 billion. It Apple currently supplies its facilities by 93 percent of renewable energy worldwide. In 2013, the company built a 20 MW solar array in 10-acre land next to its Maiden data center. The solar farm is predicted to produce 42 MW of renewable power at peak. In February 2015, Apple purchased 130 MW solar power energy with 25 years Power Purchase Agreement (PPA) from First Solar Company in Monterey County, California. The purchased renewable energy would power all Apples' stores, offices, headquarter, and data center in California. The company also owns a 20 MW solar facility in Nevada and 50 MW solar plants in Arizona. Apple has recently completed its renewable project, a 50 MW solar Farm, which will power Apple's data center in Mesa, Arizona entirely by renewable energy. In Singapore, Apple worked with Sunseap, a local renewable energy, to install 32 MW solar panels on 800 city rooftops. The rooftop solar panels will be installed on both public building and Apple's building. The renewable energy generated will supply Apple's offices and part of its data center in Singapore. In September 2016, Apple joined RE100 and pledged to achieve 100 percent renewable energy worldwide and clean manufacturing supply chain. The company claims to have its operations in the U.S., China, and other 21 countries powered by 100 percent renewable energy combining buys and onsite generation energy. The company is working with its suppliers around the world to develop renewable energy projects and reduce the energy usage. The company is building 200 MW solar plants in China which includes 170 MW solar projects in Mongolia. The projects predict to generate enough energy to power 265,000 Chinese homes annually. Apple is also working on its 4 GW of clean renewable energy worldwide and target to reduce more than 30 million metric tons of carbon by 2020. In two years, the energy usage of iPhone final production facility in Zhengshou, Hennan Province, China will be power by 400 MW of solar facility nearby.

b. Lockheed Martin. Lockheed Martin is an American company with its headquarters located in Bethesda, Maryland. The company specializes in aerospace, security, defense, and advance technologies. Lockheed Martin operates with revenues of $46.132 billion and employees 126,000 people globally. The company has five business areas which are Aeronautics, Information Systems and Global Solutions, Missiles and Fire Control, Mission Systems and Training, and Space Systems. The company has 590 offices and facilities across United States and worldwide. In 2015, the company operated 150,000 square foot of 2 MW solar system in Florida facilities which can produce approximately 3,300 GWh of green energy annually. The onsite generation system saves the company in energy cost up to $350,000 yearly. In total, the company has 4 MW onsite renewable energy system and they plan to add 3 MW solar systems in 2016. Lockheed Martin targets to study the onsite renewable energy generation for each business segment. By 2015, the company has successfully completed ten business cases that improve its capital funding. The company pledges to increase its onsite renewable generation by 10 MW by 2020. In early 2016, the company signs a 17 years PPA agreement with Duke Energy Renewables for 30 MW of solar power. The solar facility will provide approximately 72 GWh annually for 17 years. Half of the total energy will be used to power the Connote facility while the other half will be credits outside of PJM interconnection. Lockheed Martin has set a new goal of reducing 35 percent of carbon emissions between 2010 and 2020.

c. General Motors**.** General Motors Company (GM) is an American automotive company. The company's headquarter, GM Renaissance Center, is in Detroit, Michigan. GM specializes in manufacturing and design vehicles and vehicle parts as well as financial services. GM was founded in 1908 as General Motors Corporation. GM, General Motor Company, was formed in 2009 after the 2009 bankruptcy restructuring of General Motors Corporation . The company has offices and facilities in 37 countries around the world. The total revenue of the company was $152.35 billion in 2015. The company currently has 216,000 employees worldwide. GM presently uses 106 MW of renewable energy that is sourced from solar, landfill gas, and waste to energy. This achievement is moving GM closer to its target of using 125 MW renewable energy by 2020. According to Solar Means Business report, GM has the most solar installation than any other automotive maker in the U.S. In 2015, the company installed 850 kW solar arrays at Bowling Green Assembly, Kentucky, the Chevrolet Corvette manufacturing site. The solar system is expected to produce 1.2 GWh of energy annually which provides enough energy to produce 850 Corvettes. The company also installs a 466-kW solar array at its Rochester Operation facility in New York and its Warren Transmission plant with 800 kW array. GM will have 11.4 MW of solar array throughout its facilities in the

U.S. which will generate 15 GWh of renewable energy. As of today, the company has 22 facilities with total 48 MW solar footprints. GM also has three facilities that use landfill gas where it is working to increase the landfill gas at Fort Wayne and Orion assembly by 14 MW. At its Hamtramck assembly plant in Detroit, the solid waste from Metro Detroit is used to turn into steam to heat and cool the assembly plant. This system provides 58 percent of the plant electricity usage by renewable energy. In the near future, GM will start to power its four facilities in Mexico with 34 MW of wind energy. In 2016, GM's Arlington Assembly Plant in Texas plans to use 30 MW of wind energy to power half of its operations which is equivalent to manufacture 125,000 trucks per year. In September 2016, GM joined RE 100 and committed to achieve 100 percent renewable energy by 2050. GM is working on installing 30 MW of solar arrays on two of its facilities in China which includes 10 MW of solar rooftop for Jinqiao Cadillac plant in Shanghai and 20 MW of solar carports in Wuhan (Toole, 2016).

d. S.C. Johnson & Son. S.C. Johnson & Son is a multinational American company which is commonly known as S.C. Johnson. The company is well-known for manufacturing household cleansing products and consumer chemicals. S.C. Johnson's headquarters are located in Racine, Wisconsin. It currently has facilities in 72 countries and its name brand is sold in 110 countries worldwide. Founded in 1886 by Samuel Curtis Johnson, S.C. Johnson has become one of the leading privately own companies in the world. In 2013, the company revenue was $11.75 billion and it had 12,000 employees.

S.C. Johnson installed two 415-foot height wind turbines at its largest manufacturing facilities in Mt. Pleasant, Wis. Combined with two cogeneration turbines which was built in 2000, on average, the onsite wind turbines generate 8 GWh, enough energy to power the facility 100 percent by renewable energy. SC Johnson has been purchasing renewable energy from the local wind farm to power its manufacturing site in Bay City, Michigan. The purchased energy provides 67 percent of the facility's electricity. In late 2013, the company announced that it is reaching its goal of using 33 percent of renewable energy in its global energy usage. The plant in Toluca, Mexico is now receiving 86 percent of its electricity from the purchased renewable energy. The company also installed a wind turbine in Mijdrecht, Netherlands in 2009 and now can generate up to 50 percent of the energy needed for the company local facility. In SC Johnson's facility in Shanghai, China, several projects of solar system have been developed to heat up water for the company operations. The manufacturing facility in Medan, Indonesia is powered by the renewable energy generated from waste palm shells sources. The energy generated is used to heat up water for the manufacturing productions. The company has 23.6 GWh of onsite generation and 7.62 GWh of Renewable Energy Credits.

2.1.2 World manufacturing

a. BMW. BMW is the abbreviation of Bayerische Motoren Werker, a Germany automotive company which is famous for its luxury vehicles and motorcycle. The company was first founded in 1916 as a business entity of Rapp Motorenwrke and then changed to motorcycle production in 1923 and car production in 1928-1929. The company's headquarters are located in Munich, Germany. BMW is the parent company of Roll-Royce Motors Cars and it also own Mini cars. By 2015, BMW had a total revenue of 92.175 billion Euros. The company had 122,244 full time employees in 2015 (BMW, 2016).

In the Annual Account Press Conference 2015, BMW Group claimed that 51 percent of its energy usage worldwide came from renewable energy sources. In December 2015, the company joined RE 100 and committed to use 100 percent of renewable energy sources for all of its operation. The company targets to have two-thirds of its electricity coming from renewable sources by 2020. In 2013, the company installed four wind turbines in Leipzig, Germany and generated the renewable energy from the wind to power 100 percent of the production of BMW i3 and BMW i8. In South Africa, BMW signed a 10-year power purchased agreement to supply its Rosslyn production facility with renewable energy from biomass source. The PPA would supply the company 4.4 MW of renewable energy. The gas sources come from waste production of cattle, chicken farms and food production plans. This agreement provides over 25 percent of energy needed for the facility. By 2015, the plant has delivered 3.1 GWh which covers 4.5 percent of electricity needed by the plant. At its Spartanburg plant in South Carolina, US, the company has installed a methane gas system that supplies 50 percent of the energy required by the plant. The company used the landfill gas to generate the renewable energy to power its manufacturing facility. The system generates approximately 11 MW of renewable electricity for the factory. In June 2016, BMW announced that its new $ 1 billion Mexico plant will solely depend on renewable energy which make it the most efficient factory of BMW.

2.2 Service Industry

2.2.1 Service industry in U.S.

a. Adobe. Founded in 1982, Adobe now is an international software company that specializes in rich multimedia software products. It is famous for its Photoshop applications as well as Adobe reader and portable document format files, PDF. The company has approximately 14,154 employees of which 95% work in San Jose. As of 2016, they are a Fortune 500 company that generates 5.8 billion dollars of revenue annually.

Plan to use 100 percent renewable energy by the year of 2035, the company has already installed 20 Wind spire wind turbines in their headquarter facilities in San Jose, California. These wind turbines have the capacity of 50 KW. By 2014, the company had achieved 30 percent of its target. In 2013, the company reached carbon neutrality with limited used of RECs. Adobe signed PPAs to stabilize energy cost. Total renewable energy: 3.774 MWh in 2014. The San Jose headquarters saves $1.2 million annually and brings in $400,000 in rebates per year.

b. Amazon. Amazon web service (AWS) provides computing services such as server, storage, networking, and database to businesses and organizations. The services are operated in 13 regions of the world. It provides fast and cheap service compared to other company in the field. By 2015, AWS had the sale of $1.57 billion in the first quarter of the year and $265 million of operating income. Amazon announces that it has over one million active customers from 190 countries monthly.

Amazon Web Service has announced that it is pursuing 100 renewable energy goals following the industry trends. In 2015, it was able to produce 25 percent of its renewable energy. Amazon intends to produce up to 40 percent by the end 2016. In total, Amazon has four renewable energy facilities in the US located, respectively, in Indiana, Virginia, North Carolina, and Ohio. The solar farm is targeted to produce 170 GWh annually by October 2016. The three wind farms are expected to produce 1,490 GWh electricity yearly. Together, they produce an output of 1,600 GWh which is capable of power 150,000 US home annually. In April 2016, Amazon signed an Amicus Brief supporting the US environmental protection agency clean power plan (CPP).

c. Cisco. Cisco is a network company specializing in connectivity and users and client customize solutions. It is the biggest networking company in the world which was founded in 1984. It operates on revenue of 49 billion dollar. Some of its famous products are Ethernet Router and the popular 7960G Ip phone.

In 2015, Cisco used 1,085 million kWh to power its U.S. operations which is 96 percent of energy consumption. Cisco decided to have its 25 percent electricity needs provided by renewable energy by the year of 2017. The company signed a PPA contract for 20 years with the NRG Renew Company to build 20 MW solar facilities in Riverside county California. This solar facility will power the San Jose headquarter in California, will provide enough energy needs for 14,000 homes and remove as equivalent as 21,000 cars from the road which. Also, Cisco has four locations throughout the world that added together provide photovoltaic output of 2 MW. Altogether, the total of green power usage is 1,085 GWh which is 97 percent of the company total energy use.

d. Facebook. Facebook was created in 2004 by Mark Zuckerberg at Harvard University as social networking service. It late expanded to local Boston community college. In 2006, it allowed anyone who is 13 or older to create a profile. It employs 13,500 employees and it social network site has 1.65 billion monthly active users. The company revenue is 17.9 billion dollars and its subsidiaries include Instagram, WhatsApp's, and Oculus.

Facebook announced in December 2013 that it would power its data centers with 25 percent renewable energy resource by 2015. In 2016 it announced that it would surpass its goal to 50 percent clean renewable energy by 2018. Facebook has worked to provide 100 percent clean and renewable energy to its data centers in Lulea, Sweden and Altoona, Iowa. In Altoona, Iowa, Facebook worked with local utility to create a new 138 MW wind farm from which it purchased RECs to match a 100 percent need of electricity of the data center. Facebook is currently working with the local facility to add its surplus renewable energy of 140 MW to the grid which can provide energy for more than 40,000 homes in Iowa. In July 2015, Facebook announced that its new data center in Dallas-Fort Worth in the long term will be powered by 100 percent renewable energy provided by the 17,000 acres wind farm which located in 100 miles from the data center. Working with local energy companies, it will add 200 MW wind energy to the Texas grid.

e. Kohl's . Kohl's is a clothing retailer that was originally started by Maxwell Kohl in 1946. It was originally a food supermarket that was very popular in the Milwaukee area of Wisconsin. However, in 1962, Maxwell Kohl opened the first Kohl's department store. It is now a publicly listed company that operates on 19-billion-dollar worth of revenue. It employs 140,000 workers nationwide are on the S&P 500 list. Kohl's has more than 1,160 stores in 49 US states which make them a leader in department store section.

Kohl's has installed 163 solar panels systems on its stores across 13 states. On average, this solar energy powers approximately cover up to 40 percent of their total energy usage. This was done with a power purchase agreement (PPAs) from Sun Edison for a term of 20 years. The solar systems generate 50 MW of renewable energy thought the US. Kohl's biggest solar system is installed at its E-Fulfillment Center 3 at Edgewood, Maryland. The system includes 8360 solar panels which produce over 3 million KWh per year. The company claims to have purchased sufficient renewable energy credits to reach its goal of 100 percent energy use from 2010 to 2015. Kohl's is currently rank third in the nation as the retailer that use of renewable energy. Kohl's also installs onsite vertical turbines close to its Distribution Center in Findlay, Ohio which produce 40,000 kWh yearly. Horizontal wind turbines are installed in one of Kohl's store in Corpus Christi, Texas which generates 14,000 kWh yearly.

d. Macy. Macy's was founded by Rowland Hussey Macy in 1858 in New York. It was later sold and became a publicly owned company which owned by Federated Department. Macy's Inc. employs 172,500 employees nationwide and operates on a revenue of 27.9 billion dollars. Other subsidiaries of Macy's Inc. are Bloomingdales and Bluemercury.

In April of 2016, Macy's Inc. partnered with Sun Power Corp to installs solar power in 71 store locations. In total, the energy generated will be 39 MW. This energy generation is equivalent to powering of 2,910 homes per year. It is also removing total of 3.6 million gallons of gas used on the road. Macy's has come a long way since 2006 when its stated to take advantage of California state incentives for retailer using solar energy. The solar systems installed on 26 stores in California and all the Hawaii stores generates 3,505 MWh of renewable energy which cover 27 percent of the company total energy used.

e. Microsoft. Microsoft was founded in 1975 by Bill Gates and Paul Allen. It quickly gained a foothold in the technology market with its MS-DOS operating system and then later with its Windows operating system. It grew to become a multi-billion-dollar corporation with a vast variety of services. Among its products are the Xbox series of game consoles and games, the famous Windows operating system, Visual studio programing software, the MSN media service, as well as various network and hardware services among many other products and services as well as owned subsidiaries of Microsoft. In 2016, it operated at a revenue of 85 billion dollars and employed 114,000 workers. It is now headquartered in Redmond, Washington.

Microsoft claims to have reached carbon neutral since 2012 and 100 percent powered by renewable energy since 2014. This was achieved by combining the direct projects and renewable energy certificates such as PPAs and RECs. In 2013, the company purchased the renewable energy output from 110 MW Keechi Wind project with a 20 years PPAs commitments. Later on in 2014, Microsoft purchased 175 MW renewable energy from Pilot Hill Wind from Illinois which can power its Chicago data center and 70,000 Illinois homes. In Silicon Valley campus locate in Mountain View, California, Microsoft installed 2,288 solar panels on its building rooftop. In May 2016, the company made a commitment to have 50 percent of electricity use by its data center comes directly from wind, solar, and hydropower sources by the end of 2018 and 60 percent by the next decade. Currently, 44 percent of the energy that the Microsoft consumed came from wind, solar, and hydropower sources.

f. Pearson. The company Pearson was founded in 1844 as a building company. In 1880, it was taken over by the founder's grandson to become one of the largest construction companies of its time. From then on, the company grew and into the 1920's it halted its construction projects. It went on to acquire major media assets as well as education companies throughout England. It is now a major publisher of books, newspaper, and magazines. As of 2015, it operates on a revenue of 4.4 billion dollars.

Pearson's goal to achieve 100 percent renewable energy supply began in 2008 and not long after was reached in 2012. Together, it has 2.6 MW of wind and solar energy production capacity through all its operations. According to EAP, the annual green energy usage of Pearson is 94.6 GWh which cover 102 percent of its total energy usage. The EAP later recognized Pearson with a Green Power Purchasing award for its achievement in the reduction of carbon emissions.

g. REI – Recreation Equipment Inc. Recreational Equipment Inc. is a retailer which specialize in outdoor and recreation products. Founded in 1938, REI committed to provide affordable prices of quality climbing gear and mountaineering expeditions for outdoor lover. As of today, the company's main merchandise includes consumer-oriented goods, camping equipment, sport clothing as well as climbing and backpacking gear. REI has 143 stores in 36 states and employs 12,000 employees. The retailer operates on a revenue of 1.3 billion in 2015.

REI has total 26 stores and one distribution center that have solar panels systems installed and operated. The solar systems generate 3,760 MWh renewable electricity annually. REI also purchase RECs which equivalent to 130 stores, two distributions, and headquarters consumption. REI goal is to reach carbon neutral by 2020. The company also purchase green power from local utilities companies. The total renewable energy usage annually is 78.2 MWh which is 116% its total energy consumption.

h. The North Face. The North Face is a company founded in 1966 and then later acquired by Kenneth "Hap" Klopp in 1968. It was originally a climbing equipment retail store which in the 1980s grew to carry camping as well as ski equipment. It grew into popularity with its fashionable attire and now operates over 55 retail stores and 20 outlet locations in the US. It also has stores in South America, Europe, and Asia Pacific. The North Face Company was recognized by EAP for a Leadership Award in 2013 due to its green power purchase. The company purchase approximately 21 million kWh green energy through RECs which equivalent to 100 percent energy use by the company. In 2008, North Face also installed a 1 MW solar system on its distribution center in Visalia. The onsite generation provide 25 to 30 percent of the facility's electric needs. The company later on installed a 950-kW solar system on its head quarter in Alameda, California which produce enough energy to supply the building electric demand.

i. Walmart. Walmart was founded in 1962 by Sam Walton and quickly incorporated in 1969. It grew to contain 11,539 stores in 28 countries. It is the world's biggest company in terms of revenue and the largest private employer in terms of man power. In 2016, it employed 2.2million workers worldwide and operated on 482 billion dollars of revenue. It is a Mega Market for countless number of goods and products that include food, clothing, and electronics.

Since 2005 to present, the company has more than 300 renewable projects which are under development or in operation. Its target is to procure 7,000 GWh of renewable energy per year by 2020. In 2005, the company successfully reduced GHGs by 20% from all of its stores, distribution centers and clubs which resulted in about 3 million metric tons of GHGs. In the Approach to Renewable Energy, Walmart reported that even though its "square footage increased by 45% and sales grew 51%...emission grew only about 12%" (Malmart 2015). At present, the company has 26% of its power comes from renewable energy. By purchasing PPAs, Walmart is taking a significant step in achieving its long term goal of getting 7 billion kilowatt-hours of renewable energy by 2020. The company currently has 300 solar panels sites which produce 100 MW across 14 states and Puerto Rico. In 2015, the retail giant signed a contract to buy 58 percent of Logan's Gap Wind farm output under a 10 years PPAs. As of 2015, there is 27 percent of company electricity usage coming from renewable energy.

l. Whole Foods Market. Whole Foods Market is a leading food market that featuring natural and organic food. The company first founded in 1980 in Austin, Texas. It has 91,000 employees and 435 stores across the U.S., Canada, and United Kingdom. With the revenue of 12.9 billion dollars in 2013, the company is listed in as the 30th largest retailer in the US. Whole food market is the first certified organic supermarket according to the National Organic Program standard. The company motto of "Whole Foods, Whole People, Whole Planet" focuses on customer satisfaction and health as well as team member excellence and happiness. It also supports community and participate in environmental improvement.

The company purchased RECs from 2006 to 2012 to neutralize the carbon footprint of its stores and facilities to 100 percent. In 2009, the company made a purchase of 776 million MWh from wind farms which equivalent to 100 percent of its North America stores electric use. In early 2016, the company announces to have rooftop solar systems in 100 stores and distribution centers across nine states. This onsite generation will potentially produce up to 13.8 MW of solar power. The company also purchase long term PPAs with Solar City to power its stores. The Whole Food Market store in Gowanus, Brooklyn has onsite solar system that can power the parking lot and 30 percent of the building energy use. This particular store can generate enough renewable energy for the store usage during electricity loss.

2.2.2 Service industry in Asian-Pacific.

a. TRIAL – Japan. TRIAL Company, Inc. is the supercenters and retail chain stores which was founded 1974. The company headquarter is in Fukuoka, Japan. It specializes in produce and fresh food, apparel, home decorations, and household goods. As of June 2012, TRAIL has more than 16,000 employees including full timer and part time. The company operates on a revenue of more than 21 billion yen.

On October of 2015, TRAIL Company partnered with Canadian distributed power generation company to install rooftop solar power facilities on 32 stores. The 32 supermarket stores locate in Kyushu, Chubu, Kanto, and Tohoku area of Japan. The solar systems expected to produce 12.5 MW yearly which is 300 to 400 kW for each store. TRAIL participated in the FIT (Feed-in-Tariff) program in Japan which the generated renewable energy will be sold to the local utilities.

b. Beisia – *Japan.* The Beisia Co. Ltd.is a retail and service business company that have various stores across Japan. The company has 28 affiliates which include shopping centers, convenience stores, distribution service, food service, and real estate service. Two of its main retail business is Super Centers and Supermarkets are spread around Tokyo and 13 prefectures. It has more than 1,900 stores throughout Japan and is one of the largest company in the country. As of 2015, Beisia retail industry has almost 11,000 employees which include full time, part time, and temporary employees. The company is operating on the revenue of 8,300 billion yen estimated in 2013. In 2014, Beisa partner with Solar Power Network Japan company to install solar systems on 33 of its stores. The systems is predicted to generate 29 MW of renewable energy in total. The expected annual energy production is approximate 33.5 MWh. This project is developed to supply the store power in the case of natural disaster. In early 2015, Beisa has its first solar installation on its Isesaki Ekimae Store in Gunnma which is the first installation of the partnership contract. The solar systems are expected to produce 500 kW renewable energy, which cover up to 47 percent of the store annually demand.

c. Infosys – India. Infosys is an Indian IT company that offer business consulting, information technology and outsourcing services in banking, finance, insurance, and manufacturing. The company is founded in 1981 and is one of the largest IT company in India. It is headquartered in Banfalore, Karnataka. As of 2016, Infosys has 1,045 clients globally and 194,044 number of employees. The company's revenue is $9.501 billion with operating income is $2.375 billion. Infosys targets to use 100 percent of renewable energy and become carbon neutral by 2018. It is also the first Indian company to join the RE100 platform in 2015. The company installed a 6.6 MW solar power plant at Pocharam campus in Telangana and the operation started at the end of 2015. Together with the 0.6 MW rooftop solar system already installed, this new solar system covers all the campus electricity needs by renewable energy. Pocharam is the first facilities in India that operate entirely by renewable energy. The overall solar system is expected to produce 12 million kWh annually. The company currently has 15 MW solar power plants across its campus in India. About 30 percent of its energy demands are supplied by renewable energy which is equitant to 75,674 MWh. Infosys targets to increase its solar capacity to 170 MW with the combination of onsite and offsite installations in four years to achieve its commitment of using 100 percent renewable energy.

2.2.3 Service industry in Europe.

a. H&M. H&M is an international clothing store founded in Sweden in 1947. In 2013 it opened its 3,000th store and now has 3,716 locations worldwide. As of 2015 it employed 148,000 workers and operated on a revenue of 21.7 billion dollars US in 2016. Aside offering its fashion to a wide market it also offers online clothing market to 32 countries worldwide. In 2014, the company joined RE 100 and committed to use 80 percent renewable energy by 2015 and target to reach 100 percent renewable energy goal. At the present, 78 percent of electricity used in its global stores, offices, and warehouses are coming from renewable energy. The solar panel own by H&M generated 784,200 kWh in 2013. The company purchases RECs in America and GOs in Europe. The company's retail stores in UK and Netherland use 100 percent renewable energy purchase from the grid. The annual usage of green power is 171,632,065 kWh which cover 100 percent of its energy usage.

b. IKEA. Ikea is a multinational company that was founded in 1943 by Ingvar Kamprad. It is mostly an assemble yourself store that also sells various appliances and utensils as well as unique brand of foods. It has location in 5 continents and is looking to expand. As of 2014, it operates on a revenue of 29 billion euros and employs 147,000 employees worldwide. In 2012, IKEA was a top five commercial solar customer using 25MW of solar power in the US alone. In 2013, IKEA marked its 36th solar project by finding its 2.7 MW solar array atop its US distribution center in Maryland. BY 2013, IKEA has 90 percent of its US locations using solar power and was on its way to reach its goal of being energy independent by 2020. In 2014, it began working with APEX clean energy to build a 98 MW wind farm which would have the capacity to produce 380 GWh per year. It is first used with wind energy and it was located in Hoopeston, Illinois bringing it one step closer to its goal of 100 percent renewable energy. Currently, the company own and operate 327 wind turbines and installed approximately 700,000 solar panels on top of its 120 stores and warehouses. The company has been able to attain 67 percent renewable energy source to power its retails stores and warehouses worldwide. In some international locations such Denmark, Finland, Norway, IKEA produces enough clean energy to supply its power needs and in Canada, its produces more than double of its consume. The annual usage of green power is 183,487,801 kWh of which cover 73% its total energy uses worldwide.

c. Aviva. Aviva is a British insurance company that operate internationally. Its headquarter is in London, UK. The company has 33 million customers globally. Aviva's service includes general and life insurance, retirement saving, and fund management services. The company is operated on a revenue of 23.728 billion of Euro by 2015. The company currently manages $390 billion of assets. It has approximately 30,00 employees.

In 2014, Aviva joined RE 100 and committed to reach 100 percent renewable energy by 2025. In UK and Ireland, the company has purchase 100 percent renewable energy to supply its facilities and purchase renewables in some other country. Aviva also installed 3 rooftop solar systems in three of the offices in England and Scotland which can generate 445,520 kWh of renewable energy annually. Total energy renewable energy use by the company is 11,778 MWh in 2014 which covers 56 percent of its total electricity use.

d. SKY plc. Sky is a European media company headquartered in London, England. It was created in 1990 after the merger of Sky Television and British Satellite Broadcasting. In 2014, it acquired Sky Italia and Sky Deutschland and became Sky plc. It is the leading European media service company offering on demand television, telephone, and internet services. Its revenue was more than 9.9 billion Euros in 2015 and it employs 30,000 workers. Its lead chairman is Rupert Murdoch who owns a 39 percent stake in the company. SKY is the first media company that achieve carbon neutral in 2006. The company has been purchasing 100 percent renewable energy from the grid to power its UK and Ireland facilities since 2010. As of today, the electricity demand of the UK and Ireland sites are fulfilled by the onsite generations and renewable energy tariffs. SKY goals is to supply 20 percent of its energy need via onsite or controlled renewable generations. SKY is currently investing in Combined Cooling, Heating & Power Plant projects, 100 kW wind turbines, biomass, and PVs. The company install additional 1,000 m^3 solar panels at its campus in UK but not fully commissioned. In 2014/2015, the company claims to have achieved 6 percent against its 20 percent target of using energy from onsite our controlled renewable energy sources. (add report table). In 2016, the company join RE100 group and setting its targets to use 100 percent of its globally sites electricity by renewable energy.

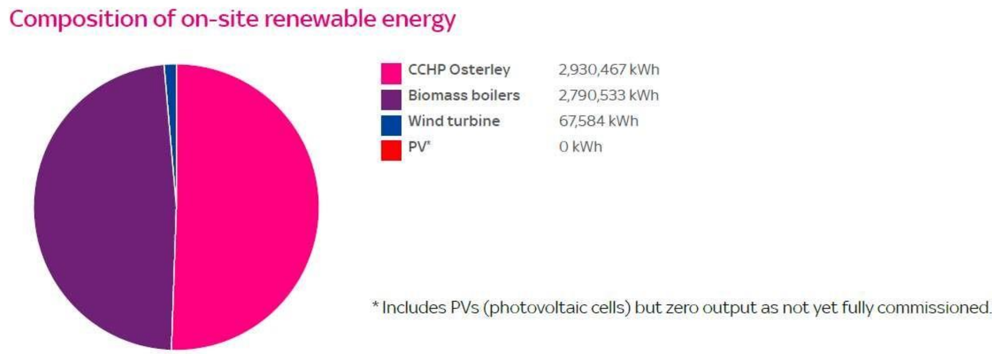

Figure 2.1 SKY on-site renewable energy

e. Aldi. Aldi was originally started as a market store in German founded in 1913. The two children of the owner took over the store in 1946. In 1960 the brothers split the operation into two separate facets Aldi Nord and Aldi Sud. Appearing as a single enterprise the two entities operate different areas of the market. Aldi Nord operates 2,500 stores in the north and west as well as the east of Germany. While Aldi Sud operates 1,600 stores in the west and south of Germany. Operations for both companies in Denmark, France, the Iberian Peninsula, as well as the United Kingdom, Australia, Hungary, Switzerland and many more. They also have stores in the United States. Aldi Nord is owner of the US Trader Joe's brand chain. The companies generated more than 50 billion Euros in 2010 and are both privately owned companies. The two brothers are among the wealthiest people of Germany. Being able to utilize solar power on its stores across Europe and North America has made Aldi a market leader in renewable energy supporter. According to Aldi official website, 10 percent of its UK and Ireland electricity consumption is powered by renewable energy. Aldi has installed solar systems in its 7 distribution centers across UK. The distribution center in Goldthorpe, near Barnsley was installed a 1.5 MWp solar system which covers 15,000 m2 rooftop. The systems generate 1.2 GWh of renewable electric annually. This is one of the biggest solar system in cold store facility in UK in 2015. Furthermore, in 2015, Aldi installed a 2.1 MW solar panels system on top of its regional distribution center in Boston, UK. This 8,240- panel system generates approximately 1,746 MWh of renewable energy per year which can power six time the electricity needed for the store annually. Early 2017, Aldi plans to install a 1.5 MWp system on its Cardiff distribution center which locates on the south coast of Wales. Aldi stores in Germany has celebrate its 1000th PV systems installed on store rooftop. The company states that renewable energy is used to cool the merchandise and for lighting in more than half of its stores in western and southern Germany. The renewable energy systems in Germany stores generates 95 million kWh which 85 percent is used to supply cooling and lighting in the stores. The remaining 15 percent of renewable energy is sent to the local grid.

f. M&S. M&S is the first retailer in the world that claims to have carbon neutral operations. In 2009, M&S signed a contract with local renewable energy company to supply its stores and offices in England and Wales by renewable energy for six years. With the commitment to use 100 percent renewable energy for electricity demand, since 2012, all of its UK and Ireland stores, warehouse, offices are power by the renewable energy came from green tariff renewable energy sources. 21 percent of its energy comes from small scale generator such as wind farm and solar system by 2014. In 2015, M&S joined RE 100 and targeted to use 100 percent of renewable energy globally and 50 percent from small scale renewable source by 2020. M&S also installed UK largest solar panel array on its East Midlands distribution center in Castle Donington in 2014. The solar system covers 900,000 sq. ft. roof and generate more than 5,000 MWh of renewable energy annually. This system will provide 25 percent of energy needed by the distribution center.

2.2.4 Service industry in Africa.

a. Woolworths. Woolworths is a national retailer located only in South Africa. It was started in 1931 by Max Sonneberg and his son Richard. It famously made its debut inside of the notable Royal Hotel. Since then it developed a business relation with Marks & Spencer of London and shared a technology agreement that is still used today. Among its products and services are food, clothing wear, financial services, and homeware. As of 2016 it operated on 4billion US dollars and employed over 18,000 workers in South Africa. Woolworths accomplished its sustainability goals for the 2007-2015 period and in the process, could supply 10% or 254,369 kWh to its headquarters. Also, in 2014, it purchased an amount of 200,000 kWh of Green Electricity certificates from the City of Cape town. Throughout its stores it was able to reduce 40% of relative electricity used as well as 31% in its corporate structures. It is currently planning on creating a 2MW solar array at its Midrand distribution center that would have the capacity to power up to 34% of the total energy needed annually. Woolworths in accordance with its commitment has set new goals to reduce its current energy use by halve in 2020 and be completely energy independent by 2030.

b. Massmart Holdings Limited. Massmart is one of South Africa's biggest retailer being the biggest wholesaler of basic food items as well as general merchandise. It was started in 1990 with the acquisition of six Makro stores in the country and has grown ever since. It operates under several divisions including a Masswarehouse and Massbuild which includes Builders Warehouse and Makro. Walmart in 2010 acquired a

51% share in its stock and is now the parent company. As of 2014 it operated on a net revenue of 3billion dollars US and employed more than 45,000 workers. Currently Massmart has over shot their goal of being 10% energy efficient and reached 18.76% energy efficiency throughout their operations. It is currently spearheading three renewable resources the first which is a 150kva Photovoltaic source which will operate in its Builders Warehouse store. It has a 700kva plant for one of its Makro stores and 520kva for another Makro store in Carnival Mall. Massmart is also a supporter of energy efficiency initiatives sponsored by South Africa's National Business Initiative.

c. Pick n Pay Stores Limited. Pick n Pay is an international supermarket store centered in South Africa which was founded in 1967. The company underwent a complete redesign which had been mostly unchanged since the 1970's. The company operates on revenue of 4 billion US dollars and employs 50,000 employees. Currently Pick n Pay is under plans to install a 300kWp solar array at its distribution center in Western Cape. It has already installed a 150kWp array in its Longsmeadow distribution center and there is a 100kWp solar array at its Hurlingham store. Its energy per square meter use has been reduced by 32% since 2008 and is now retrofitting one of its stores to test the viability for further use throughout its operations.

III. WIND TURBINE AND PV CAPACITOR MODEL AND ELECTRIC VEHICLE ENERGY INTENSITY

3.1. Wind Turbine Capacitor Factor

A wind turbine (WT) system possesses four operating phases depending on the wind speed. Let $P_w(v)$ be the instantaneous output of wind turbine at wind speed v. Then the cubic power curve is given as (Thiringer and Linders, 1993).

$$P_w(v) = \begin{cases} 0 & v < v_c,\ v > v_s \\ P_m (v / v_r)^3 & v_c \le v \le v_r \\ P_m & v_r \le v \le v_s \end{cases} \tag{3.1}$$

where v_c, v_r and v_s stands for the cut-in speed, the rated speed, and the cut-off speed respectively. Note P_m is the rated power capacity in a unit of either MW or KW depending on the size of the wind turbine. Studies (Weekes and Tomlin 2014) have shown that the wind speed in a particular location in general can be fitted with Weilbull distribution. The probability density function (PDF) and cumulative distribution function (CDF) are given below

$$f_w(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^k}\text{, for } v\geq 0 \tag{3.2}$$

$$F_w(v) = e^{-(v/c)^k}\text{, for } v\geq 0 \tag{3.3}$$

where c and k are the Weibull scale and shape parameters. Then the WT capacity factor, denoted as λ_w can be estimated as

$$\lambda_w = \frac{E[P_w(V)]\times T}{P_m \times T} = \frac{1}{v_r^3}\int_{v_c}^{v_r} y^3 f_w(y)dy + \left(F_w(v_s) - F_w(v_r)\right) \tag{3.4}$$

where T is the number of hours in a year. The value of λ_w falls in the range of [0, 1]. An example of Weibull wind speed distribution is in Figure 3.1

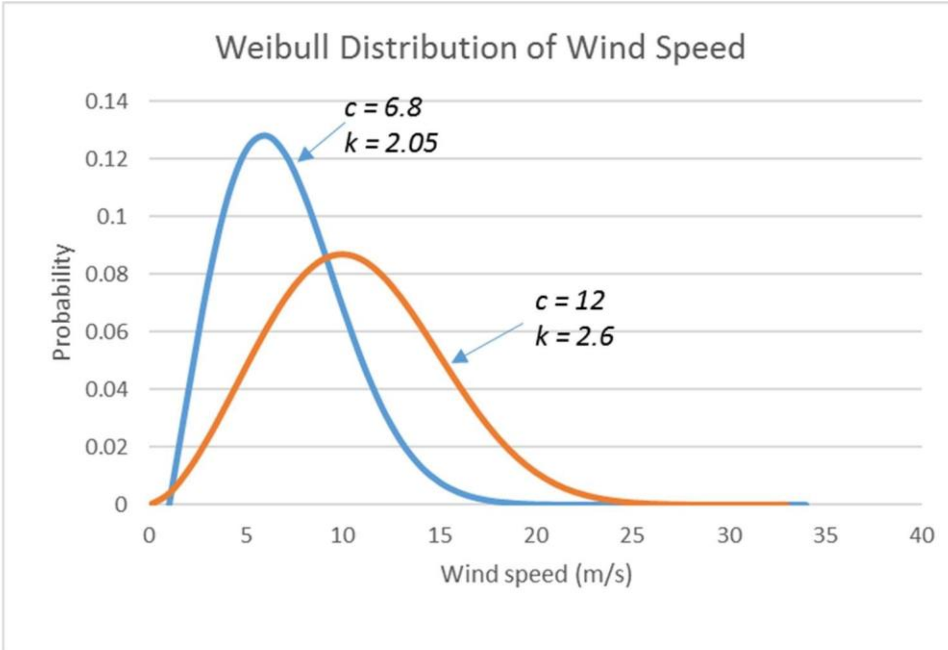

Figure 3. 1: Weibull Wind Speed Distributions

3.1.1 Wind speed at the height of wind turbine tower. The wind speed introduced in the model is the wind flow just near the Earth's surface. However, in reality, wind speed is typically slowest at the ground level yet increases in height (Blackadar and Tenneskes, 1968). Due to a "no-slip" boundary condition, the frictional drag the surface causes wind speed to be zero and pressure gradient forces cause the wind speed to increase with height (Letchford and Zachry, 2009). A few hundred meters above the Earth's surface there is a wind gradient in the wind flow, and the wind speeds are affected by such wind gradient. According to Heier (2005), the wind speed at reference height (measured in meters) can be measured using the following equation:

$$v_w(h) = v_g\left(\frac{h}{h_g}\right)^k \text{; for } h > h_g \qquad (3.5)$$

Where v_w(h) is the velocity of the wind (m/s) at height *h*. Velocity of the wind at height h_m (m) is denoted at v_m (m/s). The parameter *k* is the Hellman exponent that depends on the coastal location and the shape of the terrain on the ground, and the stability of the air. Table 3.1 provides example values of the Hellmann exponent. This research uses the unstable air above human inhabited areas *k*= 0.27.

Table 3. 1 Hellmann Exponent

Location	***k***
Unstable air above open water surface	0.06
Neutral air above open water surface	0.1
Unstable air above flat open coast	0.11
Neutral air above flat open coast	0.16
Stable air above open water surface	0.27
Unstable air above human inhabited areas	0.27
Neutral air above human inhabited areas	0.34
Stable air above flat open coast	0.4
Stable air above human inhabited areas	0.6

3.2. Solar PV Capacitor Factor (in Northern Hemisphere)

The output power of a PV system depends on multiple factors that are summarized in Table 3.2. Unless specified, the unit of all angles is radians (rad).

Table 3. 2: Key Parameters in Solar PV Power Generation

No.	Factor	Symbol	Explanation
1	weather condition	W_t	random variable
2	PV size (m^2)	A	PV module area
3	PV efficiency	η	10-20% for commercial PV
4	calendar date	d	$d \in \{1, 2, \ldots, 365\}$
5	solar hour (rad)	ω	related to the local time
6	PV temperature (^{o}C)	T_o	operating temperature
7	latitude (rad)	ϕ	depends on location
8	PV azimuth angle (rad)	α	if facing south
9	PV tilt angle (rad)	β	between PV and ground
10	Solar zenith angle (rad)	φ	between the zenith and the Sun's ray
11	solar PV incident angle	θ	Between the norm to PV and the Sun's ray
12	local hours	t	t=1, 2, …, 24

We present a three-step procedure to calculate the PV power output based on the early studies in (Cai et al. 2010). These steps are summarized as follows

Step 1: For PV facing the south, the sunrise and sunset time in day $d \in \{1, 2, \ldots, 365\}$

$$\cos(-\omega_{rise}) = \cos(\omega_{set}) = -\tan(\phi - \beta)\tan\delta \tag{3.5}$$

with

$$\delta = 0.40928\sin\left(\frac{2\pi(d+284)}{365}\right) \tag{3.6}$$

where, δ is the declination angle, ω_{rise} and ω_{set} are the sunrise and the sunset angles in day *d* perceived from the PV panel. There is no power output before sunrise and after sunset.

Step 2: Computing the total solar irradiance incident on the PV surface at time *t* on date *d*

$$I_t = 1370\left(0.7^{(\cos\varphi)^{-0.678}}\right)\left(1+0.034\cos\left(\frac{2\pi(d-4)}{365}\right)\right)\left(\cos\theta+0.1\left(1-\frac{\beta}{\pi}\right)\right) \tag{3.7}$$

where

$$\cos\varphi = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \tag{3.8}$$

$$\begin{aligned}\cos\theta = {} & \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\alpha + \cos\delta\cos\phi\cos\beta\cos\omega \\ & + \cos\delta\sin\phi\sin\beta\cos\omega\cos\alpha + \cos\delta\sin\beta\sin\omega\sin\alpha\end{aligned} \tag{3.9}$$

In Equation 3.7, I_t is the solar irradiance (W/m^2) received by the PV under a clear sky condition and φ is the solar zenith angle given by Equation (3.8) and it is the angle between the zenith and the center of the Sun. ω is the solar hour angle determined by time *t*. For instance, ω=0 is the solar noon time. Starting from ω=-π/2 at 6am, and doing increases of 15 degrees every hour until reaching ω=π/2 at 6pm. To maximize the energy yield, the PV panel faces the South and its tilt angle shall equal the local latitude, namely α=0 and β=ϕ, then equation (3.9) can be simplified as

$$\cos\theta = \cos\delta\cos\omega \tag{3.10}$$

Step 3: The actual output of a PV system considering the uncertain weather condition can be estimated as

$$P_t = W_t \eta A I_t \left[1 - 0.005(T_o - 25)\right] \tag{3.11}$$

where P_t is the actual output power (unit: W) of the PV system at time *t*. W_t is a random variable representing the stochastic weather at time *t*. It varies from 1 and 0 to mimic a clear, partially cloudy, overcast, or raining condition (Lave and Kleissl 2011). The capacitor factor of a PV system can be estimated by

$$\lambda_{PV} = \frac{1}{P_{PV}^{\max}} \sum_{t=1}^{T} P_t \tag{3.12}$$

Where: $P_{PV}^{\max}$ is the rated capacity of a PV system. The PV capacity factor model presented here assumes that the equipment is located in the northern hemisphere. For PV in the southern hemisphere, simply set $\alpha=\pi$ and ϕ should be a native angle.

3.3 Electric Vehicle Energy Intensity Rate

For battery-powered vehicles, the electricity required to move an object from one location to another depends on the mass of the object, the traveled distance, and the moving speed. For example, the battery capacity of a Nissan Leaf is 0.024MWh (or 24 KWh), and the driving range of a fully charged Leaf can reach up to 112 km at 100 km/hour (Nissan, 2015). The electric vehicle energy intensity rate is defined as the amount of battery energy consumed in order to move one-kilogram objective over one kilometer at a specific speed (e.g. 100 km/hour). Let q_v be the electric vehicle energy intensity rate at speed v, then

$$q_v = \frac{E_{EV}}{m \times d_{\max}} \tag{3.13}$$

where E_{EV} is the battery capacity in MWh, $d_{\max}$ (unit is km) is the driving range at speed v, and m is the vehicle gross weight in *kg*. The unit of q_v is MWh/kg/km. For instance, the gross weight of the Nissan Leaf is 1,800 kg (including passengers). At v=100 km/hour, we obtain q_{100} as follows

$$q_{100} = \frac{24}{112 \times 1800} = 1.19 \times 10^{-7} \ MWh/kg/km \tag{3.14}$$

For instance, to move a 4,000-kg object over 100 km at a speed of 100 km/hour, the amount of electricity consumed is q_{100}×4,000×100=0.04762 MWh. The driving distance of fully charged electric truck is typically in a range between120 and 160 km (Daclison-Dickey, 2013). Hence battery charging stations along the traveling route is required to accommodate the e-truck transportations beyond the driving range.

IV. NET ZERO CARBON MANUFACTURING FOR SINGLE FACILITY PLUS WAREHOUSE AND E-TRANSPORT -DETERMINISTIC DEMAND

4.1 Systems and Model Settings

4.1.1 Design setting. In this phase of the research, we consider a single manufacturing site and a warehouse network with electric truck (e-truck) as a sole transportation tool to ship products between two facilities. The energy needed to perform regular operations for these two facilities are provided by the onsite renewable energy generation systems. Two types of renewable generators are considered for this research which include wind turbine (WT) and photovoltaic (PV). Furthermore, the e-vehicle also use the onsite renewables to charge its battery. The goal of this study is to create the net zero carbon emission manufacturing-warehouse zone.

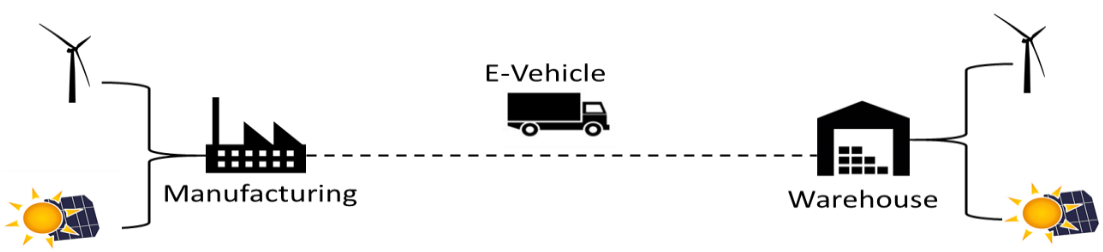

Figure 4. 1: A single facility and warehouse setting with onsite generation

The ideal model is to produce enough energy using onsite generation to supply the electricity demand for the facilities. However, the output of WT and PV will be uncertain due to stochastic weather conditions thus will occasionally create energy shortage and surplus. To meet the needs of the energy usage during the shortage period, where the output of renewable energy is less than the demand, the plant will use the energy imported from the main grid. On the other hand, in the scenario of surplus, where the onsite energy generated is more than the consumption, it can be fed back to the main grid. Net metering or feed-in-tariff are the current two mechanisms that faceplate the onsite generation system to exchange the renewable energy with the main grid. This practice will maintain the net zero carbon emission of the network as the shortage energy borrowed from the grid is offset with the surplus energy sent to the main grid.

4.2 Optimization Algorithm

4.2.1. Production-inventory model. A production inventory model is considered where multiple products are produced in a single factory over multiple periods. Each item has a bill of materials described by its production cost, inventory cost, and backorder cost. Based on the following notation, the mathematical model for a linear multiple period production inventory model is formed.

x_{ij} : decision variable for quantity of product type i made in period j

y_{ij} : decision variable for inventory level of product type i in period j

z_{ij} : decision variable for backorder level of product type i in period j

o_{ij} : cost for producing a unit of product type i in period j

h_{ij} : cost for holding a unit of product type i in period j

b_{ij} : cost for backordering a unit of product type i in period j

D_{ij} : demand rate of product type i in period j

v_{is} : amount of resource s consumed for making a unit of product type i

w_{sj} : total availability of resource s in period j

With the three decision variables x_{ij}, y_{ij}, and z_{ij}, the mathematical model is formed to determine the optimal values of the production, inventory, and backorder level that meet the demand and minimize the total production cost. Denoted as Problem P0, the problem is formulated as follows

Problem P0

Minimize:

$$K(\mathrm{x,y,z}) = \sum_{i=1}^{m}\sum_{j=1}^{n} o_{ij} x_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n} h_{ij} y_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n-1} b_{ij} z_{ij} \quad (4.1)$$

Subject to

$$x_{ij} - y_{ij} + z_{ij} \geq D_{ij}, \qquad \text{for all } i \text{ and } j=1 \quad (4.2)$$

$$x_{ij} + y_{i,j-1} - y_{i,j} - z_{i,j-1} + z_{ij} \geq D_{ij}, \qquad \text{for all } i \text{ and } j \geq 2 \quad (4.3)$$

$$\sum_{i=1}^{m} v_{is} x_{ij} \leq w_{sj}, \qquad \text{for given } s= 1,2 \text{, and } j= 1,2,..J \quad (4.4)$$

$$z_{i,J} = 0 \qquad \text{for } i = 1,2, \text{ and } j = 1,2,\ldots J \quad (4.5)$$

The objective function (4.1) aims to minimize the total cost comprised of production, holding and backorders costs. Constraint (4.2) prescribes that the total production of period j =1 is greater or equal to the demand for that period with no initial inventory but with backorder. Constraint (4.3) states that the total production level of product type i considering the previous period inventory and backorder must meet the demand of product type i in period j. Constraint (4.4) indicates that the total amount of each resource s used to make the products must be less than or equal the total amount of resource s available in period j. For the last period, the backorder level of any product type i must have a balance of zero. It indicates that there is no backorders at the end of the last production period, as shown in constraint equation (4.5).

4.2.2. Cost model of onsite generation system.

a. Installation cost. $C_{in}(\mathbf{P}^c)$ stands for the annualized installation cost for the onsite renewable energy distribution grid (DG) with $P^c{}_g$ is generation type g capacity

$$C_{in}(\mathrm{P}^c) = \frac{r(1+\theta)^n}{(1+r)^n - 1}\sum_{g=1}^{G} a_g P_g^c = \phi \sum_{g=1}^{G} a_g P_{gk}^c \tag{4.6}$$

where a_g is the capacity cost per MW of generation type g. The capital recovery factor, ϕ, is given by $\phi = [r(1+r)^n]/[(1+r)^n - 1]$ where n is the number of years to pay the equipment loan, and r is the interest rate, note that r = 0.05.

b. Operating and maintenance cost. As mentioned above, this research considers two types of renewable energy: wind and solar power. Even though these natural resources are accessible, the companies still incur in the following costs: (1) leasing land to install the WT, PV, and accessory units; and (2) replacement or repair of worn out components due to aging. Operation and maintenance (O&M) cost correlate with the cost of equipment usage and system monitoring. $C_{om}(\mathbf{P}^c)$ stands for the annual DG operating and maintenance (O&M) cost which is given as follows.

$$C_{om}(\mathrm{P}^c) = \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G} b_g \lambda_{gjk} P_{gjk}^c \tag{4.7}$$

where P_{gjk} is the actual output of generation type g during period j at location k, b_g is the average O&M cost in producing 1 MWh electricity by generation type g, *and* λ_{gjk} is the capacity factor of generation type g for the period j at location k. Let τ_g be the operation hours per year for generation type g. Equation 4.7 assumes the sun is above the horizontal 50 percent of the time for a standard year of 8760 hours. Thus, the maximum daytime hours of sun will be 4380 hours for any point on Earth (τ_{PV} = 4,380 hours). On the other hand, the maximum wind duration per year will be 8760 hours at any point on Earth (τ_{WT} = 8760), though its speed varies.

c. Carbon credit. Various incentive programs are proposed by various governments around the world to stimulate the investment in wind and solar energy. Among the most popular ones are carbon credits and equipment subsidies. The last ones are offered as one-time carbon credits to the renewable energy producer. $C_{cr}(\mathbf{P}^c)$ represents the annual carbon credits for the manufacturing facility where

$$C_{cr}(\mathrm{P}^c) = \tau_g \sum_{j=1}^{J} \sum_{g=1}^{G} c_g \lambda_{gjk} P_{gjk}^c \tag{4.8}$$

Let c_g be the carbon credits ($/MWh) for renewable energy type g. If the incentive program or the subsidy policy for a specific generation type g has expired, this model can be flexible by simply setting $c_g = 0$ for that particular renewable technology.

4.2.3. Net zero carbon manufacturing for single factory plus warehouse and e-transport. Based on the above production inventory model and generation system cost model, a new mathematical model is formed to determine the appropriate system capacity to install in the factory and warehouse location to meet the production demand as well as minimize the annual total cost of operation. Problem's notations are listed in table below.

Table 4. 1 The Notation for the Problem

Notation	Explanation
P_{1k}^{c}	wind turbine capacity at location k (k=1 is the manufacturing facility and k=2 is the warehouse, decision variable
P_{2k}^{c}	PV capacity at location k (k=1 is the manufacturing facility and k=2 is the warehouse), decision variable
x_{ij}	quantity of product *i* made in period *j*, decision variable
y_{ij}	inventory of product *i* in period *j*, decision variable
z_{ij}	backorder of product *i* in period *j*, decision variable
o_{ij}	cost for producing unit *i* in period *j*
h_{ij}	cost for holding unit *i* in period *j*
b_{ij}	cost for backordering unit *i* in period *j*
$_{ij}$	transportation cost for unit *i* in period *j*
D_{ij}	demand for product *i* in period *j*
v_{is}	the amount of resource *s* consumed for making unit *i*
w_{sj}	total available resource of *s* in period *j*
q	the electric transport energy intensity rate
w^{p}	the payload per trip between factory and warehouse
w^{v}	the vehicle self-weight per trip factory and warehouse
d	the distance between factory and warehouse
n	the number of yearly trips between factory and warehouse
τ	number of hours in a year
a_g	capital cost for renewable energy type *k*
b_g	operation and Management cost for renewable energy type *k*
c_g	carbon credits for renewable energy type *k*
λ_{gjk}	capacity factor of month *j* and renewable energy type *g* at location *k*
e_i	energy consumed for each product type i
E	energy consumed by the warehouse
h	warehouse operation hours
C_{DG}	Total cost of the distributed generation system

Mathematical model

Problem P1

Minimize:

$$f(\text{x},\text{y},\text{z},\text{P}^c) = \sum_{i=1}^{m}\sum_{j=1}^{n}(o_{ij} + u_i)x_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n}h_{ij}y_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n-1}b_{ij}z_{ij} + C_{DG}(\text{x},\text{P}^c) \quad (4.9)$$

$$\text{Where } C_{DG} = \phi\sum_{g=1}^{G}a_g P_{gk}^c + \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G}b_g \lambda_{gjk} P_{gjk}^c - \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G}c_g \lambda_{gjk} P_{gjk}^c \quad (4.10)$$

Subject to:

$$x_{ij} - y_{ij} + z_{ij} \geq D_{ij}, \quad \text{for all } i \text{ and } j=1 \quad (4.11)$$

$$x_{ij} + y_{i,j-1} - y_{i,j} - z_{i,j-1} + z_{ij} \geq D_{ij}, \quad \text{for all } i \text{ and } j\geq 2 \quad (4.12)$$

$$\sum_{i=1}^{m} v_{is}x_{ij} \leq w_{sj}, \quad \text{for given } s= 1,2 \text{ , and } j= 1,2,..J \quad (4.13)$$

$$z_{i,J} = 0 \quad \text{for } i = 1,2, \text{ and } j = 1,2,\ldots J \quad (4.14)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}x_{ij}e_i + qnd(w^p + w^v) = \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G}\lambda_{1,gj}P_{1,gj}^c \quad (4.15)$$

$$hE + qnd(w^v) = \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G}\lambda_{2,gj}P_{2,gj}^c \quad (4.16)$$

$$P_{gjk}^c \geq 0., \; x_{ij}, y_{ij}, z_{ij} \geq 0 \quad (4.17)$$

In equation (4.9), it can be observed that if renewable energy is allowed to increase, more compensation will return to the company. Constraint (4.15) indicates that the total energy generated by the renewable energy system needs to be balanced with the total energy consumed by the manufacturing and the electrical vehicle at each month *j* and renewable energy type g . Let w^v be the weight of empty vehicle while w^p is the weight of each product transported. In this constraint, q is the transport energy intensity rate. Constraints (4.16) prescribes the total energy produced by onsite generation shall be equal to the total energy consumed by the warehouse and the e-vehicles where h is the yearly operation hours of the warehouse and E is power consumed by the warehouse. The last constraint (4.17) states that all the decision variables are non-negative and the production, inventory, and backorders variables are integer.

4.3. Climate Data

The generation WT and PV systems rely on the geographic location of the facilities to sustain the energy required for operation. Since the weather is unpredictable and impossible to control, the study of weather profile history is suggested to forecast the future seasonal weather conditions of specific locations.

For accurate analysis of the weather pattern, a data range of eleven years is utilized in the model. In order to demonstrate the varying types of climate conditions, the weather profiles are divided into different categories such as clear day, scattered cloud (SC), partially cloudy (PC), mostly cloudy(MC), overcast, rain, fog, storm/T-storm and snow. The average daily wind velocity in m/s is also gathered for a period range of eleven years. All the information about the weather conditions and wind speeds are retrieved from Weather Underground web portal (WU 2017). To demonstrate the previous conditions, two cities for each significant weather condition were selected due to their relative location from each other and their dramatic weather conditions.

4.3.1 Large wind locations. Voted as the world windiest city, Wellington is the best choice to test the model under large wind conditions. Wellington is the capital of

New Zealand with the second largest population in New Zealand. Located at the Roaring Forties and receive the wind blow from Cook Strait, it made Wellington become the windiest place in the world with the average wind speed of 7 m/s above the ground surface. Figure 4.2 is the histogram of Wellington weather conditions in 2016. Figure 4.3 presents the wind speed data for this city at a height of 80 meters.

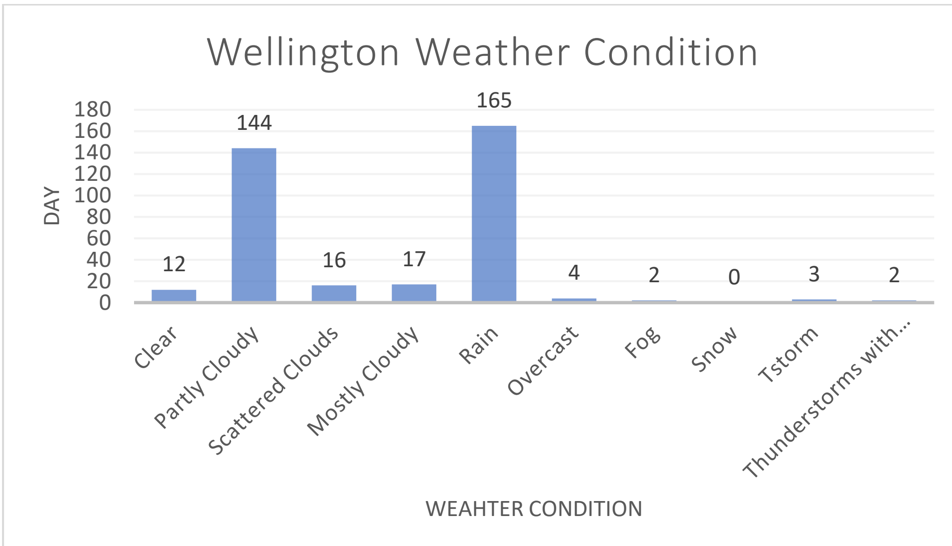

Figure 4. 2: Wellington Weather Condition in 2016

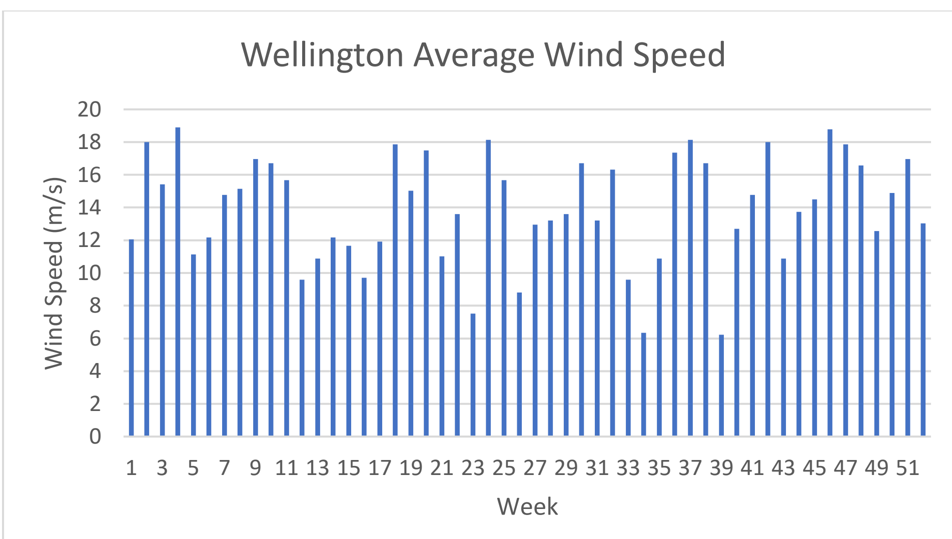

Figure 4. 3: Wellington Average Wind Speed at the Height of 80 Meters

Christchurch is located at the South Island of New Zealand and it is the largest city in the South. Located more than 500 kilometers south of Wellington, Christchurch is the third largest city in New Zealand, behind Auckland and Wellington. Below is the histogram of Christchurch weather conditions in 2016.

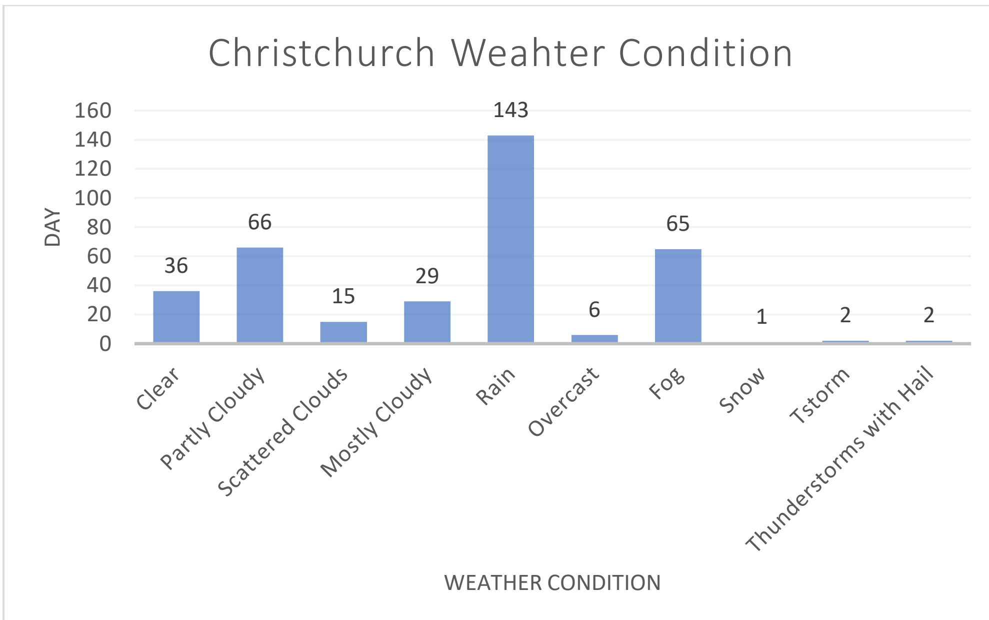

Figure 4. 4: Weather conditions of Christchurch in the 2016

4.3.2 Strong sun. The city of Aswan is an ideal location to test the model under mostly sunny weather conditions. Aswan is a city located in the south of Egypt, on the first bank of the Nile River. Aswan is known as one of the sunniest cities in the world. Average high temperature is steadily about 40 degrees in Celsius (104 ^{o}F) where the average low temperature is about 25 degrees in Celsius (77 ^{o}F)). Figures 4.5 and 4.6 are the histograms demonstrating the weather conditions and wind speed of Aswan in the year 2016, respectively.

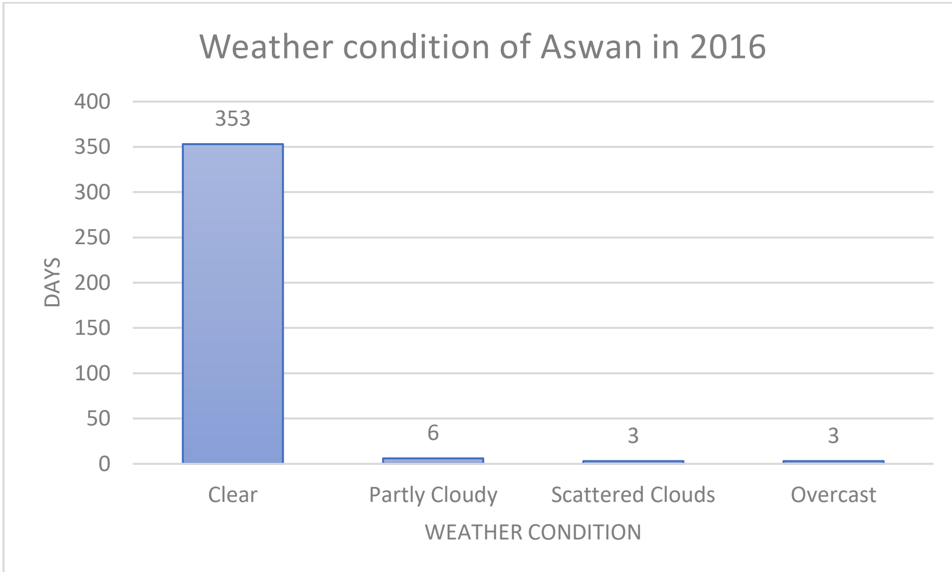

Figure 4. 5: Weather conditions of Aswan in 2016

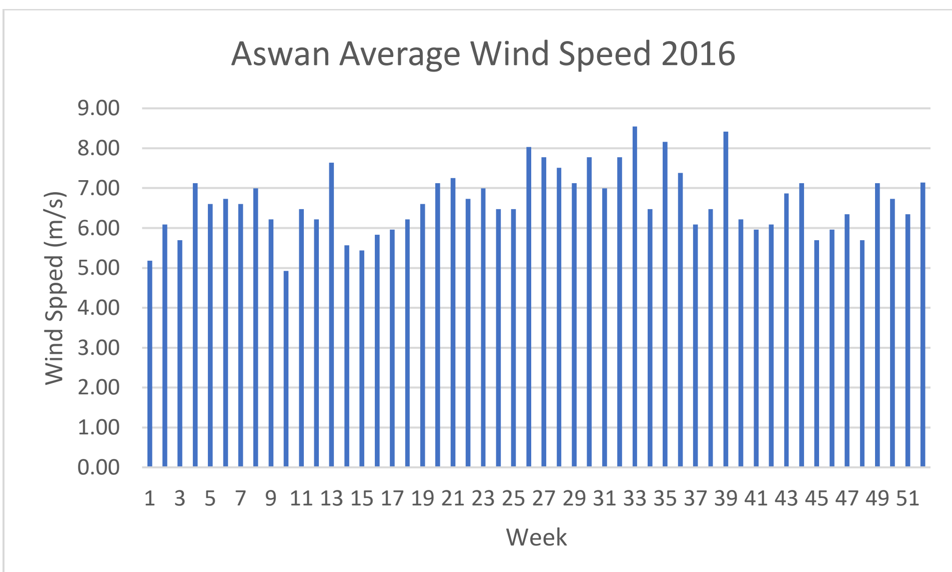

Figure 4. 6: Average Wind Speed of Aswan at the 80-meter height in 2016

The city of Luxor in Egypt is chosen due to its convenient location in southern Egypt (Upper Egypt) along the Nile river. Luxor is 239 km south of Asswan. Luxor has a similar climate as Asswan as it is also one of the sunniest city in the world. The city is one of the driest place on the Earth where rainfall does not occur very often. Average temperature of Luxor is between 22 ^oC (72 ^oF) and 40 ^oC (104 ^oF). Figures 4.7 and 4.8 are the histograms demonstrating the weather conditions and wind speed profile of Luxor in year 2016.

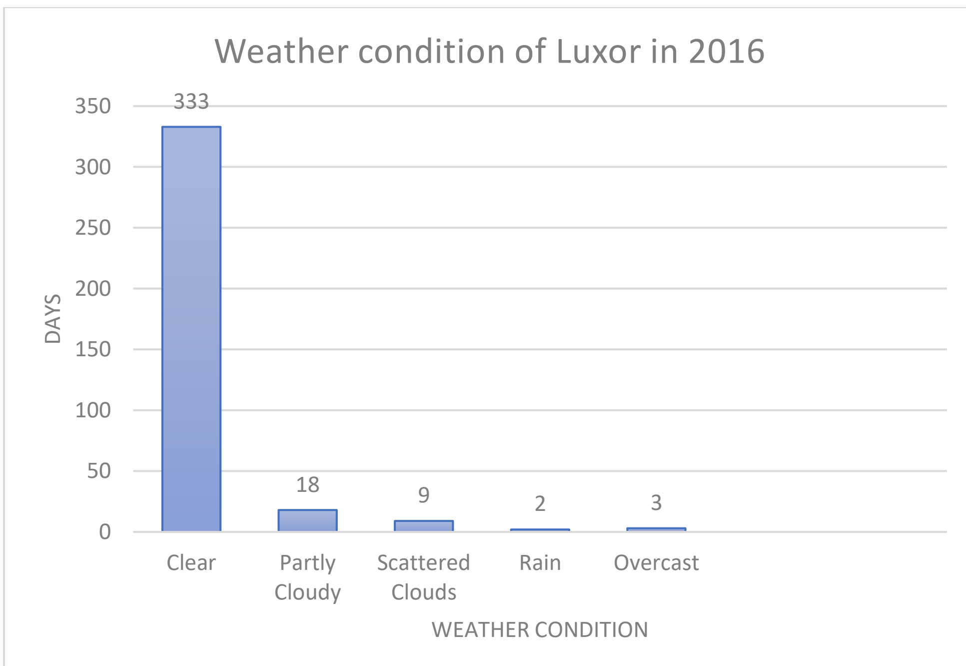

Figure 4. 7: Weather conditions of Luxor in 2016

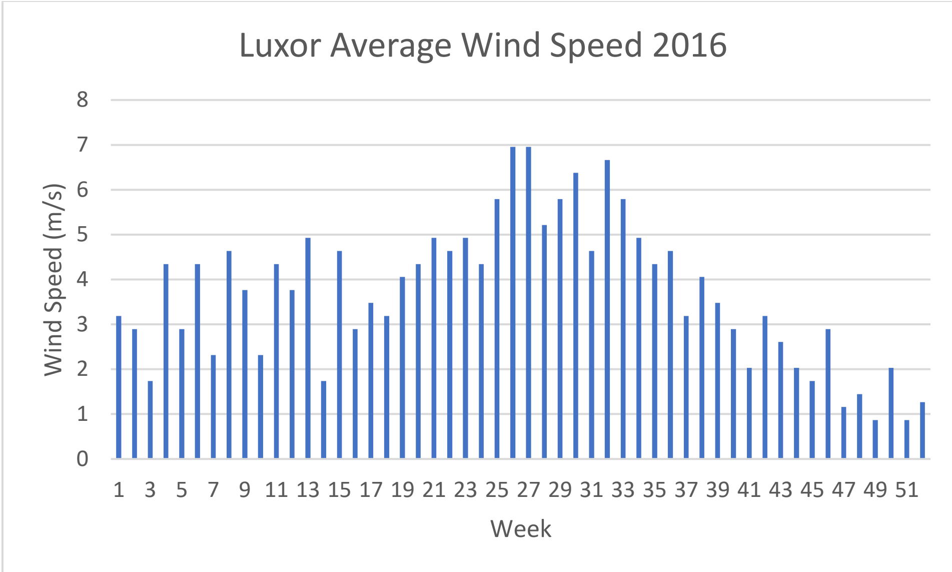

Figure 4. 8: Average Wind Speed of Luxor at the 80-meter height in 2016

4.3.3 Mix of large wind and strong sun. Yuma is located in the southwestern part of Arizona state. The city is known for its extreme weather pattern which features a hot desert climate. Yuma is the driest and sunniest city in the United States with annual average possible sunshine of 90 percent according to National Oceanic and Atmospheric Administration. The histogram graphs in Figures 4.9 and 4.10 illustrate the weather and wind conditions of Yuma in the year of 2016, respectively.

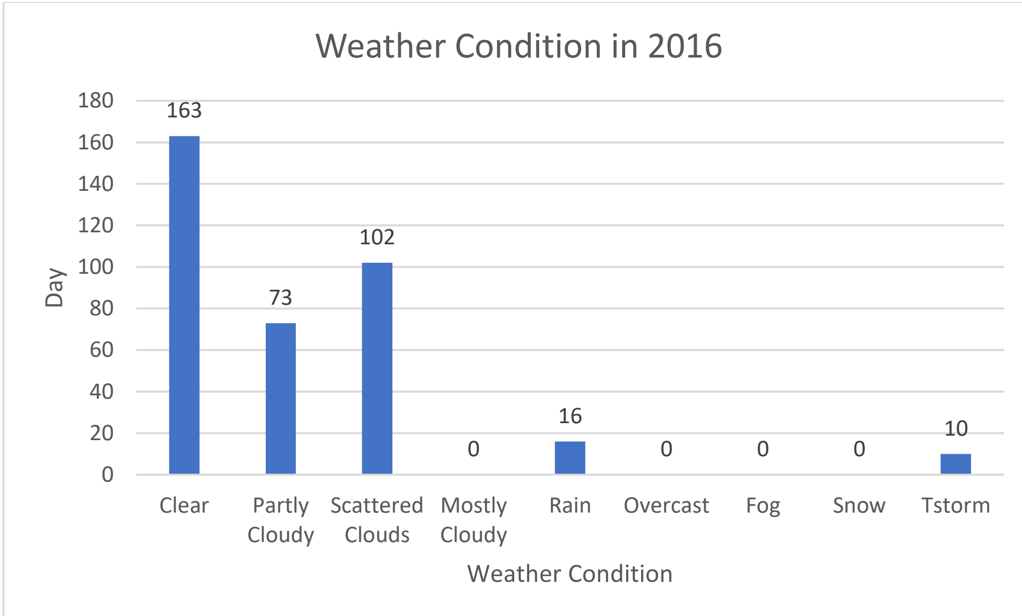

Figure 4. 9: Weather Condition of Yuma in 2016

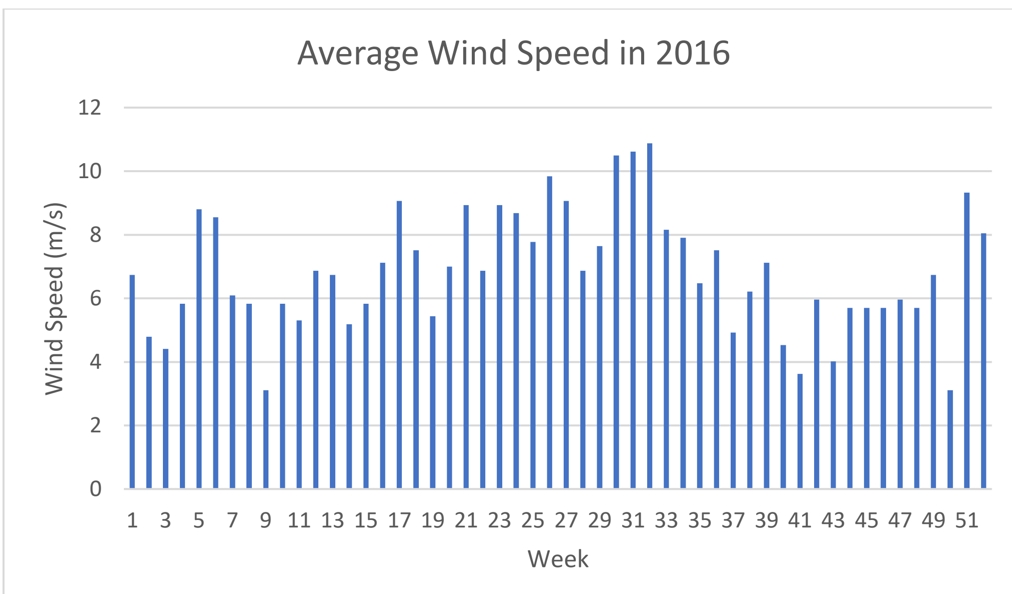

Figure 4. 10: Average Wind Speed of Yuma at the 80-meter height in 2016

San Francisco is a popular tourist destination in the U.S. Located in the north end of San Francisco Peninsula. It is known for its cool summers and diverse mix of architecture and landmarks. The climate of San Francisco is classified as Mediterranean Climate with dry, sunny, and warm summer while the weather condition in the winter is mild, wet, and occasionally stormy. The weather and wind conditions of San Francisco in 2016 are demonstrated in the Figures 4.11 and 4.12 below.

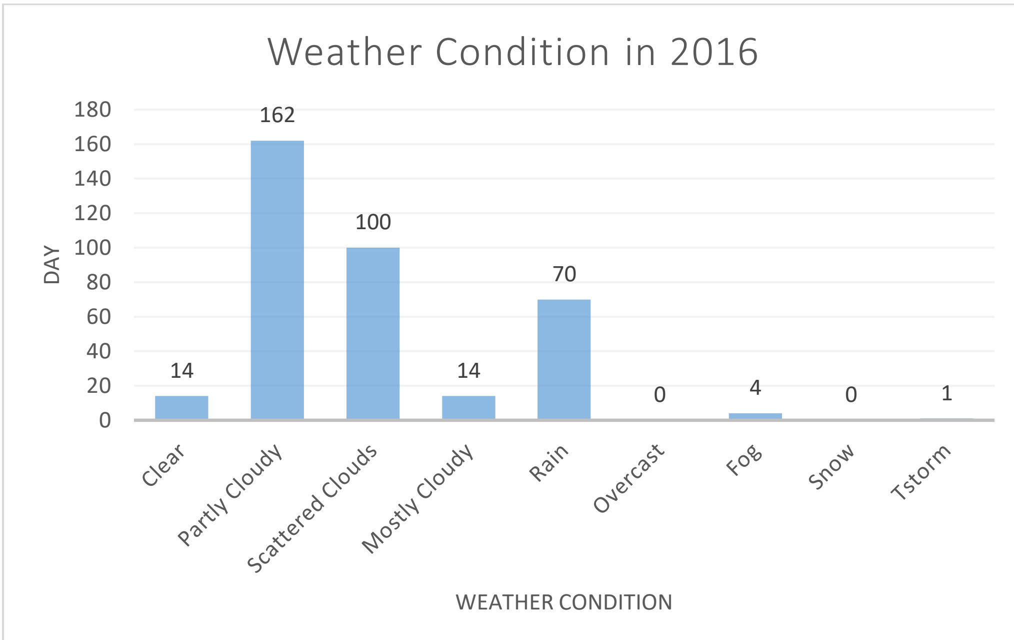

Figure 4. 11: Weather Condition of San Francisco in 2016

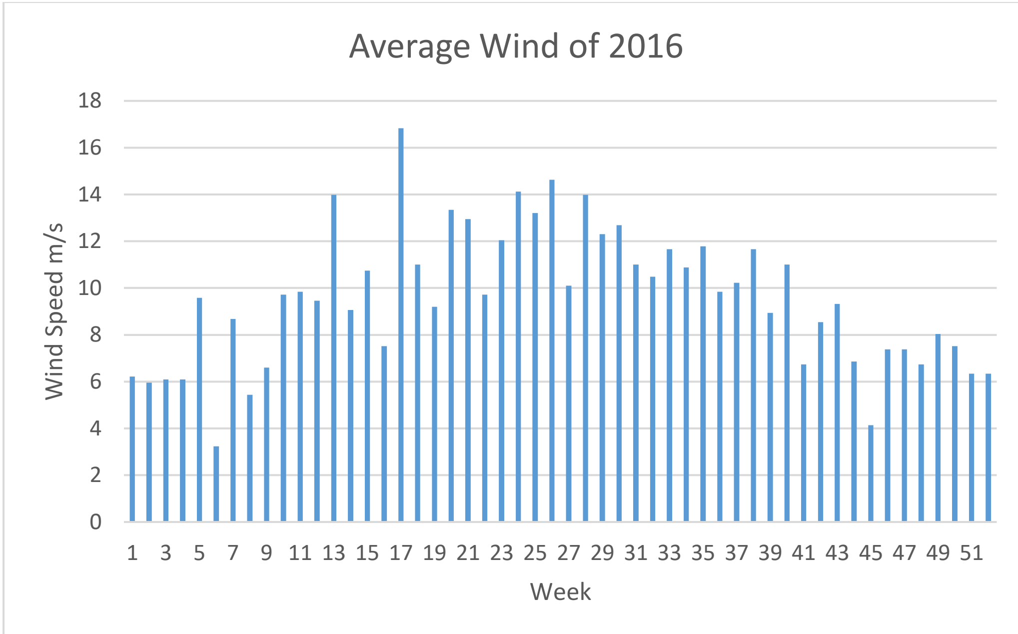

Figure 4. 12: Average Wind Speed of San Francisco at the 80-meter height in 2016

Weather conditions and wind speed for each city are collected to obtain historical data and capture a long range of climate conditions. In total, there are 4,015 daily wind speed measurements for each city and an overall total of 32,120 wind speed samples will be used to estimate the WT capacity factor for the model. Similarly, the daily weather conditions for each city are also collected with total of 4,015 data points for each city and a total of 32,120 observations for the time frame from 2006 to 2016 for the eight cities that are used in the model. The size of the data set used for the model is 64,240 data points. The average wind speed and weather conditions of six cities are demonstrated in Table 4.2 below.

Table 4. 2: Average Wind Speed and Weather Conditions of Six Cities

Country	New Zealand		Egypt		USA	
City	Wellington	Christchurch	Aswan	Luxor	Yuma	San Francisco
Latitude (Deg)	41.29	43.53	24.09	25.69	32.69	37.77
Ground AWS	6.71	3.84	5.93	1.44	2.97	4.05
Ground SWS	2.91	1.77	2.29	0.67	1.4	1.83
Clear days	6	20	356	337	165	28
Scattered Cloud	68	41	5	11	109	95
Partially Cloudy	109	98	3	14	65	136
Mostly Cloudy	5	11	0	0	0	13
Overcast	1	3	0	1	0	2
Rain	170	131	0	1	13	65
Fog	2	56	0	0	1	24
Storm/T-Storms	3	3	0	0	11	3
Snow	0	3	0	0	0	0

Note: AWS=average wind speed (m/s), SWS=standard deviation of wind speed (m/s).

As observed from the table, Wellington has strong wind velocity with AWS of 6.71 m/s, yet it only has 6 clear days. On the other hand, Luxor has 337 clear days but the average wind speed (AWS) is only 1.44 m/s. San Francisco has medium wind speed with AWS of 4.05 m/s and it has 28 clear days. Since the wind speeds and weather conditions of eight cities are diverse, they can represent the areas where most of the human beings reside.

4.3.4 Estimating capacity factor of wind turbine. Wind speed data shown in Table 4.3 usually are recorded and provided by the Automated Surface Observing Systems (ASOS) of the local airport which is often placed at 8-10 meters above the ground. However, we need to consider the height of the wind turbine to accurately calculate the turbine capacity factor. Using Hellmann exponent k=0.27 and the equation to calculate wind speed at specific height, mentioned in Section 3.1 (Chapter 3), the wind speed at h= 80 meter height would be $v_w(80)=v_g(80/10)^{0.34}=2.03v_g$. This is twice of the wind speed at h_g=10 m.

Table 4. 3: Wind Speed of Week 1 in Wellington (unit: m/s)

	Day	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006
10-m above ground	1	2.7	5.8	8.5	8.9	7.6	5.4	9.4	8.5	2.7	11.6	3.6
	2	4.0	5.8	8.5	12.5	6.7	8.9	11.6	8.5	7.2	11.6	10.7
	3	7.6	6.3	12.5	9.8	5.4	8.9	8.1	9.8	11.1	8.9	9.8
	4	11.6	6.3	9.4	4.0	6.3	8.1	9.4	4.5	6.3	3.6	10.2
	5	2.7	10.2	8.9	3.6	11.1	5.8	5.4	7.6	4.5	8.9	5.4
	6	4.0	6.7	7.6	5.8	8.1	5.8	10.7	10.7	8.5	12.5	4.5
	7	8.9	4.9	10.2	7.6	6.3	10.7	12.0	11.1	8.9	5.4	7.6
80-m tower	1	4.7	10.1	14.8	15.6	13.3	9.4	16.4	14.8	4.7	20.3	6.3
	2	7.1	10.2	14.9	21.9	11.8	15.7	20.4	14.9	12.5	20.4	18.8
	3	13.3	11.0	21.9	17.2	9.4	15.7	14.1	17.2	19.6	15.7	17.2
	4	20.4	11.0	16.5	7.1	11.0	14.1	16.5	7.8	11.0	6.3	18.0
	5	4.7	18.0	15.7	6.3	19.6	10.2	9.4	13.3	7.8	15.7	9.4
	6	7.1	11.8	13.3	10.2	14.1	10.1	18.8	18.8	14.9	22.0	7.8
	7	15.7	8.6	18.0	13.3	11.0	18.8	21.2	19.6	15.7	9.4	13.3

The wind speed data for the first week of Wellington city are used to demonstrate how to estimate the capacity factor (CF) of WT. The first section of the table lists the daily ground wind speed in Wellington between 2006 and 2016. Assuming k=0.27, the corresponding wind speed in 80-m height is calculated and the results are shown in the second section of the table. The typical height of a WT tower of 1.5 - 2.5 MW capacity is 80 meters. Figure 4.13 plots the weekly wind turbine CF for all the eight cities based on the 2.5 MW WT installation.

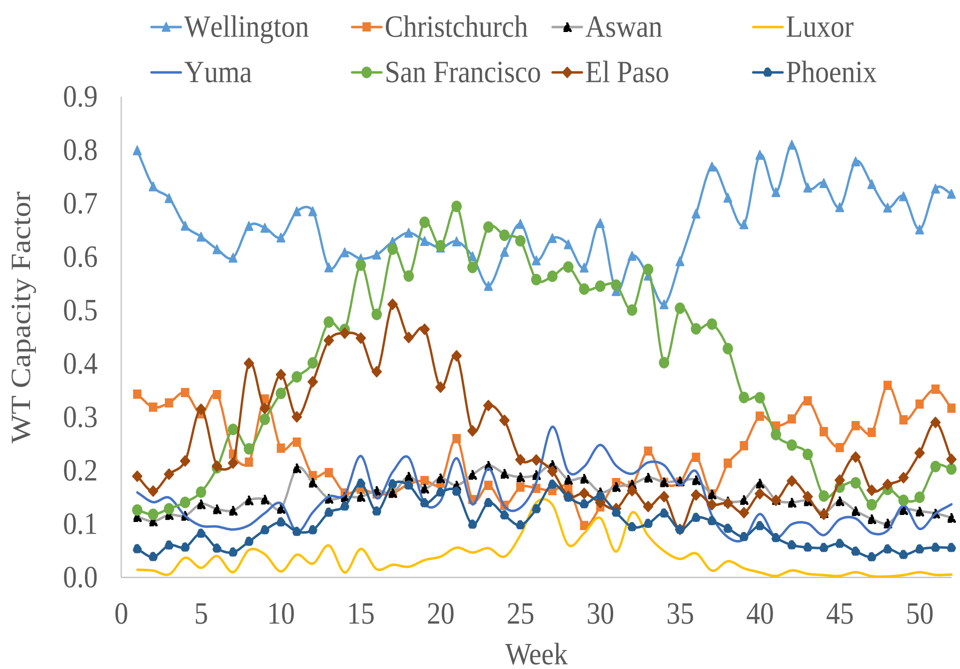

Figure 4. 13: Weekly Wind Turbine Capacity Factor of Eight Cities

4.3.5 Estimating capacity factor of solar PV. The daily weather conditions retrieved from the WU portal are broken down into eight states as clear, rain, partial cloud, scatter cloud, mostly cloudy, fog/storm, overcast, and snow. For illustration purposes, Table 4.4 lists the daily weather state of Week 1 in Wellington between 2006 and 2016.

Table 4. 4: Daily Weather Condition from 2006 to 2016 in Wellington

Day	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006
1	Clear	PC	Rain	SC	Rain	PC	SC	SC	SC	Rain	PC
2	Rain	SC	PC	PC	Rain	SC	PC	Rain	SC	Rain	Rain
3	Rain	Rain	Rain	SC	PC	SC	Rain	Rain	PC	PC	Rain
4	Rain	PC	Rain	SC	SC	PC	Rain	SC	PC	SC	Rain
5	Clear	PC	Rain	Clear	PC	Fog	SC	SC	SC	PC	Rain
6	PC	MC	PC	PC	PC	Rain	PC	PC	Rain	PC	Rain
7	PC	Rain	PC	PC	PC	PC	PC	PC	Rain	PC	PC

Based on the daily weather conditions, the number of days with a particular state can be counted, and the results are summarized in the last row in Table 4.5. For instance, the total number of "Clear" days for Week 1 in Wellington is 3 over eleven years, and the total number of "Rain" days is 25. For a given day in that week, the probability of a particular weather state now can be estimated. For instance, the probability of a "Clear" day is 3/77=0.04, and the probability of "PC" is 31/77=0.4. These probabilities are used to simulate the PV generation for Week 1 in Wellington.

Table 4. 5: The Probabilities of Weather States for Week 1 in Wellington

Day	Clear	SC	PC	MC	OC	Rain	Fog/Storm	Snow
1	1	4	3	0	0	3	0	0
2	0	3	3	0	0	5	0	0
3	0	2	3	0	0	6	0	0
4	0	4	3	0	0	4	0	0
5	2	3	3	0	0	2	1	0
6	0	0	7	1	0	3	0	0
7	0	0	9	0	0	2	0	0
Sum	3	16	31	1	0	25	1	0
Probability	**0.04**	**0.21**	**0.40**	**0.01**	**0.00**	**0.32**	**0.01**	**0.00**

Under the clear sky condition, the solar irradiance incident on PV surface, denoted as I_t (W/m^2), can be precisely estimated. The detailed steps to estimate I_t are provided in Chapter 3. The random output of PV is primarily caused by the uncertain weather states. To estimate the solar irradiance in different weather states, the weather coefficient W_t is introduced to quantifying the actual amount of I_t incident on the PV surface. For instance, if it is "Clear", W_t=1, meaning the PV receives 100 percent of I_t. If it is "PC," then only 50 percent of I_t reaches the PV surface. In a snowy day, W_t=0 because the PV surface is likely to be covered by snows. The values of W_t corresponding to different weather states are listed in Table 4.6. Now the actual PV generation can be estimated based on the PV capacity formula in Section 3.2 (Chapter 3).

Table 4. 6: Weather Coefficients under Different States

No.	1	2	3	4	5	6	7	8
State	Clear	SC	PC	MC	Overcast	Rain	Fog/Storm	Snow
W_t	1	0.7	0.5	0.3	0.2	0.1	0.1	0

We developed a Matlab program to simulate the daily weather state for eight cities. The PV generation is averaged over a week, and then divided by the rated PV peak power to obtain the capacitor factor. This simulation process is repeated for 52 times to obtain the weekly capacity factor in each city across a year. To reduce the simulation variability, the 52-week simulation run is repeated over 100 years, and the capacity factor is obtained by dividing the weekly PV energy over its rated capacity. Figure 4.14 plots the weekly PV capacitor factors of eight cities. The CF of Aswan and Luxor is above 0.4 on average, while the lowest CF occurs in Wellington and Christchurch with the average below 0.15.

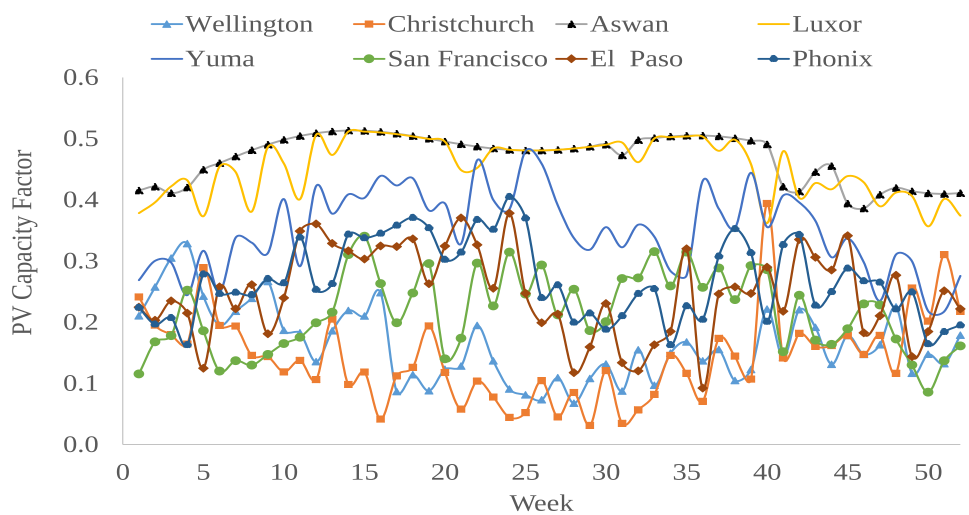

Figure 4. 14: The Weekly Solar PV Capacity Factor of Eight Cities

4.4. Numerical Experiment

4.4.1 Background. A numerical experiment is constructed based on a single manufacturing-warehouse system as seen in Figure 4.1. Production data used for this research are associated with electricity intensive manufacturing processes, such as a semiconductor fab facility which operate 24 hours and 7 days a week. There are two types of products considered with different demands for each period: product A and product B. The production demand for 52 weeks, one-year period is presented in Figure

4.15. Parameters associated with production, inventory, backorder and transportation logistics are shown in Table 4.7.

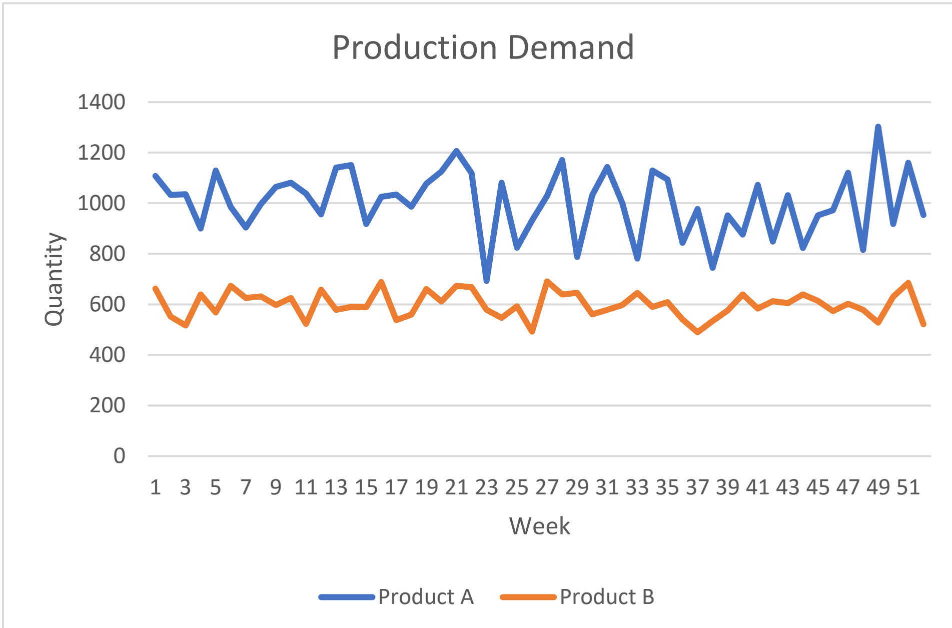

Figure 4. 15: Production Demand of Product A and Product B

Table 4. 7: Production, Inventory, Backorders, Logistics and Energy Data

Comments	Notation	Product A (i=1)	Product B (i=2)	Unit
Energy consumed	e_i	0.9	1.2	MWh/unit
Production cost (w.o.* energy)	p_i	400	600	$/unit
Holding cost	h_i	80	120	$/period/unit
Backlog cost	b_i	150	250	$/unit
Shipping cost (no EV recharge)	π_i	10	15	$/unit
Shipping cost (with EV recharge)	π_i	14	19	$/unit
Labor hours/item	v_{i1}	16	24	hours/unit
Machine hours	v_{i2}	100	200	hours/unit
Weight (including package)	m_i	3	4	Kg/unit
Mean demand	$\mu_{D_{ij}}$	1000	600	units/period
Standard deviation	$\sigma_{D_{ij}}$	120	50	units/period

*w.o.=without

Table 4. 8: Machine and Labor Resources in the Factory

Week	Labor Resource (hours)	Machine or Tool Resource Hours	Week	Labor Resource (hours)	Machine or Tool Resource (Hours)
1	38,516	278,847	27	37,860	279,542
2	34,429	244,299	28	39,153	281,016
3	33,472	239,044	29	32,345	237,514
4	34,210	248,699	30	34,562	249,292
5	36,680	261,478	31	36,814	263,851
6	36,660	269,935	32	35,001	251,627
7	34,063	249,447	33	32,159	239,152
8	35,786	261,961	34	37,138	269,049
9	36,243	261,441	35	36,784	267,032
10	36,989	268,359	36	30,487	223,362
11	33,739	240,138	37	31,639	226,421
12	35,560	263,343	38	28,497	208,141
13	36,920	262,138	39	33,601	241,714
14	37,695	268,946	40	33,727	249,509
15	33,051	240,437	41	35,735	259,884
16	38,113	276,789	42	32,750	237,912
17	33,914	241,252	43	35,657	257,745
18	33,569	243,591	44	32,635	240,033
19	38,010	274,606	45	34,452	249,525
20	37,688	270,170	46	33,684	244,778
21	40,853	291,900	47	37,094	267,545
22	38,946	283,740	48	30,751	226,419
23	28,867	215,059	49	38,739	270,781
24	34,891	248,255	50	34,252	250,829
25	31,466	230,446	51	40,363	292,169
26	30,652	219,114	52	32,078	230,129

As mentioned in the problem statement, e-trucks are used to transport finished goods between the factory and the warehouse. The self-freight of the truck is w_v= 5,000 kg, and the electric vehicle energy intensity rate is q_v =1.19×10^{-7} MWh/kg/km (Section 3.3). The annual electricity demand of the warehouse is L = 7 MW on average and the yearly operating hours is t_w = 8,760 hours. Assume the truck will travel n_k = 186 round trips per year from factory to warehouse and back (i.e. once every two days). In this model, the maximum driving range d_{max} = 150 km is assumed for the e-truck. Two critical resources for the production are the labor hours and machine hours. Table 4.8 presents the available resources over a 52-week horizon in the factory. Since the actual production resources are confidential to wafer fabs, these data are estimated based on the working experience of one of the authors in the paper in Pham et al. (2017).

Data associated with installation, maintenance and carbon credits of WT and PV systems are listed in Table 4.9. Though the actual values may vary, the presented values are derived based on the studies by Freris and Infield (2008) and NREL report (2013). Today the efficiency of most commercial PV panels can be η=0.15. In the northern hemisphere, the PV is usually oriented to the South, whth an azimuth angle α=0 rad. It is the opposite if the PV is located in the southern hemisphere. In addition, a lifetime n_e=20 years are usually assumed for WT and PV. In this research, we consider the loan period of WT and PV is n_e = 20 years with the interest rate i_e= 0.05. The unit for power and energy are MW and MWh where 1 MW=10^3 kW=10^6 W, and 1 MWh=10^3 kWh=10^6 Wh.

Table 4. 9: Cost and Operation Parameters of WT and PV systems

WT			PV		
Symbol	Value	Unit	Symbol	Value	Unit
a_g	1.5×10^6	\$/MW	a_g	3×10^6	\$/MW
b_{gj}	10	\$/MWh	b_{gj}	8	\$/MWh
c_{gj}	0	\$/MWh	c_{gj}	35	\$MWh
τ_g	168	hour/period	τ_g	84	hour/period
v_c	3	m/s	η	0.15	N/A
v_r	12	m/s	T_o	45	^{o}C
v_s	25	m/s	α	0	rad
n_e	20	Year	n_e	20	year
i_e	0.05	n/a	i_e	0.05	n/a

4.4.2 Result Analysis and Discussion. To implement the problem, the mathematical model is coded using a Modeling Language for Mathematical optimization (AMPL). The optimization tool used is CPLEX solver running in AMD Radeon R6 processor, 1800 Mhz, 4 logical processors, and maximum of 12 gigabytes RAM. The model has a total of 316 variables which include production, inventory, and backorders for Products A and B as well as the power grid capacity for both manufacturing plant and warehouse. Parameters of the problem are set up as matrix in a data file and can be easily changed or adjusted directly. The same model is also implemented in Excel Solver to confirm the result generated from AMPL. As a result, the two solvers provide similar outcomes to the problem. Figures 4.17 and 4.18 present the outcome for the production and inventory levels for Products A and B which meet the deterministic demand for each week. The objective values and distributed generation capacities for both models are displayed in Table 4.11.

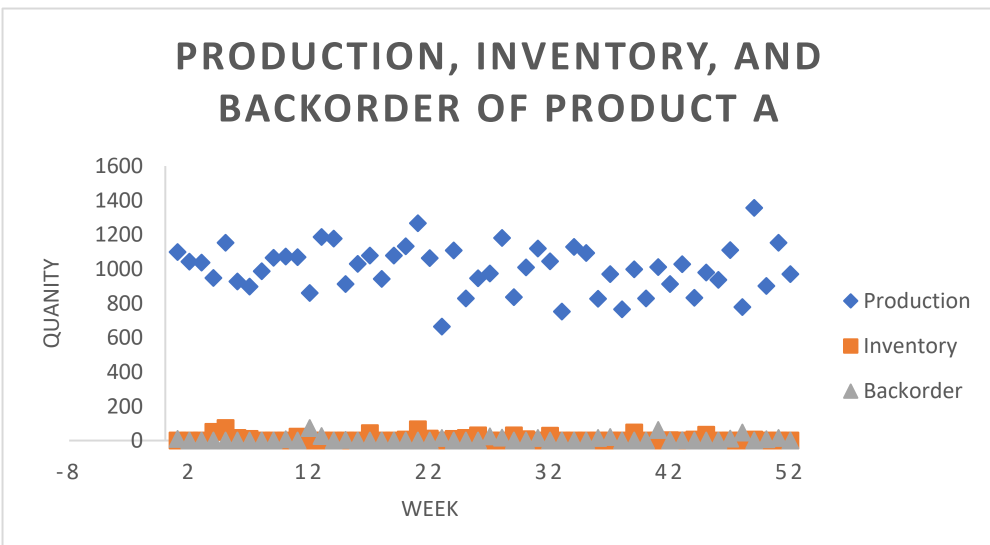

Figure 4. 16: Production, Inventory, and Backorder of Product A

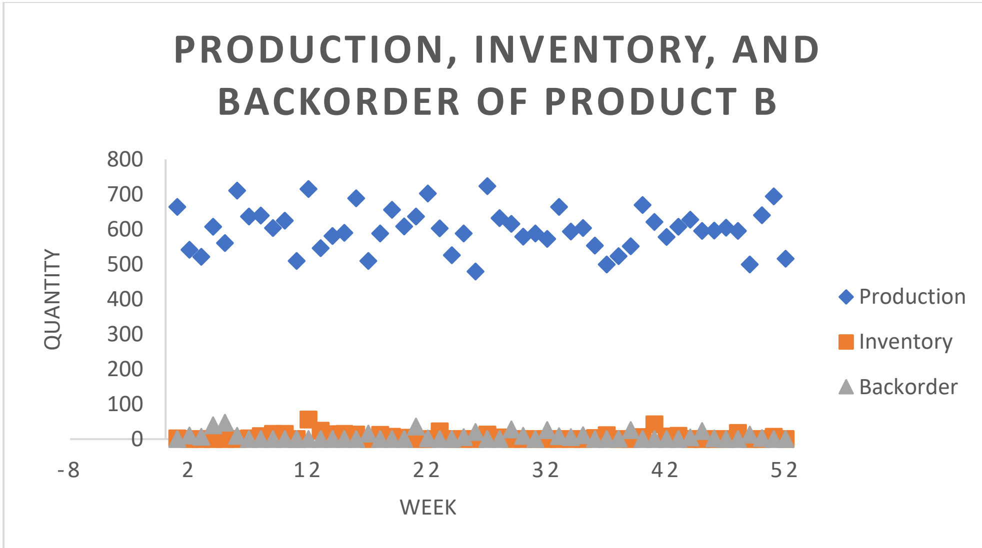

Figure 4. 17: Production, Inventory, and Backorder of Product B

Table 4. 10: Factory and Warehouse locations

Case	Factory	Warehouse
Large wind (New Zealand)	Wellington	Christchurch
Strong sun (Egypt)	Aswan	Luxor
Mixed strong sun and large wind (U.S.)	Yuma	San Francisco

Table 4. 11: Optimal Solutions of Onsite Generation Capacity

	Factory		Warehouse		
Scenario	**Type**	**DG capacity**	**Type**	**DG Capacity**	**Total Cost**
Large Wind	WT	14.74 MW	WT	30.1077 MW	$46,643,700.00
Strong Sun	PV	40.85 MW	PV	30.59 MW	$53,032,600.00
Mixed Large Wind and Strong Sun	WT	66.87 MW	WT	18.18 MW	$51,480,500.00

In the large wind case (Wellington and Christchurch) which has the highest levels of WT capacity factors, we solve the mathematical model and the optimal cost is $46,643,700.00. Given the carbon credit of $35/MWh for PV, the model chooses WT due to the large wind condition in Wellington and Christchurch. Hence the resulting aggregate installed capacity of WT in the factory is 14.74 MW and 30.11 MW for the warehouse location.

The climate conditions in the strong sun location has low wind speed in both the factory and warehouse sites. Even though WT installation cost is much lower than PV, the model still chooses PV due to the given strong solar irradiance of Aswan and Luxor. The installed capacity of PV in factory is 40.85 MW and at the warehouse is 30.59 MW. The total annualized cost of the strong sun case is $53,032,600.

In the last case, mixed large wind and strong sun, the factory is located in Yuma, Arizona with high solar irradiance, and the warehouse is in San Francisco with large wind speed. In this mixed case, the model chooses WT for both the factory and warehouse system. The outcome can be explained as follows. Even though Yuma has strong sun, the model still chooses WT due to the low cost of WT system and the large number of operation hours for the WT as it can generate power in 24/7. The resulting aggregate installed capacity of WT in the factory is 66.87 MW and the capacity of WT in the warehouse is 18.18 MW.

4.5 Conclusion

The study presented in this chapter was conducted at a practical level to represent the operational conditions of real zero-carbon supply chains as much as possible. Wind turbine (WT) and photovoltaic (PV) are alternative clean power sources which replace traditional energy sources. Real data is collected in different cities, and a linear multi-period production inventory model is used to find the minimum total cost (objective function value) and the wind turbine (WT) capacity, photovoltaic (PV) capacity, production, inventory, and backorders in each period (decision variables). This chapter focused on chasing the most economic efficient way to replace traditional energy with renewable energy to meet the factory and warehouse demands. The results from various scenarios with data from different cities show that wind and PV generation is a proven technology for manufacturing factories and warehousing activities to meet the electricity consumption needs. As a result, the facilities can avoid borrowing electricity from main grid when there is no wind or solar power available. In the next chapter, the model will be extended to stochastic product demand under a multi-factory and single-warehouse environment.

V. INTEGRATING MICROGRID POWER FOR NET-ZERO ENERGY PRODUCTION-LOGISTICS WITH DEMAND UNCERTAINTY

5.1 Model Setting

In this chapter, the model setting is similar to Chapter 4 as e-trucks will be employed to ship finished goods from factories to warehouse. The facilities and e-trucks will be powered by the onsite microgrid system. Each microgrid system is comprised of several WT units and (or) solar PV arrays. It is assumed that the distance between two adjacent facilities is large enough so that wind profiles and weather conditions are not correlated. In this chapter, we will also consider the adoption of a charging station on the route between factories and warehouse. Assume the e-truck will charge its battery before departing the facilities. If the maximum driving range is smaller than the distance between two facilities, charging stations are available on route to recharge the vehicle batteries. With this setting in mind, we aim at designing a net-zero carbon zone across manufacturing, transportation, and warehousing facilities at minimum cost.

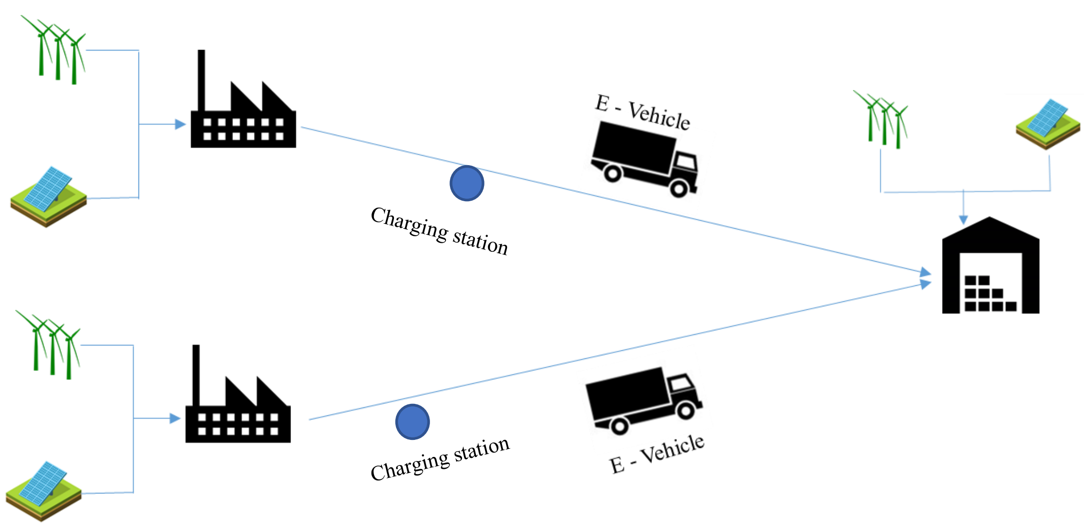

Figure 5. 1: Multi-Factory and One Distribution Center with Microgrid Generation

Since the daily wind speed and the weather conditions are stochastic, the output power of the microgrid system at a random point in time may be above or below the facility's electricity load. If the output power is less than the load, the gap is fulfilled by importing the electricity from the main grid. In order to attain net-zero energy criteria, this "borrowed" electricity must be "returned" later on. This can be realized, for instance, when large wind speed or strong sunshine prevails in certain days, making the microgrid system to produce surplus energy. Feed-in-tariff and net-metering are the two market schemes that enable the surplus electricity to be fed into the main grid. The production-logistics system achieves the net-zero energy performance if the "borrowed" electricity is offset by the surplus microgrid energy during the course of a year. Before presenting the optimization model, the related notation is summarized in Table 5.1 below.

Table 5. 1: Model Parameters and Decision Variables

Notation	Description
I	=Total number of products
J	=Total number of production periods
K	=Total number of facilities where k=0 for the warehouse
G	=number of renewable generation sources, for g=1, 2, .., G
R	=number of resources required for producing the products, for r=1, 2, .., R
p_{ijk}	=cost of making a unit of product i in period j in facility k ($/unit)
h_{ij}	=unit holding cost of product i in period j ($/unit-period)
b_{ij}	=unit backorder cost of product i in period j ($/unit)
π_{ik}	=cost of shipping a unit of product i from facility k to the warehouse ($/unit)
v_{iks}	=resource s consumed for making a unit of product i in facility k
w_{sjk}	=available resource of s in period j in facility k
q_v	=electric transport energy intensity rate (MWh/kg/km)
w^p	=the payload per trip between factory and warehouse (kg)

w^v	=vehicle self-weight (kg)
d_k	=distance between factory *k* and the warehouse (km)
D_{ij}	=demand for product *i* in period *j*
$\mu_{D_{ij}}$	=mean demand for product *i* in period *j*
$\sigma_{D_{ij}}$	=standard deviation of demand for product *i* in period *j*
n	=number of yearly trips between factory and warehouse
t_w	=annual operating hours of the warehouse (hours)
τ_g	=number of hours of generation *g* (hours) in each production period
a_g	=capacity cost for renewable generation *g* ($/MW)
b_g	=operation and maintenance cost for renewable generation *g* ($/MWh)
c_g	=carbon credits for renewable generation *g* ($/MWh)
λ_{jgk}	=capacity factor of renewable generator *g* in period *j* at location *k*
e_{ik}	=energy consumed for producing one unit of product *i* (MWh/unit)
L	=electricity demand (load) of the warehouse (MW)
γ	=probability that the product demand is met
ϕ	=capital recovery factor
w_v	=self-weight of the e-truck
ζ	=random wind profile and solar incidence on PV

Decision Variable	Description
x_{ijk}	=quantity of product *i* made in period *j* in facility *k*
y_{ij}	=inventory of product *i* in period *j* in the warehouse
z_{ij}	=backorder of product *i* in period *j*
P^c_{gk}	=capacity of generation source *g* in facility *k*

5.2 A Stochastic Optimization Model

We design a production-logistics system comprised of multiple factories and one central warehouse which are powered entirely by onsite WT and PV systems. Each factory will manufacture two types of product A and B. The finished goods from both factories will then be shipped to the warehouse using e-truck. The objective of this study is to determine the production quantity, inventory level, and backorders such that the uncertain demands (stochastic demands) in each period are satisfied. Demand uncertainty reflects uncertainty of customer demand for a product and **it does not have stability**. To achieve the net zero energy target, the generation capacity of onsite microgrid systems is also optimized so that the cost of the entire production-logistics system including energy is minimized. Denote as Problem P2, the stochastic planning model formulated as follows

Problem P2:

Minimize:

$$f(\mathrm{x},\mathrm{y},\mathrm{z},\mathrm{P}^c)=\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(p_{ijk}+\pi_{ijk})x_{ijk}+\sum_{i=1}^{I}\sum_{j=1}^{J}h_{ij}y_{ij}+\sum_{i=1}^{I}\sum_{j=1}^{J-1}b_{ij}z_{ij}$$
$$+\phi\sum_{g=1}^{G}\sum_{k=0}^{K}a_g P_{gk}^c+E_\zeta\sum_{g=1}^{G}\sum_{k=0}^{K}\sum_{j=1}^{J}\left(b_g\tau_{gk}P_{gk}(\zeta)-c_g\tau_{gk}P_{gk}(\zeta)\right) \quad (5.1)$$

Subject to:

$$\Pr\left\{\sum_{k=1}^{K}x_{ik,1}+y_{ik,0}-y_{ik,1}+z_{ik,1}<D_{i1}\right\}\le 1-\gamma \text{ ; for } j=1, \text{ and } \forall i \quad (5.2)$$

$$\Pr\left\{\sum_{k=1}^{K}x_{ijk}+y_{ij-1,k}-y_{ijk}-z_{ij-1,k}+z_{ijk}<D_{ij}\right\}\le 1-\gamma \text{ ; for } j=2,3,..,J\text{-}1, \text{ and } \forall i$$

(5.3)

$$\Pr\left\{\sum_{k=1}^{K}x_{iJk}+y_{iJ-1,k}-y_{iJk}-z_{iJ-1,k}<D_{iJ}\right\}\le 1-\gamma\text{ ;} \qquad \text{for } j=J, \text{ and } \forall i \quad (5.4)$$

$$\sum_{i=1}^{I}v_{ikr}x_{ijk}\le w_{jkr}, \qquad \text{for } \forall j,\ \forall r, \text{ and } k=1,2..,K \quad (5.5)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(e_{ik}+q_v d_k m_i)x_{ijk}+q_v n_k d_k w^v=E_\zeta\sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gk}P_{gk}(\zeta)\text{, for } k=1,2\ \ldots,K.$$

(5.6)

$$t_w L + \sum_{k=1}^{K} q_v n_k d_k w_v = E_\zeta \sum_{j=1}^{J} \sum_{g=1}^{G} \tau_{g0} P_{g0}(\zeta) \text{, for } k=0. \quad (5.7)$$

$$z_{iJ} = 0, \qquad \text{for } \forall i; \quad (5.8)$$

$$P_{gk}^{c} \geq 0, \qquad \text{for } k=0, 1, 2, \ldots, K, \text{ and for } g=1, 2, \ldots, G \quad (5.9)$$

x_{ijk}, y_{ij}, z_{ij} are non-negative integers (5.10)

Problem P1 is a mixed-integer stochastic programming model due to the uncertainties in product demand. The product quantity, inventory level, and backorders for each production period are decision variables that are denoted as *x, y,* and *z*. $\mathbf{P}^c$ are the decision variables to determine the power capacity of WT and PV in each facility. Objective function (5.1) intends to minimize the total cost of manufacturing, warehousing, transportation, and energy. The first three summations demonstrate the cost of production, inventory, and backorders. The last two summations represent the costs associated with onsite microgrid systems which include installation cost, operation and management cost, and carbon credits. The expected cost of microgrid systems is adopted to accommodate the intermittency of wind and solar generation.

There are nine constraints in the model. Constraints (5.2) to (5.4) are chance constraints that represent production, inventory, and backorder level meeting the product demand, and γ is the service level represented by the probability of meeting the uncertain demand. Backorders are not permitted in the first and last production period, then z_{i0}=0, and z_{iJ}=0. Constraint (5.5) is to ensure that the resource *r* used to make product *i* in period *j* at factory *k* cannot exceed the available resource capacity. Constraint (5.6) is the energy balance equation which states that the annual electricity consumed by the factory *k* and e-vehicle need to be counterbalanced with the renewable energy generated by onsite microgrid system. The same logic is applied to constraint (5.7) where it states that the total energy consumed by the warehouse and e-truck is offset by the onsite microgrid energy. Constraints (5.9) and (5.10) simply define the non-negativity of x_{ijk}, y_{ij}, z_{ij}, and P^c_{gk}.

5.3 Heuristic Approach to Solve Stochastic Optimization Model

Since Problem P2 is a mixed-integer stochastic programming model with chance constraints, it is difficult to be solved analytically. To made the problem tractable, we propose a heuristic approach in which we convert the chance constraints into deterministic counterparts. Assuming that the product demand is normally distributed in each period, let $\mu_{D_{ij}}$ and $\sigma_{D_{ij}}$ be the mean and the standard deviation of the demand for product i in period j, D_{ij}. Constraints (5.2) -(5.4) can be translated into deterministic constraints as follows:

$$\sum_{k=1}^{K} x_{i1} + y_{i0} - y_{i1} + z_{i1} \geq \mu_{D_{i1}} - Z_{1-\gamma}\sigma_{D_{i1}}; \qquad \text{for } j=1, \text{ and } \forall i \tag{5.11}$$

$$\sum_{k=1}^{K} x_{ij} + y_{ij-1} - y_{ij} - z_{ij-1} + z_{ij} \geq \mu_{D_{ij}} - Z_{1-\gamma}\sigma_{D_{ij}}; \quad \text{for } j=2, 3, .., J\text{-}1, \text{ and } \forall i \tag{5.12}$$

$$\sum_{k=1}^{K} x_{iJ} + y_{iJ-1} - y_{iJ} - z_{iJ-1} \geq \mu_{D_{iJ}} - Z_{1-\gamma}\sigma_{D_{iJ}}; \qquad \text{for } j=J, \text{ and } \forall i \tag{5.13}$$

Where $Z_{1-\gamma}$ is the Z-value of the standard normal distribution at probability of 1-γ. For our study, we choose γ=0.9 which has $Z_{1-\gamma}$ =1.28. As the result, we replace the chance constraint in Problem 1 with the deterministic constraints. Denote as Problem P3, the new model is formulated as follows:

Problem P3

Minimize:

$$f(\mathrm{x,y,z,P}^c) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(p_{ijk} + \pi_{ijk})x_{ijk} + \sum_{i=1}^{I}\sum_{j=1}^{J} h_{ij} y_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J-1} b_{ij} z_{ij} + \phi \sum_{g=1}^{G}\sum_{k=0}^{K} a_g P_{gk}^c + E_\zeta \sum_{g=1}^{G}\sum_{k=0}^{K}\sum_{j=1}^{J}\left(b_g \tau_{gk} P_{gk}(\zeta) - c_g \tau_{gk} P_{gk}(\zeta)\right) \quad (5.14)$$

Subject to:

$$\sum_{k=1}^{K} x_{i1} + y_{i0} - y_{i1} + z_{i1} \geq \mu_{D_{i1}} - Z_{1-\gamma}\sigma_{D_{i1}}; \quad \text{for } j=1, \text{ and } \forall i \quad (5.15)$$

$$\sum_{k=1}^{K} x_{ij} + y_{ij-1} - y_{ij} - z_{ij-1} + z_{ij} \geq \mu_{D_{ij}} - Z_{1-\gamma}\sigma_{D_{ij}}; \quad \text{for } j=2, 3, .., J\text{-}1, \text{ and } \forall i \quad (5.16)$$

$$\sum_{k=1}^{K} x_{iJ} + y_{iJ-1} - y_{iJ} - z_{iJ-1} \geq \mu_{D_{iJ}} - Z_{1-\gamma}\sigma_{D_{iJ}}; \quad \text{for } j=J, \text{ and } \forall i \quad (5.17)$$

$$\sum_{i=1}^{I} v_{ikr} x_{ijk} \leq w_{jkr}, \quad \text{for } \forall j, \ \forall r, \text{ and } k=1, 2.., K \quad (5.17)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(e_{ik} + q_v d_k m_i)x_{ijk} + q_v n_k d_k w^v = E_\zeta \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gk} P_{gk}(\zeta), \text{ for } k=1, 2 \ldots, K. \quad (5.18)$$

$$t_w L + \sum_{k=1}^{K} q_v n_k d_k w_v = E_\zeta \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{g0} P_{g0}(\zeta), \quad \text{for } k=0. \quad (5.19)$$

$$z_{iJ} = 0, \quad \text{for } \forall i; \quad (5.20)$$

$$P_{gk}^c \geq 0, \quad \text{for } k=0, 1, 2, \ldots, K, \text{ and for } g=1, 2, \ldots, G \quad (5.21)$$

x_{ijk}, y_{ij}, z_{ij} are non-negative integers (5.22)

The steps to solve Problem P3 are presented as a flow chart. The purpose is to depict how one can solve the model starting at collecting weather data at each facility, calculate the capacitor factor data, and then merge the data into the model to get the optimal results. Figure 5.2 shown below is the problem-solving process chart.

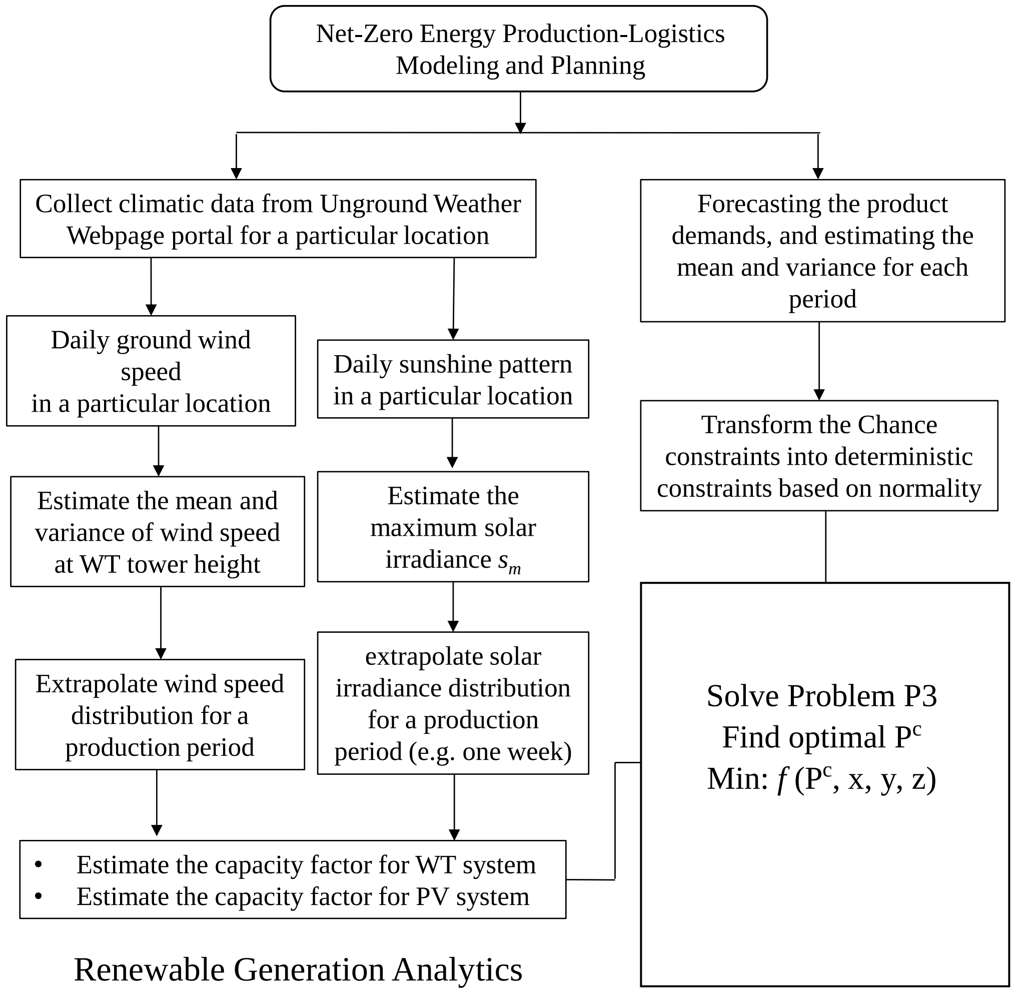

Figure 5. 2: Process Chart to Solve the Model (Pham et al. 2017)

5.4 Numerical Experiment for Single Factory – Single Warehouse Model

5.4.1 Problem setting and data. We first implement P3 on a single factory and a single warehouse setting. Similar to Chapter 4, the production data used for this experiment are also associated with the wafer production facilities that operate in 24/7 mode. Two types of products are manufactured at the factory which are Product A and Product B. The product demands for each week are uncertain but follow a normal distribution. The mean demand for Product A per week is 1,000 units with the standard deviation of 120 units. The mean demand for Product B per week is 600 units with standard deviation of 50 units. The parameters associated with production, inventory, backorders, transportation, and energy which are used to solve Problem P1 (Chapter 4) will also be applied to solve Problem P2. For the reader convenience, the parameters are listed again in Tables 5.2-5.4 below.

Table 5. 2: Cost and Operation Parameters of WT and PV systems

WT			PV		
Symbol	Value	Unit	Symbol	Value	Unit
a_g	1.5×10^6	$/MW	a_g	3×10^6	$/MW
b_{gj}	10	$/MWh	b_{gj}	8	$/MWh
c_{gj}	0	$/MWh	c_{gj}	35	$MWh
τ_g	168	hour/period	τ_g	84	hour/period
v_c	3	m/s	η	0.15	N/A
v_r	12	m/s	T_o	45	^{o}C
v_s	25	m/s	α	0	rad
n_e	20	Year	n_e	20	years
i_e	0.05	n/a	i_e	0.05	N/A

Comments	Notation	Product A (i=1)	Product B (i=2)	Unit
Energy consumed	e_i	0.9	1.2	MWh/unit
Production cost (w.o. energy)	p_i	400	600	$/unit
Holding cost	h_i	80	120	$/period/unit
Backlog cost	b_i	150	250	$/unit
Shipping cost (no EV recharge)	π_i	10	15	$/unit
Shipping cost (with EV recharge)	π_i	14	19	$/unit
Labor hours/item	v_{i1}	16	24	hours/unit
Machine hours	v_{i2}	100	200	hours/unit
Weight (including package)	m_i	3	4	Kg/unit
Mean demand	$\mu_{D_{ij}}$	1000	600	units/period
Standard deviation	$\sigma_{D_{ij}}$	120	50	units/period

Table 5. 3: Machine and Labor Resources in the Factory

Week	Labor Resource (hours)	Machine or Tool Resource (hours)	Week	Labor Resource (hours)	Machine or Tool Resource (hours)
1	38,516	278,847	27	37,860	279,542
2	34,429	244,299	28	39,153	281,016
3	33,472	239,044	29	32,345	237,514
4	34,210	248,699	30	34,562	249,292
5	36,680	261,478	31	36,814	263,851
6	36,660	269,935	32	35,001	251,627
7	34,063	249,447	33	32,159	239,152
8	35,786	261,961	34	37,138	269,049
9	36,243	261,441	35	36,784	267,032
10	36,989	268,359	36	30,487	223,362
11	33,739	240,138	37	31,639	226,421
12	35,560	263,343	38	28,497	208,141
13	36,920	262,138	39	33,601	241,714
14	37,695	268,946	40	33,727	249,509
15	33,051	240,437	41	35,735	259,884
16	38,113	276,789	42	32,750	237,912
17	33,914	241,252	43	35,657	257,745
18	33,569	243,591	44	32,635	240,033
19	38,010	274,606	45	34,452	249,525
20	37,688	270,170	46	33,684	244,778
21	40,853	291,900	47	37,094	267,545
22	38,946	283,740	48	30,751	226,419
23	28,867	215,059	49	38,739	270,781
24	34,891	248,255	50	34,252	250,829
25	31,466	230,446	51	40,363	292,169
26	30,652	219,114	52	32,078	230,129

Table 5. 4: Cost and Operation Parameters of WT and PV systems

WT			PV		
Symbol	Value	Unit	Symbol	Value	Unit
a_g	1.5×10^6	$/MW	a_g	3×10^6	$/MW
b_{gj}	10	$/MWh	b_{gj}	8	$/MWh
c_{gj}	0	$/MWh	c_{gj}	35	$MWh
τ_g	168	hour/period	τ_g	84	hour/period
v_c	3	m/s	η	0.15	N/A
v_r	12	m/s	T_o	45	^{o}C
v_s	25	m/s	α	0	rad
n_e	20	Year	n_e	20	years
i_e	0.05	n/a	i_e	0.05	N/A

As mentioned in the problem station, transportation cost is added in this model to accurately estimate the cost of operation. To estimate the transportation cost, two scenarios are considered with d_{max}=150 km.

- **Scenario 1**: If an e-truck can travel from the factory to the warehouse without recharging the battery (i.e. $d_k<d_{max}$) on route, then π_1 = $10 per unit and π_2 = $15 per unit.
- **Scenario 2**: If an e-truck requires the battery recharging because of $d_k>d_{max}$, then π_1 = $14 per unit and π_2 = $19 per unit. These larger costs vs. the ones in scenario one are to include bills for recharging the vehicles and the e-truck waiting time.

5.4.2 Result analysis and discussion. To test the model in different cities, Problem P3 is coded using a Modeling Language for Mathematical Programing (AMPL) software using the CPLEX solver running in the AMD Radeon R6 processor, which runs at 1.8 GHz and contains 4 cores, and 12 GB DRAM. The current model has a total of 316 decision variables including production quantity, inventory, and backorders, and the capacity of onsite WT and PV of each facility. Parameters of the problem are arranged as a matrix in a data file and can be easily changed or adjusted to solve the problem varying the values for the parameters. Figures 5.3 and 5.4 present the resulting production, inventory, and backorders for Products A and B across 52 weeks. The model is solved with γ=0.9 to meet the product demands.

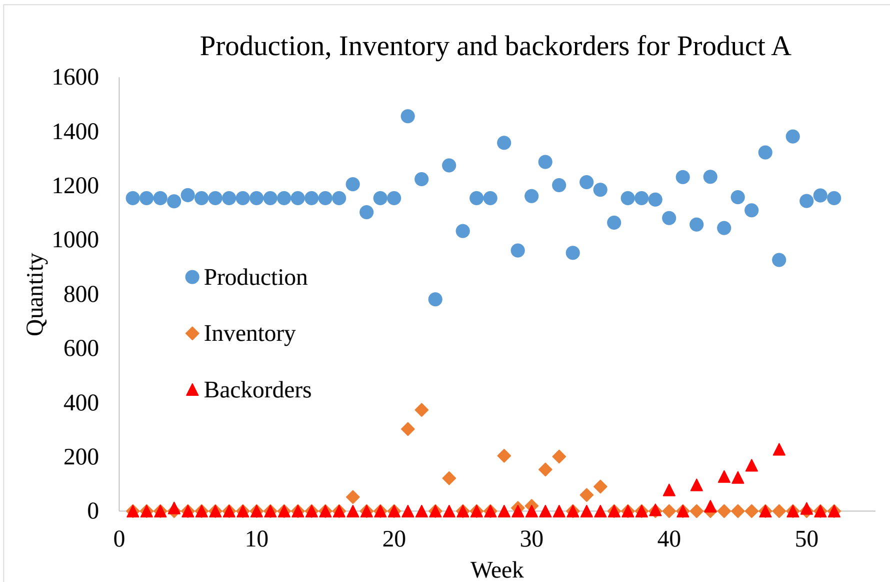

Figure 5. 3: Decision on Product A for Model P2-1

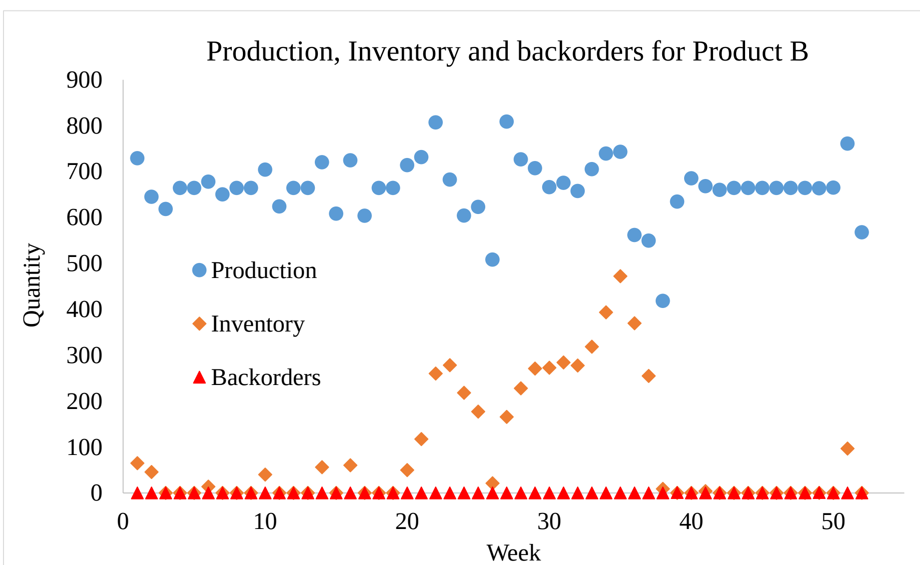

Figure 5. 4: Decision on Product B for Model P2-1

Table 5. 5: Results of Three Different Production-Logistics Systems

Case	1	2	3
City	Wellington	Aswan	Yuma
Facility	Factory	Factory	Factory
Wind profile	Strong wind	Low wind	Medium wind
Weather condition	Weak sun	Strong sun	Strong sun
Generation type	WT	PV	WT
Capacity (MW)	16.59	46.09	75.34
City	Christchurch	Luxor	San Francisco
Facility	Warehouse	Warehouse	Warehouse
Wind profile	Strong wind	Low wind	Medium wind
Weather condition	Weak sun	Strong sun	Medium sun
Generation type	WT	PV	WT
Capacity (MW)	30.08	30.55	18.18
Travel distance (km)	439	238	1051
Annualized system cost	$54,229,900	$61,257,100	$59,869,200

Case 1 represents the strong wind scenarios in the factory and the warehouse. For Case 1, the model chooses WT generation type for both the factory and warehouse. Given the carbon credit of $35/MWh for PV system, the model chooses WT system due to the significant strong wind condition in both locations. The minimum total cost is $54,229,900 which covers production-inventory cost, energy, and transportation cost. The installed capacity for the factory is 16.5 MW while for the warehouse is 30.08 MW.

In Case 2, we consider the city of Aswan and Luxor with strong sun condition and low wind speed profile. Opposite to Case 1, in this experiment, the model chooses to install PV generation system for both the factory and the warehouse despite the installation and maintenance cost for PV system is twice of the WT system. It is predictable since both cities have strong sunshine throughout the year. The capacity required for onsite PV generation is 46.12 MW for the factory and 30.57 MW for the warehouse. The annual minimum operational cost is $61,265,100.

In Case 3, we study a mixed weather scenario in which the factory is located in Yuma, AZ which has strong sun profile with medium wind speed, and the warehouse is located in San Francisco, CA with medium wind speed and medium sunshine. In this experiment, the model chooses WT for both the factory and the warehouse as optimal solutions. Even though Yuma is known for its strong sun, the model still chooses wind generation despite the PV carbon credit of $35/MWh. The installed WT capacity in the factory is 75.34 MW and the WT capacity in the warehouse is 18.18 MW. The annualized system cost is $59,869,200.

5.5 Multi-Factory Production and Logistics Systems

5.5.1 System setting and parameters. In this experiment, we will solve Problem P3 under a two-factory and one-warehouse setting. The two factories will be located at Yuma, Arizona and El Paso, Texas, and Phoenix, Arizona is chosen for the warehouse site. The average weather conditions of the cities can be observed in Table 5.6 and the average wind speeds for all the cities are shown in Figure 5.5.

Table 5. 6: Average weather condition of 4 cities

Country	USA			
City	Yuma	San Francisco	El Paso	Phoenix
Latitude (Deg)	32.69	37.77	31.76	33.45
Ground AWS	2.97	4.05	2.8	3.76
Ground SWS	1.4	1.83	1.05	1.78
Clear days	165	28	61	66
Scattered Cloud	109	95	111	115
Partially Cloudy	65	136	108	133
Mostly Cloudy	0	13	5	4
Overcast	0	2	1	1
Rain	13	65	31	25
Fog	1	24	2	0
Storm/T-Storms	11	3	41	22
Snow	0	0	5	0

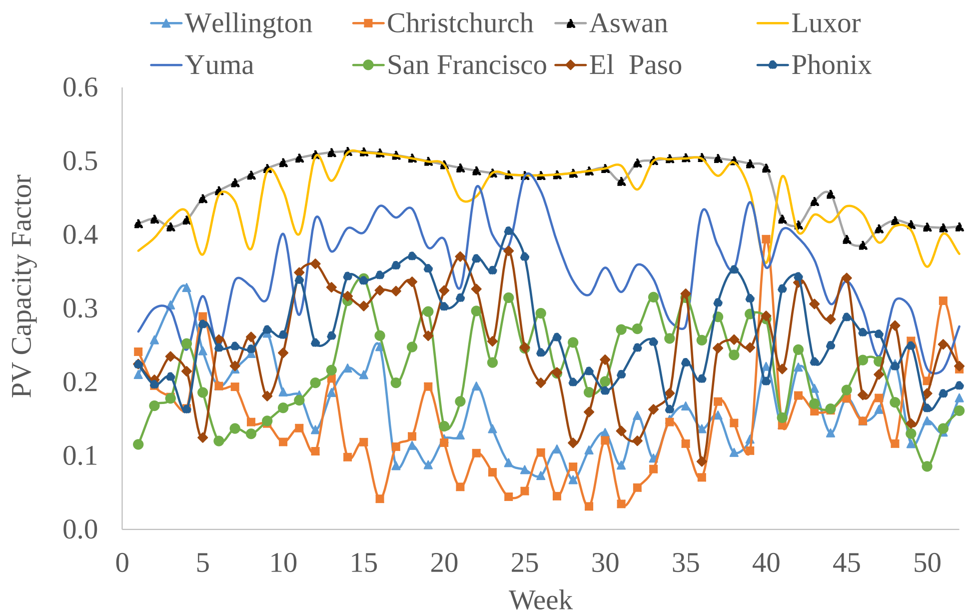

Figure 5. 5: The Weekly Solar PV Capacity Factor of Eight Cities

Two factories located in Yuma and San Francisco are capable of manufacturing two types of products, namely A and B. All the finished goods will be shipped to the warehouse located at Phoenix via e-truck. Assume the frequency between the factories and the warehouse is n_k = 186 trips/year. All the parameters and setting for this experiment will be the same as Section 5.4. The available labor and machine hours for each factory are listed in Table 5.7.

Table 5. 7: Production demand for two factories

(Factory 1=Yuma, Factory 2=El Paso)

Week	Labor Hours Factory 1	Labor Hours Factory 2	Machine Hours Factory 1	Machine Hours Factory 2	Week	Labor Hours Factory 1	Labor Hours Factory 2	Machine Hours Factory 1	Machine Hours Factory 2
1	22,339	16,177	153,366	125,481	27	21,959	15,901	153,748	125,794
2	19,969	14,460	134,365	109,935	28	22,709	16,444	154,559	126,457
3	19,414	14,058	131,474	107,570	29	18,760	13,585	130,633	106,881
4	19,842	14,368	136,784	111,915	30	20,046	14,516	137,111	112,182
5	21,275	15,406	143,813	117,665	31	21,352	15,462	145,118	118,733
6	21,263	15,397	148,464	121,471	32	20,301	14,701	138,395	113,232
7	19,757	14,306	137,196	112,251	33	18,652	13,507	131,533	107,618
8	20,756	15,030	144,078	117,882	34	21,540	15,598	147,977	121,072
9	21,021	15,222	143,793	117,648	35	21,335	15,449	146,868	120,165
10	21,453	15,535	147,598	120,762	36	17,682	12,804	122,849	100,513
11	19,568	14,170	132,076	108,062	37	18,351	13,288	124,532	101,890
12	20,625	14,935	144,839	118,504	38	16,528	11,969	114,477	93,663
13	21,413	15,506	144,176	117,962	39	19,488	14,112	132,943	108,771
14	21,863	15,832	147,920	121,026	40	19,562	14,165	137,230	112,279
15	19,170	13,881	132,241	108,197	41	20,726	15,009	142,936	116,948
16	22,106	16,008	152,234	124,555	42	18,995	13,755	130,852	107,060
17	19,670	14,244	132,688	108,563	43	20,681	14,976	141,760	115,985
18	19,470	14,099	133,975	109,616	44	18,928	13,707	132,018	108,015
19	22,046	13,303	151,033	123,573	45	19,982	14,470	137,239	112,286
20	21,859	15,829	148,593	121,576	46	19,536	14,147	134,628	110,150
21	23,695	17,158	160,545	131,355	47	21,515	15,580	147,150	120,395
22	22,589	16,357	156,057	127,683	48	17,836	12,915	124,530	101,889
23	16,743	12,124	118,283	96,777	49	22,469	16,270	148,930	121,852
24	20,237	14,654	136,540	111,715	50	19,866	14,386	137,956	112,873
25	18,250	13,216	126,745	103,701	51	23,410	14,127	160,693	131,476
26	17,778	12,874	120,513	98,601	52	18,605	13,473	126,571	103,558

5.5.2 Results and discussion. The model outputs for the production-inventory level that meet the stochastic demand weekly with 90% confidence level are demonstrated in Figures 5.6 and 5.7. Figure 5.6 represents the production-inventory level for Product A in both Factories 1 and 2 while Figure 5.7 displays the production-inventory level for Product B in both factories. This model has total of 422 decision variables which include production quantity of each factory, warehouse inventory, and backorders as well as the onsite generation capacity of WT and PV in each facility.

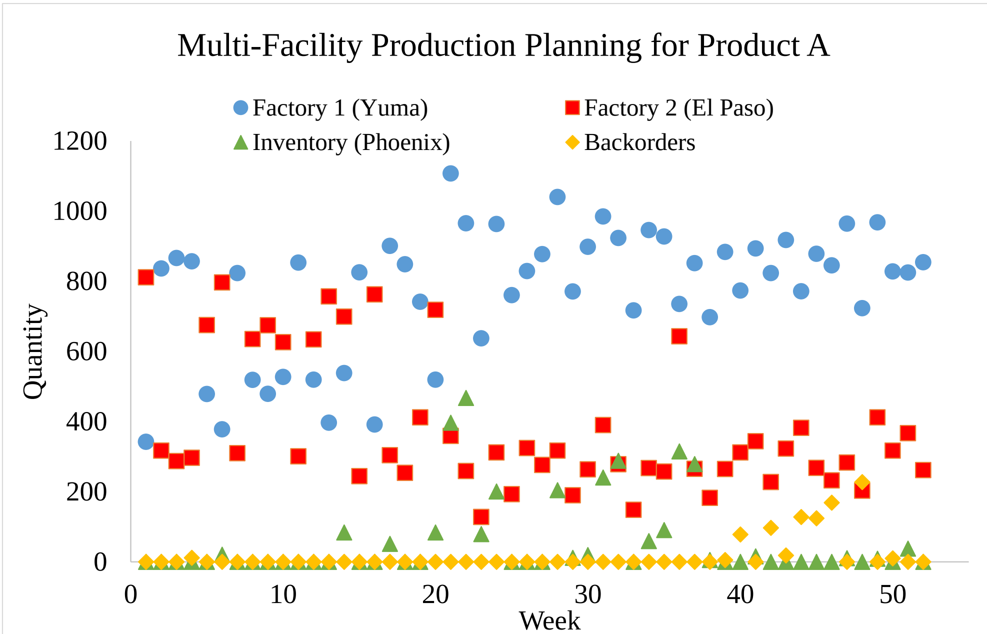

Figure 5. 6: Results of Product A

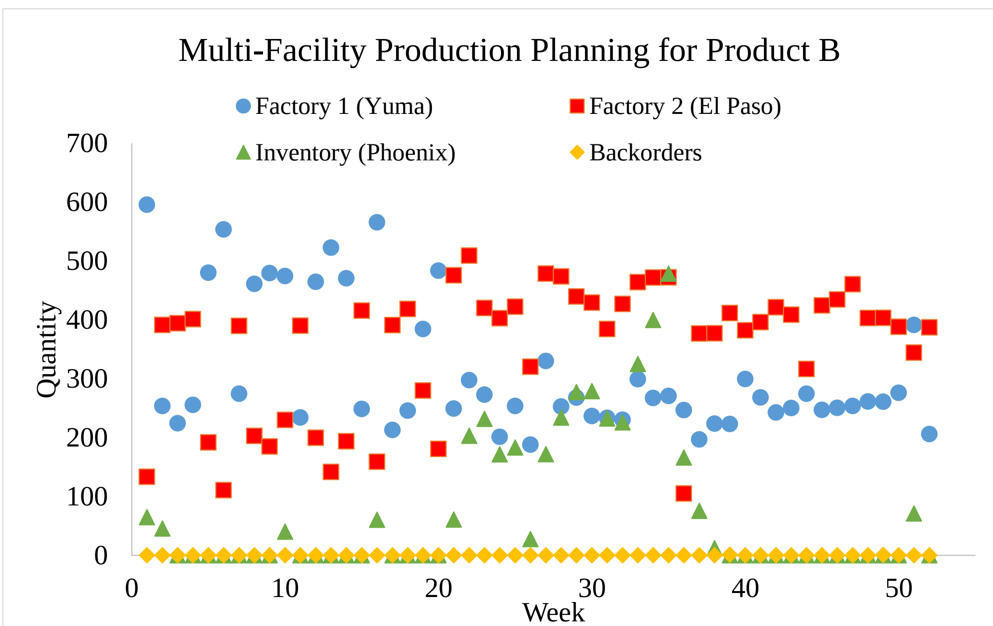

Figure 5. 7: Results of Product A

The results of the model are presented in three cases and summarized in Table 5.8. Case 4 is the baseline corresponding to the situation where the PV capacity cost is \$3M/MW and its carbon credit is \$35/MWh. We solve Problem P3 and the annualized system cost is \$61,243,500. Despite the strong sunshine in Phoenix and the favorable carbon credit of \$35/MWh, the model chooses WT as the power generator. The same results are observed in El Paso and Yuma where WT is more cost-effective than PV regardless of strong sunshine in these sites.

Table 5. 8: Comparisons under Different PV Cost and Carbon Credits

	Case 4		Case 5		Case 6	
PV capacity Cost (\$/MW)	3×10^6		2×10^6		1.5×10^6	
PC Carbon credit (\$/MWh)	35		0		0	
	Type	Capacity (MW)	Type	Capacity (MW)	Type	Capacity (MW)
Factory 1 (Yuma)	WT	43.8	WT	43.8	PV	36.81
Factory 2 (El Paso)	WT	18.56	WT	18.56	WT	18.56
Warehouse (Phoenix)	WT	72.41	PV	52.95	PV	52.95
Annualized system cost	\$61,243,500		\$60,903,800		\$57,828,100	

Cases 5 and 6 are designed for sensitivity analysis. In Case 5, the PV capacity cost is reduced to \$2M/MW with no carbon credit. The model chooses PV for Phoenix, and WT for Yuma and El Paso with the cost of \$60,908,800. This is slightly lower than the cost in Case 4. In Case 6, the PV capacity cost goes down to \$1.5M/MW which is the same as the WT cost. The model shows that El Paso still chooses WT, but in Yuma PV becomes more cost-effective than WT. The annualized cost is \$57,828,100, which is 5.6% lower than Case4.

Finally, we compute the levelized energy cost (LEC) of each location, and determine which site is cost-effective for large-scale microgrid generation. LEC is the net present value of the unit-cost of electricity over the lifetime of a generating asset. Based on the results in Table 5.9, using $70/MWh as the reference utility price, Wellington, Christchurch, San Francisco and El Paso are cost-effective in harnessing onsite wind generation. Phoenix is a city favorable for PV generation, but at the $3M/MW capacity cost, its LEC is more than twice of current utility price. If we project the utility price in 20 years, the rate will reach $120/MWh under 3% annual increase. This means all the eight cities except Phoenix are favorable to install WT, PV or both over the 20-year horizon.

Table 5. 9: Levelized Cost of Renewable Energy

(H=high, M=medium, L=Low)

City	Annual Non-Energy Cost ($)	Annual Energy Cost ($)	Annual Electricity Use (MWh)	$/MWh	Cost Effective
Wellington	46,207,500	2,950,330	95,509	31	H
Christchurch	840,685	4,231,300	61,216	69	H
Aswan	46,207,500	8,513,820	95,509	89	M
Luxor	840,685	5,695,030	61,216	93	M
Yuma	46,207,500	10,019,800	95,509	105	M
San Francisco	840,685	2,801,190	61,216	46	H
Yuma	25,008,900	5,824,760	55,562	105	M
El Paso	17,611,900	2,633,280	39,987	66	H
Phoenix	839,714	9,324,970	61,262	152	L

VI. NET ZERO CARBON SUPPLY CHAIN NETWORK UNDER DETERMINISTIC AND STOCHASTIC DEMAND

6.1 Supply Chain with Microgrid Power and Deterministic Demand

6.1.1 Model setting. Figure 1 describes a supply chain comprised of multiple manufacturers, warehouses, and stores, and e-trucks that are used to transport product between different locations. Assume all the factories are capable of manufacture Products A and B. Similar to the previous chapters, the energy needed to operate the entire supply chain is provided by the onsite microgrid generations. Each microgrid will consider two type of renewable energy which are wind turbine (WT) and photovoltaic (PV). The e-vehicle fleet also use the onsite generated energy to charge their battery. If the driving distance between two facilities is greater than the driving range of e-vehicle battery, charging stations will be created within the route so the e-vehicles can recharge their battery. With the use of onsite renewable energy generation for production and transportation, our goal is to create a supply chain network with net zero carbon emissions.

Net-metering will be considered also in the case of energy surplus or shortage. If the energy output cannot meet the load demand of the facilities, conventional energy can be borrowed to power the facilities. This amount of "borrowed" energy will be paid back during a period when the energy generated by the onsite generation system exceeds the amount required by the local facilities.

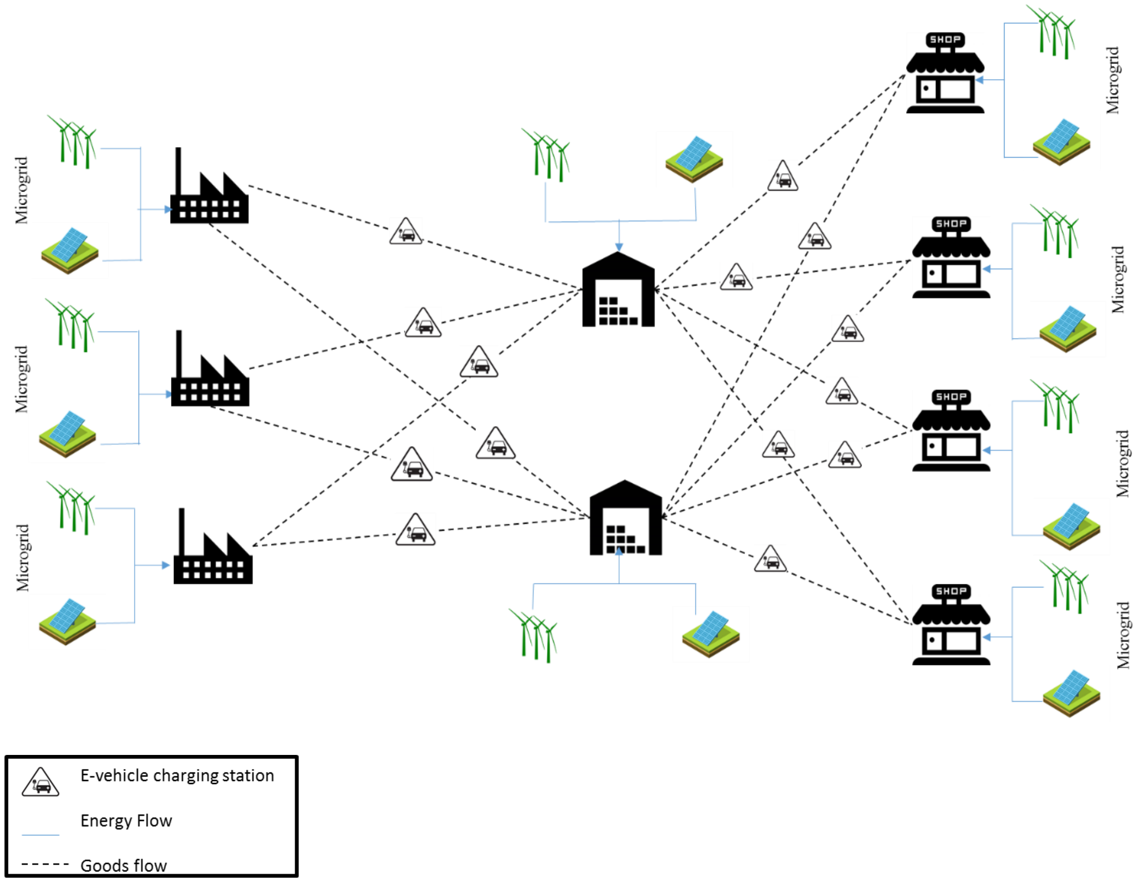

Figure 6. 1: Supply Chain with Microgrid Generation

6.1.2 Optimization Algorithm.

a. Mathematical model notations.

Notation	Explanations
I	number of product types
J	number of production periods
M	number of factories
K	number of warehouses
S	number of retail stores
G	number of renewable generation sources
R	number of resources required for production

p_{im} cost of making a unit of product *i* at factory *m* ($/unit)

h_{ik} unit holding cost of product *i* at warehouse *k* ($/period)

b_i unit backorder cost of product *i* ($/unit)

π_i cost of shipping a unit of product *i* ($/unit)

v_{iml} resource *l* consumed for making a unit of product *i* in factory *m*

w_{ljm} available resource of *l* in period *j* in factory *m*

q_v electric transport energy intensity rate (MWh/kg/km)

m_i the weight of product *i* (kg)

w^v vehicle self-weight (kg)

d_m distance between factory *m* and the warehouse (km)

d_s distance between retail store *s* and the warehouse (km)

D_{ijs} demand for product *i* in period *j* for retail store *s*

$\mu_{D_{ij}}$ mean demand for product *i* in period *j*

$\sigma_{D_{ij}}$ standard deviation of demand for product *i* in period *j*

n_{mk} number of yearly trips between factory *m* and warehouse *k*

n_{jks} number of yearly trips between warehouse *k* and retail store *s*

t_w annual operating hours of the warehouse (hours)

t_s annual operating hours of retail stores (hours)

τ_g number of hours of generation *g* (hours) in each production period

a_g capacity cost for renewable generation *g* ($/MW)

b_g operation and maintenance cost for renewable generation *g* ($/MWh)

c_g carbon credits for renewable generation *g* ($/MWh)

λ_{jgm} capacity factor of renewable generator *g* in period *j* at factory *m*

λ_{jgk} capacity factor of renewable generator *g* in period *j* at warehouse *k*

λ_{jgs} capacity factor of renewable generator *g* in period *j* at retail store *s*

e_{im} energy consumed for producing one unit of product i at factory *m* (MWh/unit)

L_w electricity demand (load) of the warehouse (MW)

L_s electricity demand (load) of the retail store (MW)

γ probability that the product demand is met

ϕ capital recovery factor

ζ random wind profile and solar incidence on PV

Decision Variable	Explanations
x_{iju}	quantity of product *i* made in period *j* in facility *u*
y_{ijk}	inventory of product *i* in period *j* in warehouse *k*
z_{ij}	backorder of product *i* in period *j* in warehouse *k*
P_{gm}	capacity of generation source *g* in manufacturer *m*
P_{gk}	capacity of generation source *g* in warehouse *u*
P_{gs}	capacity of generation source *g* in retail store *s*

a. Net zero carbon supply chain network with microgrid generation and e-transport. We design a production-logistics-retail network where each facility is powered by onsite microgrid generation. Each factory will produce multiple products and the finishing goods will be shipped and stored at warehouse. The goods then will be distributed to retail stores based on the store's demand for each period. E-trucks are employed to ship the goods between facilities. The objective of the model is to determine the production quantity, inventory level, and backorders such that the demand for each period at each store is satisfied. In order to achieve the net zero carbon target, the generation capacity of onsite microgrid system is also optimized so that the cost of the entire supply chain network including energy and transportation is minimized.

Problem P4:

Minimize:

$$f(\mathrm{x},\mathrm{y},\mathrm{z},\mathrm{P}^c)=\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}(p_{ijm}+\pi_i)x_{ijm}+\sum_{i=1}^{I}\sum_{j=1}^{J-1}\sum_{k=1}^{K}h_{ik}y_{ijk}+\sum_{i=1}^{I}\sum_{j=1}^{J-1}b_i z_{ij}$$

$$+\phi\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{s=1}^{S}a_g(P_{gm}^c+P_{gk}^c+P_{gs}^c)$$

$$+\tau_g\sum_{g=1}^{G}\sum_{k=0}^{K}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{s=1}^{S}(b_g-c_g)(\lambda_{gjm}P_{gm}^c+\lambda_{gjk}P_{gk}^c+\lambda_{gjs}P_{gs}^c) \tag{6.1}$$

Subject to:

$$\sum_{m=1}^{M}\sum_{k=1}^{K}(x_{ijm}-y_{ijk}+z_{ijk})\geq\sum_{s=1}^{S}D_{ijs}, \qquad j=1 \text{ and } \forall i,\ \forall k,\ \forall u,\ \forall s \tag{6.2}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K}(x_{ijm}+y_{i,j-1,k}-y_{ijk}+z_{ijk}-z_{i,j-1,k})\geq\sum_{s=1}^{S}D_{ijs},$$

$$\text{for } j=2,3,..,J\text{-}1 \text{ and } \forall i,\ \forall k,\ \forall u,\ \forall s \tag{6.3}$$

$$\sum_{i=1}^{I}v_{ilm}x_{ijm}\leq w_{ljm}, \qquad \text{for } \forall i \text{ and } \forall j \tag{6.4}$$

$$z_{ik,J}=0 \qquad \text{for } \forall i \text{ and } \forall k \tag{6.5}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(e_{im}+q_v n_{mk}d_m m_i)x_{ijm}+q_v n_{mk}d_m w^v=\tau_g\sum_{j=1}^{J}\sum_{g=1}^{G}\lambda_{gjm}P_{gm}^c \tag{6.6}$$

$$t_w L_w+\sum_{j=1}^{J}q_v n_{mk}d_m w^v+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}(m_i D_{ijs}+w^v)q_v n_{jks}d_s=\tau_g\sum_{j=1}^{J}\sum_{g=1}^{G}\lambda_{gjk}P_{gk}^c \tag{6.7}$$

$$t_s L_s+\sum_{j=1}^{J}q_v n_{jks}d_s w^v=\tau_g\sum_{j=1}^{J}\sum_{g=1}^{G}P_{gs}^c \tag{6.8}$$

$$P_{gu}^c, P_{gk}^c, P_{gs}^c\geq 0, \qquad \text{for } \forall g,\ \forall k,\ \forall u,\ \forall s \tag{6.9}$$

$x_{ijm,}\, y_{ijk,}\, z_{ijk}$ are non-negative integers (6.10)

Problem P4 is a mixed-integer linear programming model in which **x**, **y**, and **z** are decision variables representing the production, inventory, and backorders in each period; $\mathbf{P}^c$ is the decision variables for the power capacity of WT and PV in each facility. Objective function (6.1) is to minimize the total cost comprised of manufacturing, transportation, warehousing, and energy. The first three summations represent the production (including shipping), inventory and backorder costs. The last two summations capture the costs associated with microgrid installation, maintenance & operations, and carbon credits. The expected cost of microgrid systems is adopted to accommodate the intermittency of wind and solar generation.

Constraint (6.6) is the renewable energy balance equation, stating that the annual electricity consumed by factory *k* and the forward logistics is fully offset by onsite microgrid energy. q_v is the electric vehicle energy intensity rate at speed *v* for which calculation information can be found in chapter 3. Constraint (6.7) defines the energy balance of the warehouse, stating that the total warehouse energy including the reverse logistics to the factories and the forward logistics to retail stores is fully offset by the onsite microgrid energy. n_{jks} is the number of weekly trips between warehouse *k* and retail store *s* where $n_{jks} = \frac{Demand \times product\ weight}{\max\ weight\ of\ good\ allow}$. Constraint (6.8) indicates that the total energy used by the retail stores including the reverse logistics is fully offset by the onsite microgrid energy. Constraints (6.9) and (6.10) simply define the non-negativity of x_{ijk}, y_{ij}, z_{ij}, and P^c.

6.1.3 Renewable Generation Analytics.

a. Climate Data Collection. To demonstrate the feasibility of net-zero energy supply chain operations, ten cities located in different regions of U.S. are selected to test the model in P4. The latitude, average wind speed, and weather conditions of each city are summarized in Table 6.1. Note that San Francisco, San Jose, Los Angeles, Sacramento are in California, Tucson, Yuma, and Phoenix are in Arizona, Reno and Las Vegas are in Nevada, and Salt Lake City is in Utah. The daily wind speed and the weather patterns of these cities are retrieved from the Weather Underground web portal (WeatherUnderground,2017). The weather conditions are classified into eight states, namely, clear day, scattered cloud (SC), partially cloudy (PC), mostly cloudy (MC), overcast, rain, fog, storm/T-storm and snow.

For each city, average wind speed and weather conditions over a range of eleven years (from 2006 to 2016) are collected to accurately capture a long range of climate conditions. There are 4,015 daily wind speed measurements collected for each city, and these speed data will be used to estimate the WT capacity factors for ten cities. This also applies for weather conditions where 4,015 data points are obtained from weather underground website for the span of eleven years. There are total of 40,150 weather conditions data collected between 2006 and 2016 for ten cities. The size of dataset for this analytic method reaches 80,300 data points.

Table 6. 1: Average Wind Speed and Weather Conditions of Ten Cities

State	California				Utah
City	Los Angeles	San Francisco	San Jose	Sacramento	Salt Lake City
Latitude (Deg)	34.05	37.77	37.28	38.58	40.76
Ground AWS	5.45	7.86	4.75	5.71	6.22
Ground SWS	1.72	2.58	2.09	3.03	2.81
Clear Days	30	28	32	102	20
Scattered Cloud	87	95	100	80	76
Partially Cloudy	150	136	141	63	123
Mostly Cloudy	17	13	8	1	7
Overcast	4	2	1	0	1
Rain	35	65	79	75	39
Fog	39	24	4	42	9
Storm/Tstorm	3	3	0	2	39
Snow	0	0	0	0	51
State	**Arizona**			**Nevada**	
City	**Phoenix**	**Yuma**	**Tucson**	**Reno**	**Las Vegas**
Latitude (Deg)	33.45	32.66	32.25	39.53	36.11
Ground AWS	3.76	2.97	5.52	4.65	6.23
Ground SWS	1.78	1.4	1.92	2.98	3.16
Clear Days	66	165	248	38	73
Scattered Cloud	115	109	34	95	114
Partially Cloudy	133	65	8	145	125
Mostly Cloudy	4	0	1	5	8
Overcast	1	0	0	1	0
Rain	25	13	22	54	20
Fog	0	1	0	1	1
Storm/Tstorm	22	11	52	10	24
Snow	0	0	0	16	0

Note: AWS = average wind speed (m/s), SWS = standard deviation of wind speed (m/s). (deg=degree)

b. Capacity Factor of Wind Turbine and Solar PV. The detailed information of calculating capacity factor for Wind Turbine and Solar PV can be found in Section 3.1 and 3.2 of Chapter 3 and Section 4.3 of Chapter 4. Figure 6.2 plots the weekly capacity factor values for all the ten cities. Figure 6.3 plots the weekly PV capacity factor for ten cities.

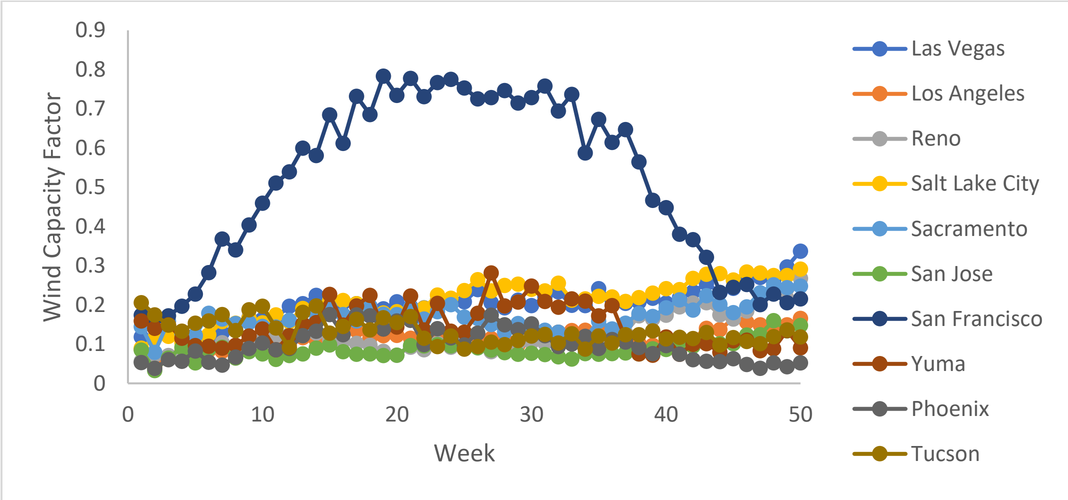

Figure 6. 2: Weekly Wind Turbine Capacity Factor of Ten Cities

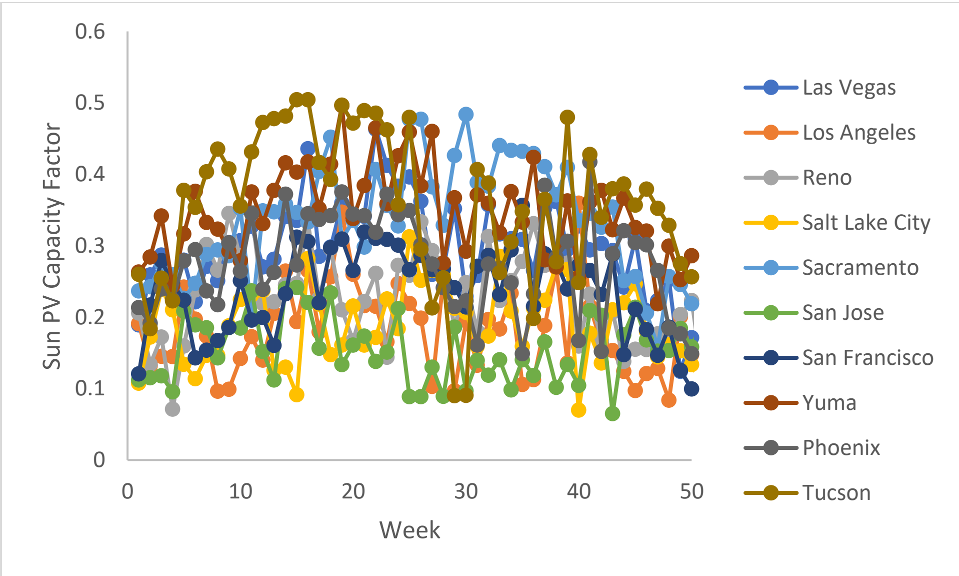

Figure 6. 3: Weekly Solar PV Capacity Factor of Ten Cities

It is noted that the wind capacity factors are calculated based on the 2.5-MW WT installation. It can be observed from Figure 6.2 that San Francisco has significantly higher WT capacity factor than other cities. On the other hand, Tucson and Las Vegas are among the top cities with high Solar PV capacity factor.

6.1.4 Numerical Experiments.

a. Background of Production System. The model will first be implemented on a multi-factory, multi-store, and a single warehouse system. Production data used for this experiment are associated with wafer production facilities which operate 24 hours and 7 days a week. Assume the supply chain will have two factories which will produce two product types, namely A and B. There will be a single warehouse that will store all the finishing goods and then will ship them to two retail stores. Each week corresponds to one planning period. The product demands for 52-week production planning are shown in Table 6.2. Other parameters associated with production, inventory, backorders, and transportation are display in Table 6.3.

Table 6. 2: Production, Inventory, Backorder, Shipping, and Energy Data

Comments	Notation	Product A (i=1)	Product B (i=2)	Unit
Energy consumed	e_i	0.9	1.2	MWh/unit
Production cost (w.o. energy)	p_i	400	600	\$/unit
Holding cost	h_i	80	120	\$/period/unit
Backlog cost	b_i	150	250	\$/unit
Shipping cost (no EV recharge)	π_i	10	15	\$/unit
Shipping cost (with EV recharge)	π_i	14	19	\$/unit
Labor hours/item	v_{i1}	16	24	hours/unit
Machine hours	v_{i2}	100	200	hours/unit
Weight (including package)	m_i	3	4	Kg/unit

(w.o.= without)

Table 6. 3: Product demand for 52-week planning

	Store 1		Store 2			Store 1		Store 2	
Week	A	B	A	B	Week	A	B	A	B
1	798	430	748	513	27	692	469	616	514
2	721	563	710	584	28	740	595	659	594
3	770	552	674	422	29	643	518	674	592
4	793	497	719	442	30	688	583	670	575
5	763	510	798	525	31	690	544	797	470
6	736	463	792	524	32	647	579	600	433
7	755	448	787	460	33	721	506	749	522
8	796	600	756	412	34	696	596	698	546
9	760	427	723	597	35	786	414	629	505
10	753	533	662	573	36	731	517	731	490
11	737	563	759	449	37	658	431	650	585
12	791	593	760	425	38	642	527	710	410
13	776	503	751	462	39	708	589	688	481
14	796	572	634	575	40	785	445	768	402
15	729	564	760	503	41	631	583	669	590
16	740	476	705	415	42	677	576	727	455
17	723	524	782	426	43	747	468	799	569
18	783	536	765	556	44	747	549	725	538
19	795	457	809	520	45	707	534	791	411
20	799	584	799	528	46	603	481	685	479
21	798	407	789	514	47	638	407	786	444
22	756	424	718	515	48	776	474	773	528
23	701	522	622	555	49	741	430	769	445
24	659	447	658	401	50	798	531	795	515
25	730	440	748	437	51	764	492	799	531
26	650	535	672	600	52	707	400	737	430

E-trucks are employed to transport finished goods between the factories, the warehouse, and the retail stores. The self-weight of each vehicle w_v = 5,000 kg, and the electric vehicle energy intensity rate is q_v =1.19×10^{-7} MWh/kg/km. The electric load for warehouse is relatively stable with L_w = 9 MW and the electric load for each retail store is assumed stable with L_s = 7 MW. The yearly operating hours of warehouse is 8,760 which is equivalent to operating in 24/7 mode. Assume the retail stores will be operating 12 hours a day and 7 days a week, the yearly operating hours of each retail stores is 4,280 hours. Round trip frequency between the factory and the warehouse is n_k=150 trips per year. The frequency between warehouses and retail stores is calculated as

$$n_{jks} = \frac{Demand \times product\ weight}{\max\ weight\ of\ good\ allow}. \tag{6.10.1}$$

Assume the driving range of an e-truck is $d_{\max}$=150 km. There are two ways of calculating the transportation cost such as:

- If $d_k < d_{max}$, then π_1 = \$10 per unit and π_2 = \$15 per unit.
- If $d_k > d_{max}$, then π_1 = \$14 per unit and π_2 = \$19 per unit.

The labor resources and machine resources needed for achieving the expected production over 52-week are presented in Table 6.5 below. Table 6.6 displays the data associated with installation, maintenance, and carbon credits of WT and PV systems.

Table 6. 4: Cost and Operation Parameters of WT and PV systems

WT			PV		
Symbol	Value	Unit	Symbol	Value	Unit
a_g	1.5×10^6	\$/MW	a_g	3×10^6	\$/MW
b_{gj}	10	\$/MWh	b_{gj}	8	\$/MWh
c_{gj}	0	\$/MWh	c_{gj}	35	\$MWh
τ_g	168	hour/period	τ_g	84	hour/period
v_c	3	m/s	η	0.15	N/A
v_r	12	m/s	T_o	45	°C
v_s	25	m/s	α	0	rad
n_e	20	Year	n_e	20	years
i_e	0.05	n/a	i_e	0.05	n/a

Table 6. 5: Labor and Machine Resources in the Factory

	Labor Resource		Machine Resource	
Week	Factory 1	Factory 2	Factory 1	Factory 2
1	31051	22486	213179	174419
2	27757	20099	186767	152810
3	26985	19541	182749	149522
4	27580	19972	190130	155562
5	29572	21414	199900	163554
6	26776	21402	206365	168845
7	27462	19885	190702	156029
8	28851	20892	200268	163856
9	29219	21159	199872	163531
10	29820	21594	205161	167859
11	27200	19696	183586	150206
12	28669	20760	201326	164721
13	28374	21553	200405	163967
14	29000	22006	205609	168226
15	26646	19295	183815	150394
16	27947	22251	211605	173131
17	27341	19799	198336	150903
18	27063	19598	200125	152366
19	24881	18491	196036	171766
20	30384	22002	206544	168991
21	30156	23850	209258	182583
22	31399	22736	216919	177479
23	23273	16852	164413	134520
24	28129	20369	189791	155284
25	25368	18370	176176	144144
26	24711	17895	167513	137055
27	30523	22102	213710	174854
28	28786	22857	214837	175775
29	26076	18883	181580	148565
30	27864	20177	190584	155933
31	29679	21492	201714	165039
32	28218	20434	192369	157392
33	25926	18775	182831	149589
34	29941	21681	205688	168290
35	29656	21474	204147	167029
36	24578	17798	170760	139713
37	25508	18470	173099	141627
38	22974	16637	159123	130192
39	27088	19616	184791	151192
40	27191	19689	190750	156068
41	26029	20863	182001	162558
42	26403	19119	181884	148813
43	28747	20817	197046	161219
44	26310	19053	183505	150141
45	27775	20113	190762	156078

b. Result Analysis and Discussion. AMPL optimization software was used to test the model of P4. Using CPLEX solver running in AMD Radeon R6 processor, the model is tested in different cities with different weather conditions. The production level at both factories, inventory level, and backlogs for Products A and B in 52 weeks are shown in Figures 6.4 and 6.5.

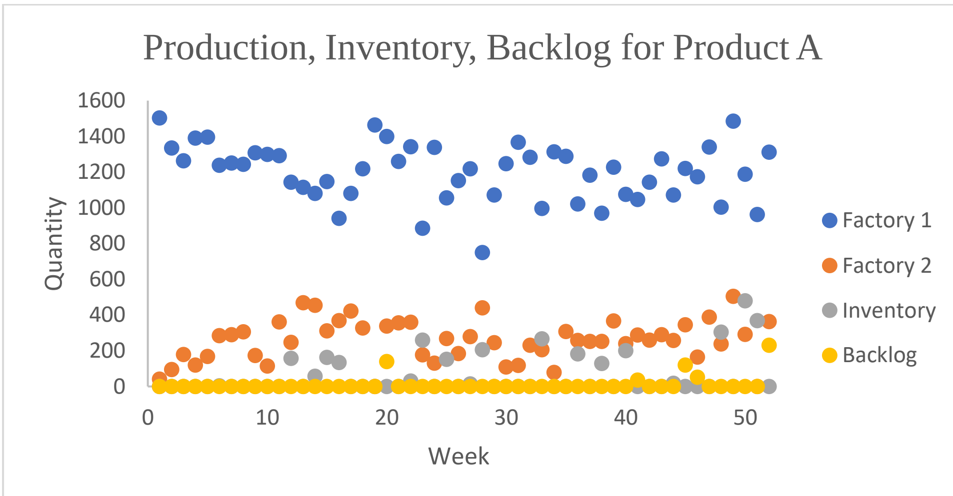

Figure 6. 4: Decision Variables Output of Product A

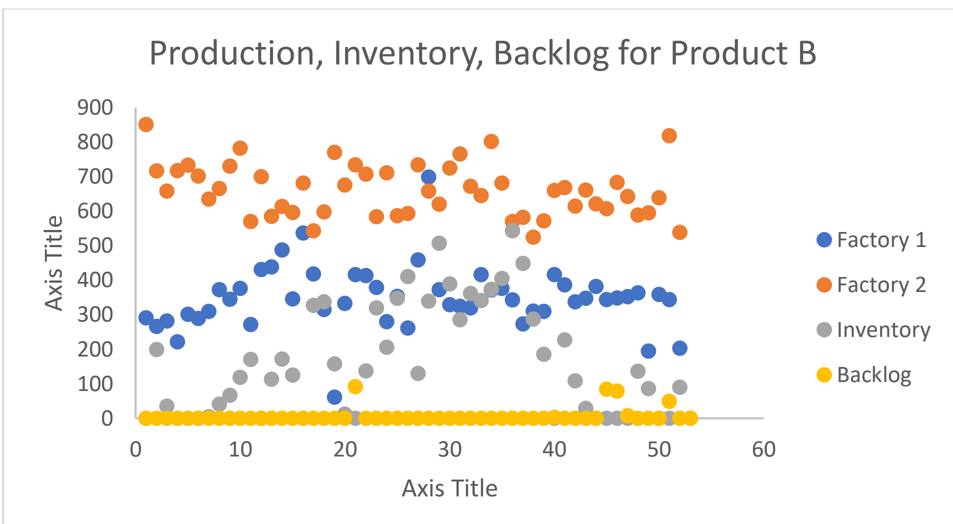

Figure 6. 5: Decision Variables Output of Product B

There are two case scenarios which are set up to test the model. The cities chosen to set up the factory facilities, warehouse, and stores are based on its weather conditions, cost metrics, demand size, and logistic factors. Figures 6.6 and 6.7 show the layouts of two scenarios with distances.

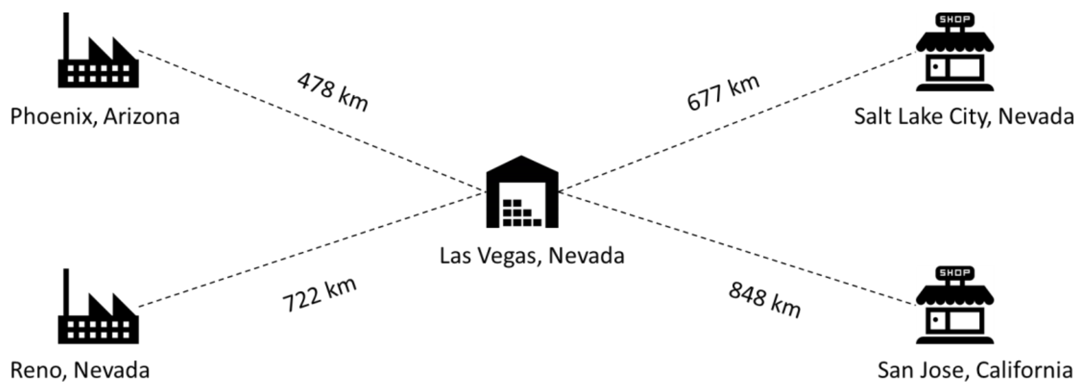

Figure 6. 6: Scenario I Supply Chain layout

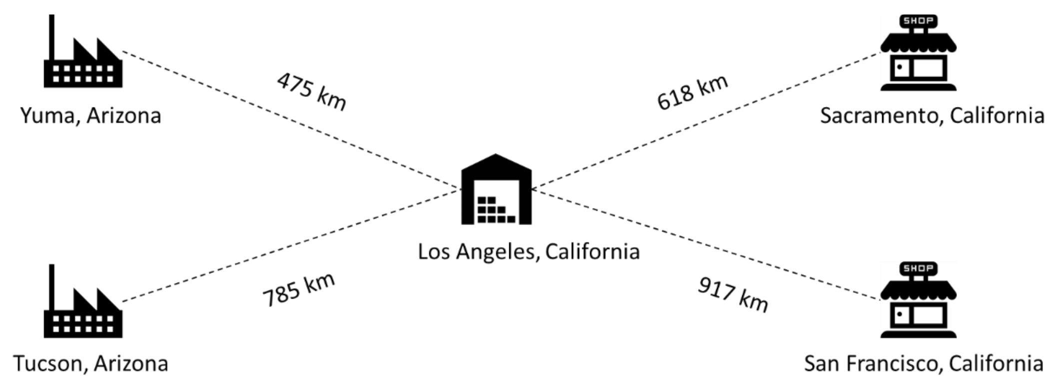

Figure 6. 7: Scenario II layout

c. Scenarios with carbon credits. In these scenarios, the cost to install WT system is \$1.5M/MW and the cost to install PV system is \$3M/MW. Due to the high PV installation costs, carbon credits of $35/MWh are considered for PV system. Table 6.6 displays the result of Production-Logistics systems of two scenarios with carbon credits.

Table 6. 6: Results of Production-Logistics Systems -Two Scenarios

Scenario I			Scenario II		
	Type	Capacity (MW)		Type	Capacity (MW)
Factory 1 - Yuma	WT	63.01	Factory 1 - Phoenix	WT	92.47
Factory 2 - Tucson	WT	48.01	Factory 2 - Reno	WT	50.64
Warehouse - Los Angeles	WT	76.95	Warehouse - Las Vegas	WT	43.47
Store 1 - Sacramento	WT	20.36	Store 1 - Salt Lake City	WT	16.48
Store 2 - San Francisco	WT	7.01	Store 2 - San Jose	WT	39.05
Annualized system cost	$86,868,199.16		Annualized system cost	$86,699,242.84	

In scenario one, the minimum total cost of production, transportation, inventory, and energy is $86,868,199. Even though Yuma and Tucson which are known for their strong sun and medium wind speed are chosen for factory location, the model still chooses to install WT systems despite the given carbon credit of $35/MWh for PV’s. This can be explained because even if Yuma and Tucson have strong sun, it is still more economical to install the wind turbine due to its low-cost in comparison to PV. Due to its strong wind , the capacity of WT at San Francisco is lower if compared to other store locations.

In scenario II, the minimum total cost of production, transportation, inventory, and energy is $ 86,699,242. Given the carbon credit of $35 MWh, the model still chooses to install WT systems in all locations. If Comparing all the factory locations, Tucson is the best location to build the factory due to its lowest capacity requirement for WT system. As for the warehouse locations, Las Vegas is the choice since it only requires 43.47 MW of WT system capacity which is significantly lower than Los Angeles. For retail store locations, San Francisco is the best location with very low capacity requirement for WT system dues to its strong wind.

d. Scenarios without carbon credits. Due to the driving forces of policy and market, the price of solar energy has declined significantly to the point where solar generation can compete with wind energy. In these scenarios, the installation price of both WT and PV system will be set at $1.5M/MW. There will be no carbon credits considered since the cost of PV system is low. Table 6.7 displays the result of Production-Logistics systems of two scenarios under the new setting.

Table 6. 7: Results of Production-Logistics System without Carbon Credits

Scenario III			Scenario IV		
	Type	Capacity (MW)		Type	Capacity (MW)
Factory 1 - Yuma	PV	52.29	Factory 1 - Phoenix	PV	67.75
Factory 2 - Tucson	PV	37.13	Factory 2 - Reno	WT	49.34
Warehouse - Los Angeles	WT	76.95	Warehouse - Las Vegas	WT	43.47
Store 1 - Sacramento	WT	20.36	Store 1 - Salt Lake City	WT	16.48
Store 2 - San Francisco	WT	7.01	Store 2 - San Jose	WT	39.05
Annualized system cost	$83,997,900.00		Annualized system cost	$83,407,400.00	

For scenario III, the total minimum cost of production, inventory, transportation, and energy is $83,997,900.00. Since the cost of WT system and PV system are set to be the same, the model chooses PV system for both Yuma and Tucson. This result is predictable since the two cities have strong sunshine. Then, the capacity required for onsite system at Yuma and Tucson in this scenario is also smaller than scenario I. As for other locations, the outputs are the same for all of them as the model choose WT systems. The total cost of scenario III is lower than the total cost of scenario I because the capacity required for the onsite system of both factories is lower in scenario III.

For scenario IV, the total minimum cost of production, inventory, transportation, inventory, and energy is $83,407,400.00. With the same capacity cost for WT and PV system, the model chooses PV system for the Phoenix factory and chooses WT for all other locations. Since Phoenix has strong sun, it is understandable that the model chooses PV as the onsite power unit. The total cost of scenario IV is slightly lower than the total cost of scenario II because the capacity required for onsite system is lower than scenario two.

6.1.5 Multi-Warehouse Supply Chain Systems

a. System Setting and Parameters. In this section Problem P4 is solved with four-factories, two-warehouses, and four-retailers. In this setting, Phoenix, Reno, Yuma, and Tucson are chosen for factory locations, and Los Angeles and Las Vegas are chosen for the warehouse locations. Salt Lake City, San Jose, Sacramento, and San Francisco are dedicated to retail store locations. The supply chain layout can be observed from Figure 6.8 which include the distances between sites.

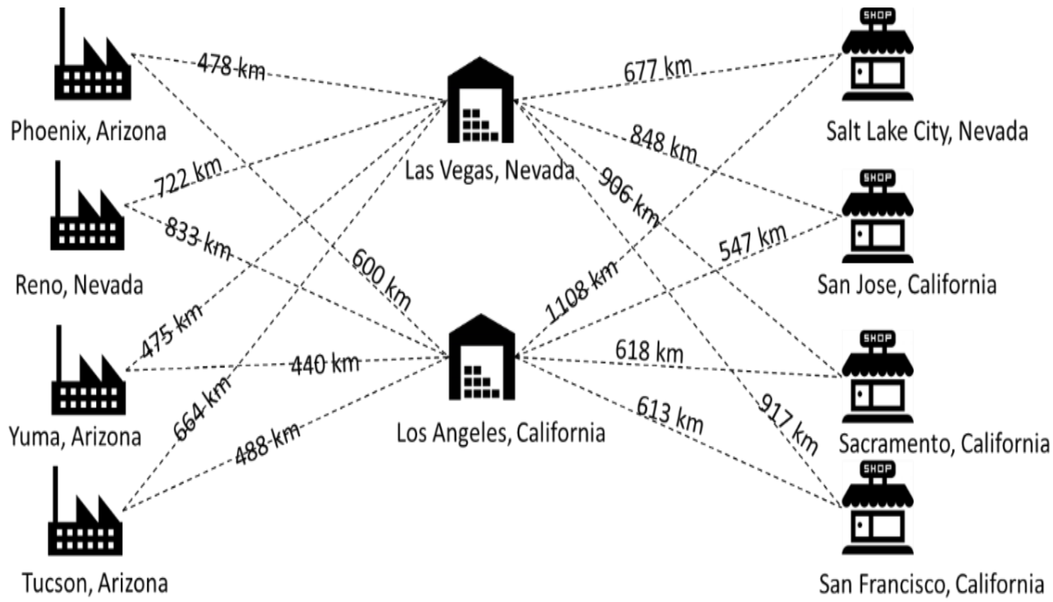

Figure 6. 8: Supply Chain Layout with Distance for Travel

All four factories can produce Products A and B to meet the demand of four retail stores and finished products are transported to warehouse in Las Vegas and Los Angeles using e-trucks. The parameters of WT and PV remain the same as in Chapter 4 when performing the numerical experiment. Table 6.8 shows the demand for four factories where Factory 1 = Phoenix, Factory 2 = Reno, Factory 3= Yuma, and Factory 4= Tucson. Table 6.9 shows the labor and machine resources available for four factories.

Table 6. 8: Product Demand for 52 Weeks

	Store 1		Store 2		Store 3		Store 4	
Week	Product A	Product B	Product A	Product B	Product A	Product B	Product A	Product B
1	698	430	748	513	723	490	724	484
2	791	563	710	584	714	443	684	469
3	670	552	674	422	760	587	639	599
4	753	497	619	442	613	595	726	482
5	763	510	748	525	615	444	664	575
6	656	463	642	524	800	467	629	409
7	715	448	647	460	751	571	771	548
8	636	600	606	412	721	469	642	488
9	660	427	723	597	665	440	645	410
10	703	533	662	573	777	531	622	572
11	737	563	759	449	692	503	706	513
12	791	593	760	425	785	538	758	421
13	726	503	751	462	663	557	680	420
14	796	572	634	575	650	446	767	460
15	729	564	800	503	748	581	635	546
16	740	476	605	415	681	464	660	447
17	773	524	782	426	622	565	646	481
18	623	536	705	556	606	583	790	541
19	795	457	799	520	656	558	646	580
20	749	584	609	528	782	534	618	501
21	778	407	749	514	724	566	637	451
22	706	424	758	515	687	593	790	574
23	701	522	622	555	689	519	602	521
24	659	447	658	401	795	507	761	590
25	730	440	748	437	794	592	667	404
26	650	535	672	600	625	474	629	557
27	672	469	616	514	781	494	689	408
28	740	595	689	594	602	445	753	466
29	643	518	674	592	693	416	662	419
30	628	583	670	575	798	525	667	477
31	690	544	797	470	681	547	739	421
32	647	579	600	433	614	424	754	593
33	721	506	749	522	757	583	670	501
34	606	596	718	546	755	494	765	544
35	786	414	629	505	694	512	772	578
36	731	517	731	490	650	597	754	450
37	658	431	650	585	661	493	667	514
38	642	527	710	410	796	563	718	588
39	708	589	688	481	613	439	653	568
40	795	445	768	402	783	437	742	466
41	631	583	669	590	703	583	688	588
42	677	576	727	455	615	513	718	589
43	747	468	799	569	756	528	708	567
44	747	549	725	538	703	491	745	480

Table 6. 9: Labor and Machine Resource Available

Labor Resources					Machine Resources				
Week	Factory 1	Factory 2	Factory 3	Factory 4	Week	Factory 1	Factory 2	Factory 3	Factory 4
1	22339	16177	22339	16177	1	153366	125481	153366	125481
2	19969	14460	19969	14460	2	134365	109935	134365	109935
3	19414	14058	19414	14058	3	131474	107570	131474	107570
4	19842	14368	19842	14368	4	136784	111915	136784	111915
5	21275	15406	21275	15406	5	143813	117665	143813	117665
6	21263	15397	21263	15397	6	148464	121471	148464	121471
7	19757	14306	19757	14306	7	137196	112251	137196	112251
8	20756	15030	20756	15030	8	144078	117882	144078	117882
9	21021	15222	21021	15222	9	143793	117648	143793	117648
10	21453	15535	21453	15535	10	147598	120762	147598	120762
11	19568	14170	19568	14170	11	132076	108062	132076	108062
12	20625	14935	20625	14935	12	144839	118504	144839	118504
13	21413	15506	21413	15506	13	144176	117962	144176	117962
14	21863	15832	21863	15832	14	147920	121026	147920	121026
15	19170	13881	19170	13881	15	132241	108197	132241	108197
16	22106	16008	22106	16008	16	152234	124555	152234	124555
17	19670	14244	19670	14244	17	132688	108563	132688	108563
18	19470	14099	19470	14099	18	133975	109616	133975	109616
19	22046	13303	22046	13303	19	151033	123573	151033	123573
20	21859	15829	21859	15829	20	148593	121576	148593	121576
21	23695	17158	23695	17158	21	160545	131355	160545	131355
22	22589	16357	22589	16357	22	156057	127683	156057	127683
23	16743	12124	16743	12124	23	118283	96777	118283	96777
24	20237	14654	20237	14654	24	136540	111715	136540	111715
25	18250	13216	18250	13216	25	126745	103701	126745	103701
26	17778	12874	17778	12874	26	120513	98601	120513	98601
27	21959	15901	21959	15901	27	153748	125794	153748	125794
28	22709	16444	22709	16444	28	154559	126457	154559	126457
29	18760	13585	18760	13585	29	130633	106881	130633	106881
30	20046	14516	20046	14516	30	137111	112182	137111	112182
31	21352	15462	21352	15462	31	145118	118733	145118	118733
32	20301	14701	20301	14701	32	138395	113232	138395	113232
33	18652	13507	18652	13507	33	131533	107618	131533	107618
34	21540	15598	21540	15598	34	147977	121072	147977	121072
35	21335	15449	21335	15449	35	146868	120165	146868	120165
36	17682	12804	17682	12804	36	122849	100513	122849	100513
37	18351	13288	18351	13288	37	124532	101890	124532	101890
38	16528	11969	16528	11969	38	114477	93663	114477	93663
39	19488	14112	19488	14112	39	132943	108771	132943	108771
40	19562	14165	19562	14165	40	137230	112279	137230	112279
41	20726	15009	20726	15009	41	142936	116948	142936	116948
42	18995	13755	18995	13755	42	130852	107060	130852	107060
43	20681	14976	20681	14976	43	141760	115985	141760	115985
44	18928	13707	18928	13707	44	132018	108015	132018	108015

b. Results Analysis. The model has total of 848 decision variables which include production level for each factory, inventory for each warehouse, and backorders as well as the onsite power capacity of WT and PV in each facility. Figure 6.9 shows the results of the production quantity of Product A at all factories that meet the deterministic demand per week. Figure 6.10 displays the inventory-backorder level of Product A for all warehouses. Figure 6.11 shows the result of the production quantity for Product B in all the factories. Figure 6.12 displays the inventory backorder level of Product B for all warehouses across 52 periods or weeks.

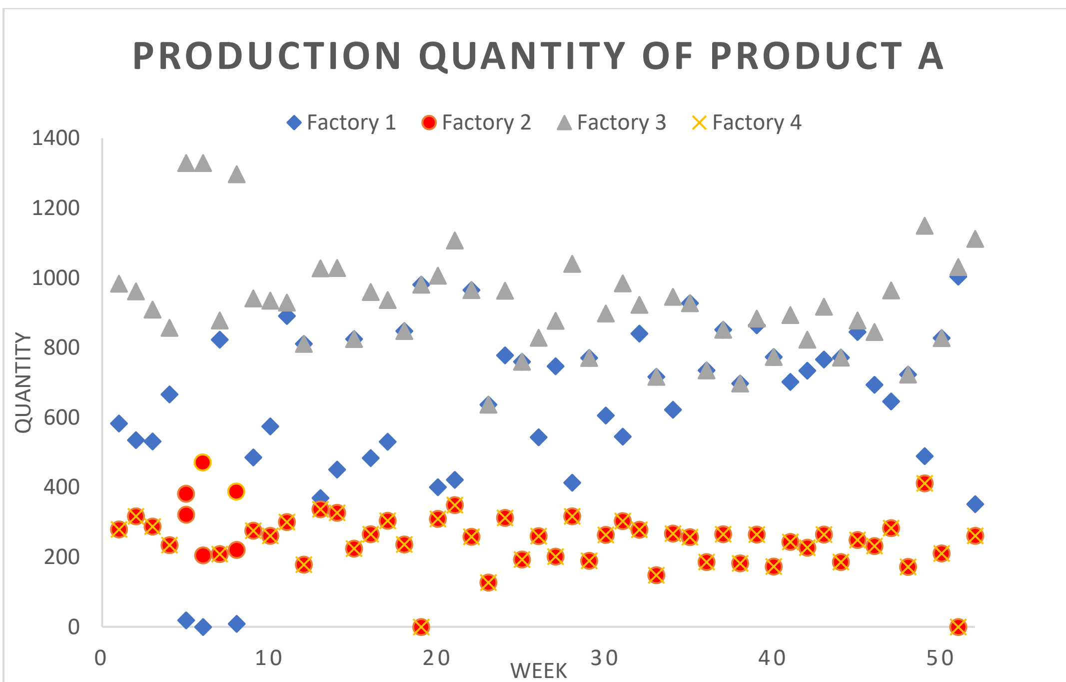

Figure 6. 9: Production Quantity of Product A

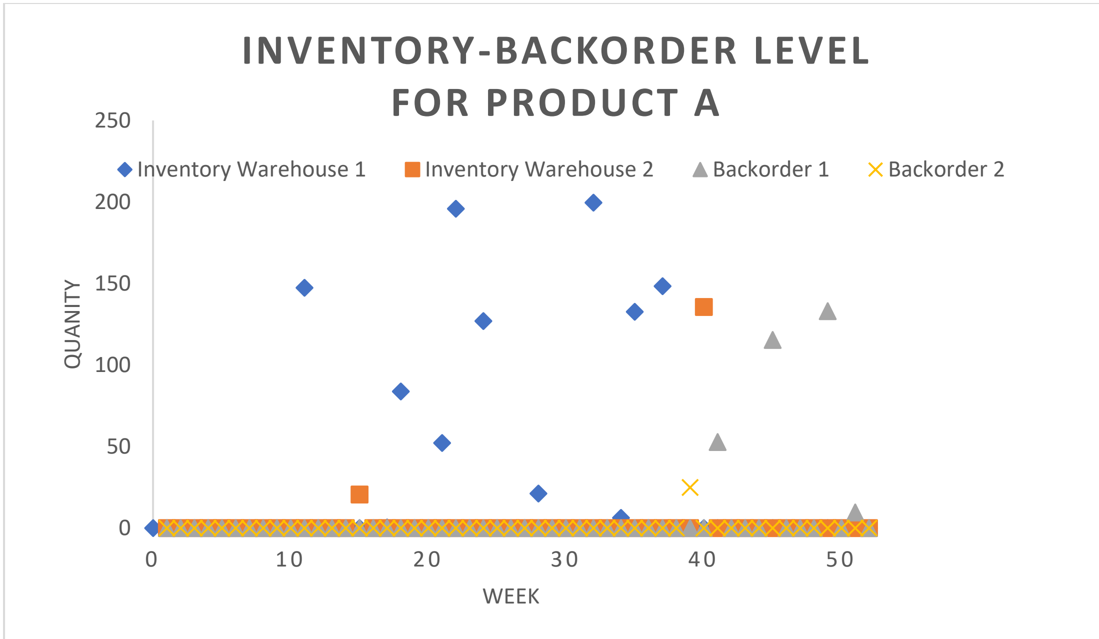

Figure 6. 10: Inventory-Backorder Level of Product A

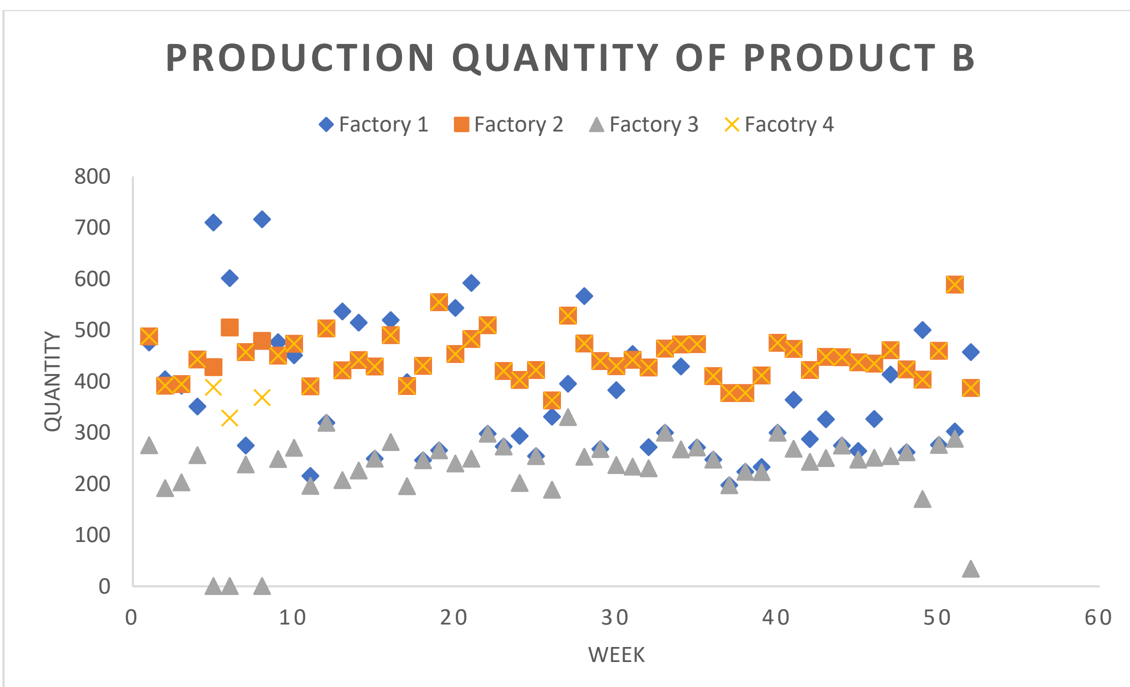

Figure 6. 11: Production Quantity of Product B

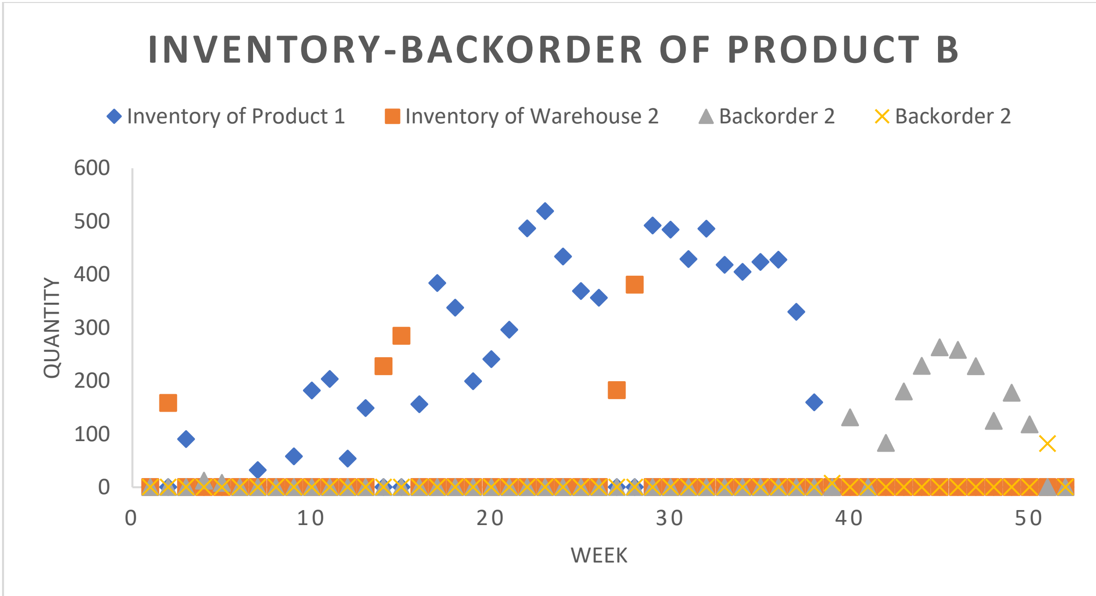

Figure 6. 12: Inventory- Backorder Level of Product B

The results of the optimization of the onsite generation capacity are presented in two cases and summarized in Table 6.10. In the first case, the installation cost of WT system is set at $1.5M/MW and the installation cost of PV system is set at $3M/MW. Since the cost of PV is high, carbon credits are considered. In the second case, the cost of installation is the same as $1.5M/MW and there will be no carbon credits.

Table 6. 10: Comparison under Different PV cost and Carbon Credits

	Case 1		Case 2	
PV Capacity Cost ($/MW)	3,000,000		1,500,000	
WT Capacity Cost ($/MW)	1,500,000		1,500,500	
PV Carbon Credits	35		0	
	Type	Capacity (MW)	Type	Capacity (MW)
Factory 1	WT	129.92	PV	97.67
Facotry 2	WT	72.68	WT	68.17
Factory 3	WT	93.27	PV	78.84
Factory 4	WT	69.97	PV	52.74
Warehouse 1	WT	43.81	WT	43.81
Warehouse 2	WT	77.5	WT	77.5
Retail Store 1	WT	16.58	WT	16.58
Retial Store 2	WT	39.2	WT	39.2
Retial Store 3	WT	20.48	WT	20.48
Retail Store 4	WT	7.05	WT	7.05
Annualized total cost	$ 165,438,000.00		$ 156,577,000.00	

In Case 1 where the PV system cost is higher than WT system, the model chooses to install WT system for all facilities even though carbon credits are applied for PV. The annualized total cost for Case 1 is $156,577,000.00. For the factory locations, Tucson has the lowest capacity requirements of 69.97 MW due to its medium wind speed. On the other hand, Phoenix has the highest capacity of 129.92 MW. For the retail store locations, San Francisco has the lowest wind capacity requirement of 7.05 MW and San Jose has the highest wind capacity requirement of 39.2 MW.

In Case 2 the installation cost of PV and WT is the same with no carbon credits, the model returns a different result than Case 1. The model chooses to install PV system for Phoenix, Yuma, and Tucson locations. Furthermore, the capacity requirement for the PV system is much smaller than the WT system. It can be explained as these cities are known to have strong sun capacity. As the result, the total annualized cost of the supply chain is $156,577,000.00 which is smaller than Case 1. For other cities, the model still chooses WT system as the cost-effective installation.

6.2 Supply Chain System with Microgrid Power and Stochastic Demand

6.2.1 A Stochastic optimization model. The design of this model is similar to the model in Section 6.1. However, unlike the previous model where the demand for each period is deterministic and known before hand, the demand in this model is unknown. Denoted as Problem P5, the stochastic model is formulated as a mixed -integer stochastic programing model because of the uncertainty in product demand and renewable generation.

Problem P5

Minimize:

$$f(\mathrm{x},\mathrm{y},\mathrm{z},\mathrm{P}^c) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m=1}^{M}(p_{ijm}+\pi_i)x_{ijm} + \sum_{i=1}^{I}\sum_{j=1}^{J-1}\sum_{k=1}^{K}h_{ik}y_{ijk} + \sum_{i=1}^{I}\sum_{j=1}^{J-1}b_i z_{ij}$$

$$+\phi\sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{s=1}^{S}a_g(P_{gm}^c+P_{gk}^c+P_{gs}^c) + \tau_g\sum_{g=1}^{G}\sum_{k=0}^{K}\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{s=1}^{S}(b_g-c_g)(\lambda_{gjm}P_{gm}^c+\lambda_{gjk}P_{gk}^c+\lambda_{gjs}P_{gs}^c)$$

(6.11)

Subject to:

$$\sum_{k=1}^{K}x_{ik1}+y_{ik0}-y_{ik1}+z_{ik1} \geq \mu_{D_{is1}} - Z_{1-\gamma}\sigma_{D_{is1}}; \quad \text{for } j=1, \text{ and } \forall i \qquad (6.12)$$

$$\sum_{k=1}^{K}x_{imj}+y_{ijk-1}-y_{ijk}-z_{ijk-1}+z_{ijk} \geq \mu_{D_{ijs}} - Z_{1-\gamma}\sigma_{D_{ijs}}; \quad \text{for } j=2, 3, .., J\text{-}1, \text{ and } \forall i$$

(6.13)

$$\sum_{k=1}^{K} x_{iJ} + y_{iJ-1} - y_{iJ} - z_{iJ-1} \geq \mu_{D_{iJ}} - Z_{1-\gamma}\sigma_{D_{iJ}}; \qquad \text{for } j=J, \text{ and } \forall i \tag{6.14}$$

$$\sum_{i=1}^{I} v_{ilm} x_{ijm} \leq w_{ljm}, \qquad \text{for } \forall i \text{ and } \forall j \tag{6.15}$$

$$z_{ik,J} = 0 \qquad \text{for } \forall i \text{ and } \forall k \tag{6.16}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(e_{im} + q_v n_{mk} d_m m_i) x_{ijm} + q_v n_{mk} d_m w^v = \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G} \lambda_{gjm} P_{gm}^c \tag{6.17}$$

$$t_w L_w + \sum_{j=1}^{J} q_v n_{mk} d_m w^v + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}(m_i D_{ijs} + w^v) q_v n_{jks} d_s = \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G} \lambda_{gjk} P_{gk}^c \tag{6.18}$$

$$t_s L_s + \sum_{j=1}^{J} q_v n_{jks} d_s w^v = \tau_g \sum_{j=1}^{J}\sum_{g=1}^{G} P_{gs}^c \tag{6.19}$$

$$P_{gu}^c, P_{gk}^c, P_{gs}^c \geq 0, \qquad \text{for } \forall g, \forall k, \forall u, \forall s \tag{6.20}$$

$x_{ijm}, y_{ijk}, z_{ijk}$ are non-negative integers (6.21)

6.2.2 Numerical experiments.

a. Multi-factory, multi-store, and single warehouse model. First the supply chain of the multi-factory, single warehouse, and multi-store network is implemented in the model. The model will have the same setting as the one in Chapter 5 with two factories producing two product types, namely product A and product B. The demand for each product in each week is uncertain but given that they will follow the normal distribution. The mean demands and standard deviations for each week in each factory are listed below in Table 6.11. The other parameters associated with production, inventory, and backorders, and transportation will be the same as the deterministic model.

Table 6. 11: Production Demand

	Product 1		Product 2	
Facility	Mean	Standard Deviation	Mean	Standard Deviation
Store 1	706	56	508	60
Store 2	709	62	500	62

i. Result Analysis and Discussion. The production quantity, inventory level, and backlogs for both Products A and B in 52 weeks for Case I are displayed in Figures 6.13 and 6.14. For Case II, the production-inventory results are shown by Figures 6.15 and 6.16. Notice that the model is solved with confidence level of γ=0.9 to meet the production demands.

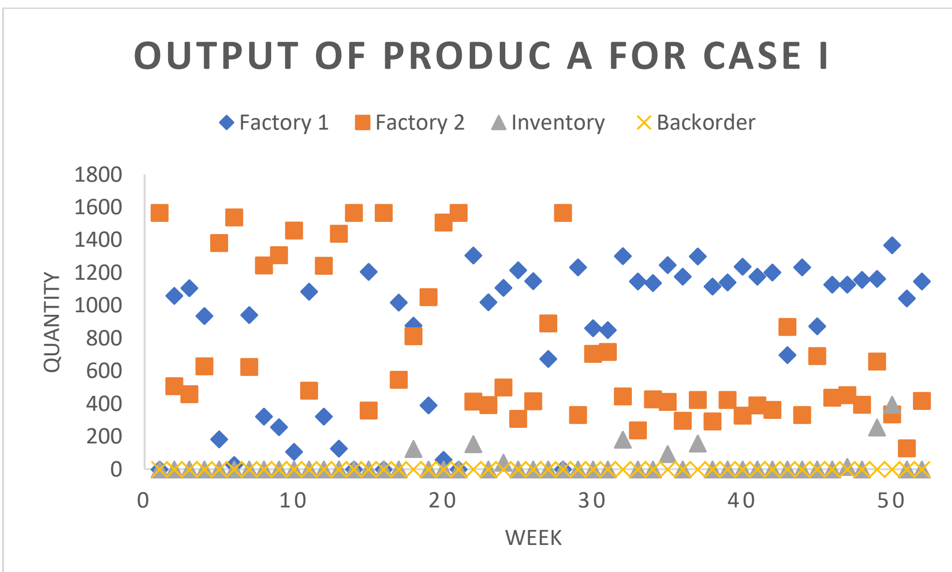

Figure 6. 13: Production Output of Product A for Case I

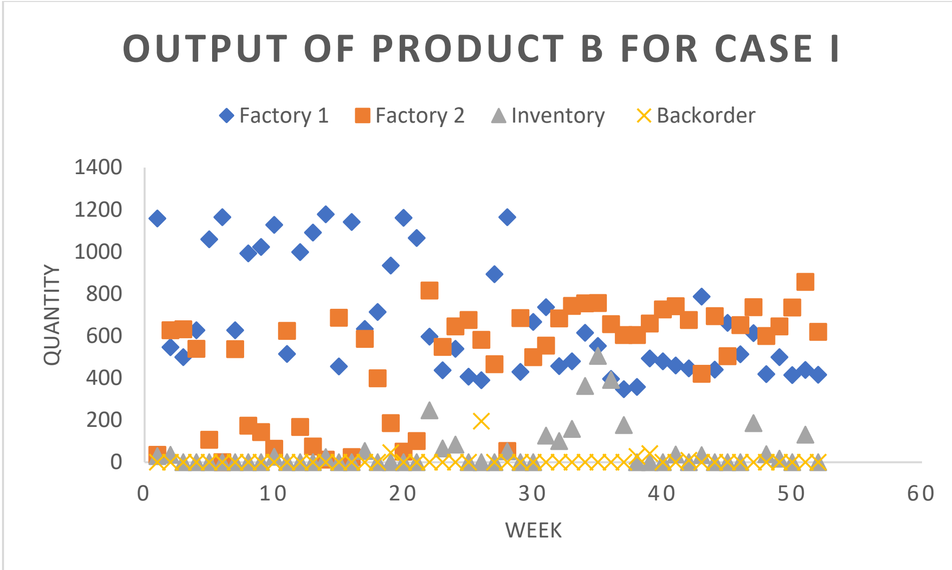

Figure 6. 14: Production Output of Product B for Case I

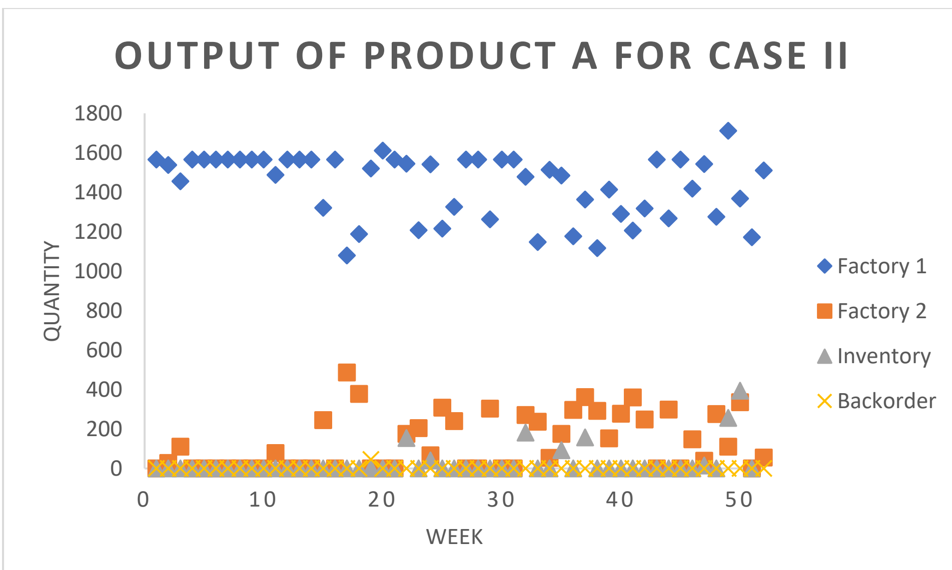

Figure 6. 15: Production Output of Product A for Case I

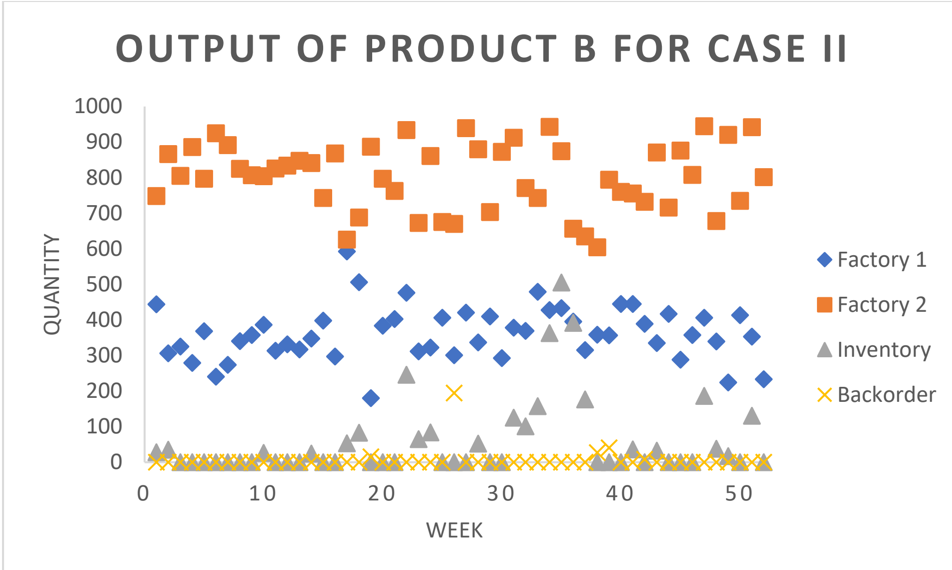

Figure 6. 16: Production Output of Product B for Case II

Two scenarios are considered to test the model in which the network layouts are similar to the deterministic model (Section 6.1.4). In Case 1, Phoenix, Arizona and Reno, Nevada are chosen to set up the manufacturing facilities while warehouse is located in Las Vegas, NV. Retail stores will be located in Salt Lake City, UT and San Jose, CA. Case 2 will have the factories located in Yuma, AZ and Tucson, AZ. The warehouse location is in Los Angeles, CA while retail stores are located at Sacramento, CA and San Francisco, CA. The layout of both cases and the travel distances can be observed in Figures 6.17 and 6.18 below.

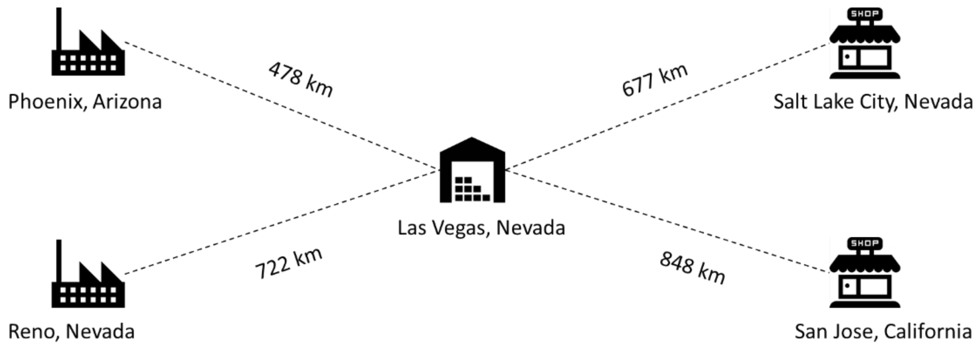

Figure 6. 17: Case 1 Supply Chain Network

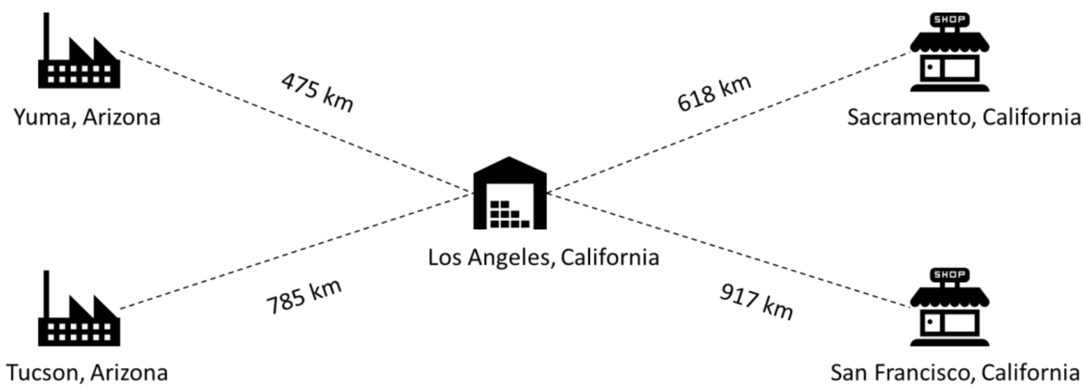

Figure 6. 18: Case 2 Supply Chain Network

ii. The Cases with Carbon Credits. For these runs, the cost of WT system installation is $1.5M/MW and the cost of PV system installation is $3M/MW. Carbon credits are also considered for PV system dues to its high installation cost. The output of decision variables of two cases with carbon credits is displayed in Table 6.12.

Table 6. 12: Results of Production-Logistics Systems of Two Cases

Case I			Case II		
	Type	Capacity (MW)		Type	Capacity (MW)
Factory 1 - Phoenix	WT	98.81	Factory 1 - Yuma	WT	72.76
Factory 2 - Reno	WT	59.55	Factory 2 - Tucson	WT	49.68
Warehouse - Las Vegas	WT	43.36	Warehouse - Los Angeles	WT	76.78
Store 1 - Salt Lake City	WT	16.45	Store 1 - Sacramento	WT	20.35
Store 2 - San Jose	WT	38.96	Store 2 - San Francisco	WT	7
Annualized system cost	$92,295,600.00		Annualized system cost	$91,983,300.00	

In Case I, the annualized total cost of production, transportation, inventory, and energy is $92,295,600 and for Case II is $91,983,300. As expected, the model chooses to install WT system for all its locations despite of carbon credits of $35/MWh being applied to PV. Compared with deterministic model (see Table 6.7 of Section 6.1.4), it can be seen that capacity requirements for all the locations in the stochastic model are very similar to the deterministic model.

iii. The Cases without Carbon Credits. For this run, the installation cost for both WT and PV systems are set at $1.5M/MW. Since the cost for both systems are low, carbon credits will not be applied to PV. Table 6.13 shows the result of running the model for the Production-Logistics system under two cases and without carbon credits.

Table 6. 13: Capacity Output of Two Cases without Carbon Credits

Case I			Case II		
	Type	Capacity (MW)		Type	Capacity (MW)
Factory 1 - Phoenix	PV	78.25	Factory 1 - Yuma	PV	55.87
Factory 2 - Reno	WT	51.05	Factory 2 - Tucson	WT	42.91
Warehouse - Las Vegas	WT	43.36	Warehouse - Los Angeles	WT	76.78
Store 1 - Salt Lake City	WT	16.45	Store 1 - Sacramento	WT	20.35
Store 2 - San Jose	WT	38.96	Store 2 - San Francisco	WT	7
Annualized system cost	$88,601,700.00		Annualized system cost	$88,836,500.00	

In this test, the model chooses to install PV system for facilities located in Phoenix, Tucson, and Yuma. Since these cities have strong sun capability, the capacity requirements for onsite generation system are much lesser compared to the WT system if chosen. The PV capacity requirement is 21 percent less than the WT capacity requirement for Phoenix, 23.21 percent in Yuma, and 13.63 percent in Tucson. As the result, the annualized total costs are lower than the previous test. For Case 1, the annualized total cost is $88,601,700, and for Case II, the annualized total cost is $88,836,500.

b. Multi-warehouse supply chain system. Using the same setting, this Section presents the results of solving Problem P5 for a multi-warehouse supply chain system under deterministic demand. The supply chain network will include four-factories, two-warehouses, and four-retail stores. Figure 6.19 shows the layout of the supply chain network and the distance between destinations. Table 6.14 shows the mean production demand and standard deviation of all the factories.

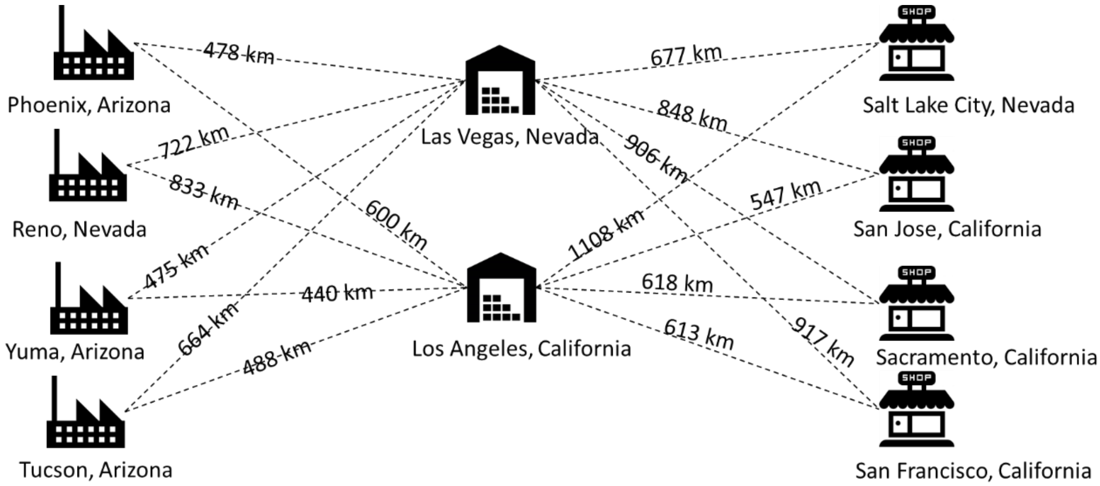

Figure 6. 19: Supply Chain Layout with Distance Travel

Table 6. 14: Mean and Standard Deviation of Demand for Product A and Product B

Facility	Product A		Product B	
	Mean	Stdv	Mean	Stdv
Store 1	780	50	740	45
Store 2	809	51	760	60
Store 3	850	60	780	62
Store 4	810	62	700	55

i. Result Analysis. In this test, the model also has total of 848 decision variables and more than 500 constraints. Figure 6.20 indicates the output of the production quantity for product A at all factories that meet the uncertain demand of each week. Figure 6.21 displays the inventory-backorders level of product A for all warehouses. Figure 6.22 shows the result of the production quantity for Product B at all factories.

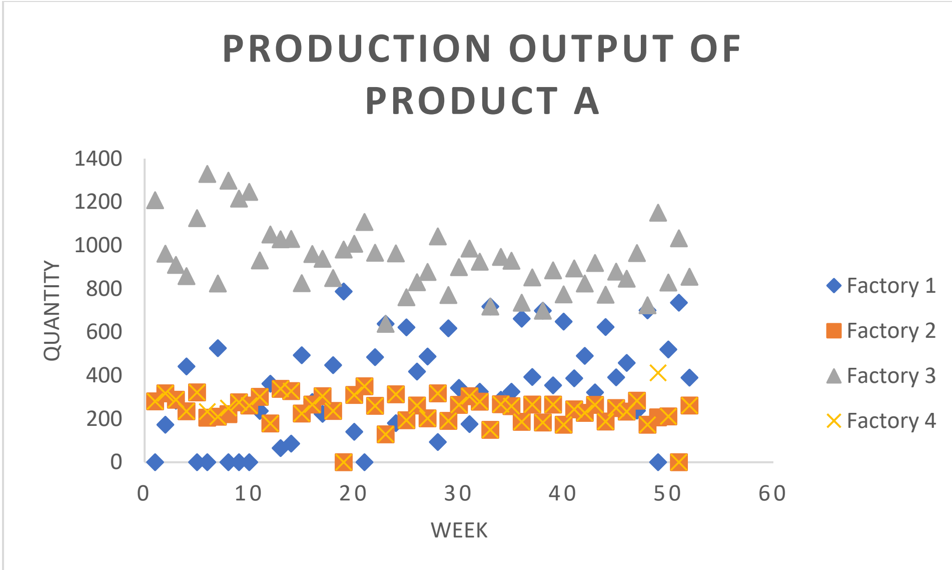

Figure 6. 20: Production Output for Product A

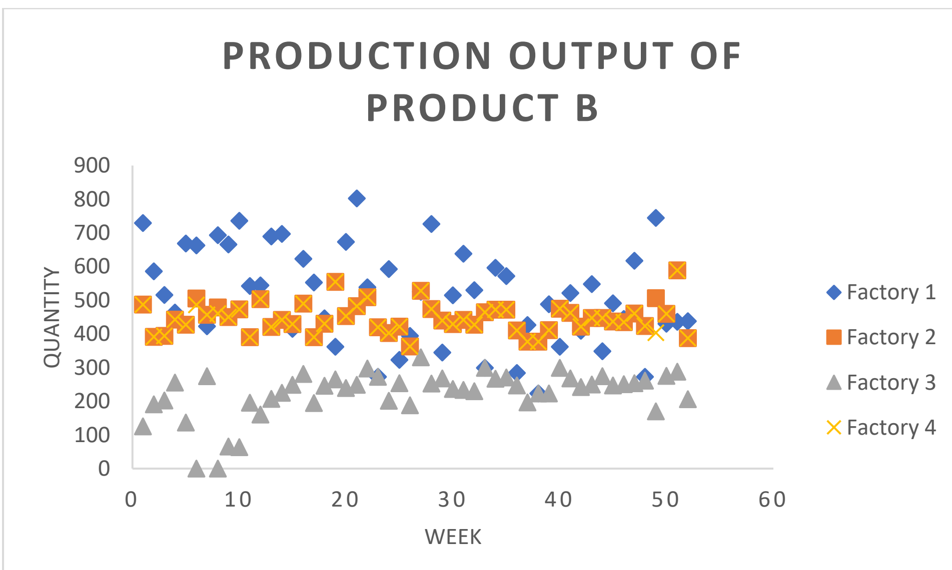

Figure 6. 21: Production Output for Product B

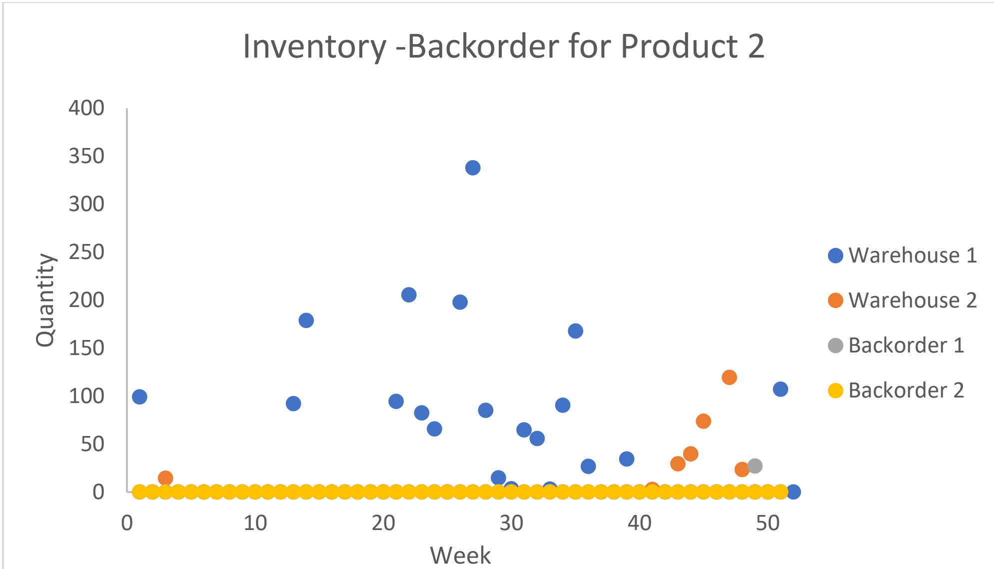

Figure 6. 22: Inventory-Backorder level for Product B

The results of the optimization of onsite generation capacity are presented in two cases and summarized in Table 6.16. In the first case, the installation cost of WT system is set at $1.5M/MW and the installation cost of PV system is set at $3M/MW. Since the cost of PV is high, carbon credits are considered. In Case 2, the cost of installation is the same as $1.5M/MW and there will be no carbon credits.

Table 6. 15: Optimization of Onsite Generation Capacity

	Case 1		Case 2	
PV Capacity Cost ($/MW)	3,000,000		1,500,000	
WT Capacity Cost ($/MW)	1,500,000		1,500,500	
PV Carbon Credits	35		0	
	Type	Capacity (MW)	Type	Capacity (MW)
Factory 1	WT	119	PV	91.12
Factory 2	WT	72.57	WT	66.04
Factory 3	WT	93.35	PV	78.82
Factory 4	WT	69.89	PV	52.91
Warehouse 1	WT	43.42	WT	43.42
Warehouse 2	WT	46.91	WT	76.91
Retail Store 1	WT	16.45	WT	16.45
Retail Store 2	WT	38.96	WT	38.96
Retail Store 3	WT	20.35	WT	20.35
Retail Store 4	WT	7	WT	7
Annualized total cost	$148,952,000.00		$140,476,000.00	

It can be observed that the annualized total cost of Case 2 is lower than the cost of Case 1 and the difference of the cost is 5.69 percent. In Case 1, since the cost of PV system is twice as high of the WT system, the model chooses to install a WT system to optimize the operation cost. However, in Case 2 where the capacity costs of WT and PV system are the same, it is more economical to install PV system dues to the strong sun capacity of the cities.

VII. CONCLUSIONS AND FUTURE WORK

Under the concept of inter-connected microgrid operation, this thesis proposes to integrate onsite renewables into a multi-site production-logistics system for attaining net-zero energy performance. The goal is to determine the production, inventory, backorders, and renewables capacity in each facility such that the total cost is minimized. To tackle the problem, we propose a renewable generation analytics framework in which over 80,000 meteorological data are collected, classified and analyzed to extrapolate the power capacity factors under various climate conditions.

Our study contributes to the production and supply chain literature in two aspects. First, we present a quantitative model to analyze the feasibility and cos-effectiveness of realizing net-zero energy production-logistics operation using onsite renewable generation. The thesis introduces two types of models: deterministic model and stochastic model. The deterministic model can be applied in the industry where the demands are known or relatively stable in each period while the stochastic model can be used in the industry where the demands are uncertain or unpredictable. The proposed renewable generation analytics methodology allows the planner to transform a complex stochastic programming problem into a two-stage deterministic optimization model.

As the second contribution, manufacturing facilities have long been treated as energy consumers. This thesis makes an early attempt to convert the manufacturers into a "prosumer" who can produce and consume energy concurrently. Eighteen cities that cover a wide range of wind and weather profiles are chosen to test and verify the proposal model. The experiments show that achieving net-zero energy operation is affordable in regions where the ground wind speed is above 5 m/s or the overcast days in a year are less than 50%. The study also shows that PV can compete with wind generation only if its capacity cost is down to \$1.5M/MW or its power efficiency increases to 30% (which is equivalent to reducing the cost by a half).

Future work can be expanded to a globalized production logistics supply chain with different transportation modes, such as electric trains. Another extension of the model can be incorporating battery storage systems into the microgrid system. An energy storage system by which excess power produced by WT or PV system can be stored locally to hedge against the periods when the wind profile and solar radiation are weak. As a result, the facilities can avoid importing electricity from the main grid when there is no wind or solar power available. Last, but not the least, with the growing deployment of electric vehicle fleet, there exist plentiful opportunities for the inter-operation between the electrical vehicles and the local microgrid systems through V2G and G2V operations in transactive energy market mechanism. In conjunction with demand response, these emerging technologies will be incorporated into the production and logistics model as the future research.

APPENDIX SECTION

APPENDIX A Single Facility Plus Warehouse and E-Transport with Deterministic Demand Optimization Programing

```
set TYPE; # WT or PV

#set parameters
param T > 0;
param C > 0;
param cap_fact {1..T, TYPE} >= 0; #factory location capacity
param wh_cap {1..T, TYPE} >=0; #warehouse location capacity
param demand_prod {i in 1..T, p in 1..C} >= 0; #production demand
param labor_dem {1..T} >= 0; # labor resources
param machi_dem {1..T} >= 0; #machine resources
param cost_prod {1..C} >= 0; #production cost
param cost_hold {1..C} >= 0; #holding cost
param cost_back {1..C} >= 0; #backlog cost
param res_labor {1..C} >=0; #labor hourly cost
param res_mach {1..C} >=0; #machine hourly cost
param ins_cost {TYPE}>= 0; #installation cost
param om_cost{TYPE} >= 0; #operation and maintenance cost
param carbon_credit{TYPE} >= 0; #carbon credit
param eng_consume{1..C} >= 0; #energy consumed per product type
param oper_hrs{TYPE} >= 0; #operation hours
param cap_recover >= 0; #capital recovery
param e_ware >= 0; #energy consumed by warehouse
param inv0; #initial inventory level
param back0; #initial backlog level

param distance >=0; #distance travel
param freq >= 0; #travel frequency
param w_goods >= 0; #weight of goods
param w_vehicle >= 0;#weight of vehicle
param density >= 0;

#Define variable
var prod_month {1..T, 1..C} >= 0; #production level
var hold_month { 0..T, 1..C} >= 0; #inventory level
var back_month { 0..T, 1..C} >=0; #backlog level
var capacity {j in TYPE}>=0; #factory capacity
var wh_capacity{j in TYPE}>=0; # warehouse capacity

#Calculate Production Cost
var ProductionC=
      sum {i in 1..T, p in 1..C} cost_prod[p]*prod_month[i,p];

#calculate inventory cost
var Inventory=
       sum {i in  1..T,p in  1..C} cost_hold[p] * hold_month[i,p];

#calaculate backorder cost
var Backorder=
```

```
      sum {i in 1..T, p in 1..C} cost_back[p] * back_month[i,p];
#calculate installation, operation and maintenance cost, and carbon credits for
factory#
var IntFact=
      sum {j in TYPE} capacity[j] * ins_cost[j]*cap_recover;
var OmFact =
      sum {i in 1..T,j in TYPE } capacity[j] * om_cost[j] *
cap_fact[i,j]*oper_hrs[j];
var Credit_fact=
      sum {i in 1..T, j in TYPE } capacity[j] * carbon_credit[j] *
cap_fact[i,j]*oper_hrs[j];

#calculate installation, operation and maintenance cost, and carbon credits for
factory#
var IntWare =
      sum {j in TYPE} wh_capacity[j] * ins_cost[j]*cap_recover ;
var OmWare =
      sum {i in 1..T, j in TYPE } wh_capacity[j] * om_cost[j] *
wh_cap[i,j]*oper_hrs[j];
var Credit_ware =
      sum {i in 1..T, j in TYPE } wh_capacity[j] * carbon_credit[j] *
wh_cap[i,j]*oper_hrs[j];

#Objective Function
minimize total_cost:
      ProductionC + Inventory + Backorder + IntFact+OmFact - Credit_fact +
IntWare + OmWare - Credit_ware;

#Constraints

#Energy balance for factory
subject to Requirement :
      (sum {i in 1..T,p in 1..C} prod_month[i,p] * eng_consume[p])+
density*distance*freq*(w_goods+w_vehicle) = (sum{i in 1..T,j in TYPE}
cap_fact[i,j]*capacity[j]*oper_hrs[j]);

#Energy balance for warehouse
subject to Warehouse:
      sum{i in 1..T,j in TYPE} wh_cap[i,j]*wh_capacity[j]*oper_hrs[j]=
8760*e_ware + density*distance*freq*(w_vehicle);

#initial inventory and backlog
subject to Init_hold{p in 1..C}: hold_month[0,p] = inv0;
subject to Init_back{p in 1..C}: back_month[0,p] = back0;

#production and demand equity
subject to Production { i in 1..T, p in 1..C}:
      prod_month[i,p] + hold_month[i-1,p] + back_month[i,p] = demand_prod[i,p]+
hold_month[i,p] + back_month[i-1,p] ;

#balancing labor resources
subject to LaborDemand {i in 1..T}: sum{ p in 1..C} prod_month[i,p] *
res_labor[p] <= labor_dem [i];
```

```
#balancing machine resources
subject to ProdDemand { i in 1..T}: sum{ p in 1..C} prod_month[i,p] * res_mach[p]
<= machi_dem [i];

#No backlog at the end of production period
subject to Ending {p in 1..C}: back_month[52, p] = 0;

##################                          DATA                              FILE
#########################################################

data;

set TYPE:= WT PV;

param T:= 52;
param C:= 2;

param cap_fact:     #Yuma with scattered and partly
      WT           PV :=
1      0.1592 0.1734
2      0.141  0.3004
3      0.1494 0.3352
4      0.1154 0.2209
5      0.0968 0.3161
6      0.0953 0.3033
7      0.0898 0.3697
8      0.0977 0.3107
9      0.1207 0.3384
10     0.1386 0.3473
11     0.0856 0.3538
12     0.1222 0.4017
13     0.1514 0.3771
14     0.1554 0.2943
15     0.2274 0.403
16     0.1485 0.4821
17     0.1979 0.3947
18     0.2243 0.3497
19     0.1386 0.397
20     0.1435 0.3867
21     0.2232 0.4469
22     0.1369 0.4646
23     0.2041 0.3862
24     0.1333 0.3433
25     0.1308 0.3837
26     0.1788 0.3905
27     0.2821 0.3776
28     0.198  0.3788
29     0.2078 0.2977
30     0.2481 0.2366
31     0.2091 0.3714
32     0.1942 0.3733
33     0.2154 0.2618
34     0.2101 0.3049
35     0.1728 0.4111
```

```
36      0.1986 0.2471
37      0.1152 0.3361
38      0.0753 0.4437
39      0.0717 0.4028
40      0.1187 0.4093
41      0.0749 0.4392
42      0.0998 0.4089
43      0.1011 0.4154
44      0.0793 0.3426
45      0.1088 0.3427
46      0.1103 0.3324
47      0.0834 0.2952
48      0.088  0.2404
49      0.1346 0.2365
50      0.091  0.2857
51      0.1197 0.2588
52      0.137  0.2494

;

param wh_cap:  #San Francisco
        WT            PV :=
1       0.1261 0.1399
2       0.118  0.1972
3       0.1286 0.1829
4       0.1407 0.0892
5       0.16   0.0813
6       0.2054 0.1935
7       0.2773 0.1129
8       0.2408 0.191
9       0.2961 0.2102
10      0.3447 0.2232
11      0.3757 0.1554
12      0.402  0.1851
13      0.4784 0.2091
14      0.4645 0.1622
15      0.5848 0.2483
16      0.4926 0.3127
17      0.615  0.2414
18      0.5643 0.2475
19      0.6652 0.2039
20      0.6212 0.2585
21      0.6948 0.2986
22      0.5806 0.1725
23      0.6561 0.2881
24      0.6406 0.2597
25      0.6303 0.3001
26      0.5577 0.2387
27      0.5641 0.2801
28      0.5813 0.2673
29      0.54   0.2409
30      0.5455 0.2421
31      0.5475 0.2016
32      0.5006 0.2583
```

```
33      0.5766 0.259
34      0.4021 0.2311
35      0.5042 0.3004
36      0.4654 0.2846
37      0.4745 0.3228
38      0.4286 0.2505
39      0.3371 0.3124
40      0.3368 0.241
41      0.2676 0.2333
42      0.248  0.2686
43      0.2305 0.2638
44      0.1524 0.1907
45      0.169  0.1571
46      0.1771 0.1826
47      0.1364 0.156
48      0.165  0.1174
49      0.1443 0.144
50      0.1502 0.109
51      0.2077 0.2216
52      0.2032 0.1706

;

param inv0 :=0;

param back0 := 0;

param demand_prod:
        1            2       :=
1       1108   662
2       1033   552
3       1036   517
4       900          639
5       1130   568
6       985          673
7       904          625
8       996          632
9       1065   597
10      1082   625
11      1039   523
12      956          659
13      1141   578
14      1151   590
15      918          589
16      1026   689
17      1035   538
18      987          560
19      1078   661
20      1126   611
21      1207   674
22      1119   668
23      693          579
24      1082   547
25      824          593
```

```
26     932           493
27     1030   691
28     1172   640
29     788           646
30     1032   561
31     1143   578
32     1001   597
33     781           646
34     1129   590
35     1094   609
36     843           540
37     977           490
38     744           534
39     952           576
40     876           639
41     1073   584
42     849           613
43     1032   605
44     823           640
45     952           614
46     972           574
47     1121   603
48     815           578
49     1303   528
50     918           630
51     1160   685
52     953           522

;


param: labor_dem := 1  33491     2  29937     3  29106     4  29747     5
31895  6  31878     7  29619     8  31117     9  31515     10  32164    11
29338  12  30921    13  32104    14  32777
15  28739    16  33141    17  29490    18  29189    19  33051    20      32771
       21  35524    22  33865    23  25102    24  30339    25  27362    26
26653  27  32922    28  34046    29  28126    30  30053
31  32011    32  30436    33  27963    34  32293    35  31985    36      26510
       37  27512    38  24779    39  29218    40  29328    41  31073    42
28477  43  31005    44  28378    45  29957    46  29289
47  32256    48  26740    49  33685    50  29783    51  35097    52  27893
;

param: machi_dem := 1  242475    2   212434   3   207863   4  216259    5
227372 6   234726   7   216910   8  227792    9  227340    10   233355  11
208816
12   228993         13  227945   14  233865   15   209075         16     240686
      17   209783         18   211817         19   238788         20   234929
      21    253825 22     24673023   187008
24    215874 25     20038726   190534         27    243079 28     24436129
206533        30    216776 31     22943532   218805         33    207957 34
233956 35   232201  36    194227 37     19688838   180992         39    210185
```

```
40      21696441    225985   42     206880  43      22412644    208723          45
216978 46      21284947    232648   48     196885  49      23546250    218112   51
254060 52      200111
;

param: cost_prod:=
       1 400
       2 600 ;

param : cost_hold:=
       1 80
       2 120 ;

param : cost_back:=
       1 200
       2 300;

param: res_labor:=
       1 16
       2 24;

param: res_mach:=
       1 100
       2 200;

param: eng_consume:=
       1 0.9
       2 1.2;

param ins_cost:=
       WT 1500000
       PV 3000000;

param om_cost:=
       WT 10
       PV 8 ;

param carbon_credit:=
       WT 0
       PV 35;

param e_ware := 7;
param oper_hrs :=
       WT     168
       PV     84;
param cap_recover := 0.0802;
param distance := 439;
param freq := 468;
param w_goods := 18000;
param w_vehicle := 5000;
param density := 0.000000119;
```

APPENDIX B: Getting Wind Data from WeatherUnderground Using R Code

```
library(weatherData)
#get station airport code
getStationCode("Reno", region = "Nevada")
#get wind data for 11 year from 2006 to 2016
year2016<-getSummarizedWeather(station_id = 'KTUS', start_date = '2016-01-01',
end_date = '2016-12-31', station_type = "airportCode",opt_temperature_columns =
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2015<-getSummarizedWeather(station_id = 'KTUS', start_date = '2015-01-01',
end_date = '2015-12-31', station_type = "airportCode",opt_temperature_columns =
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2014<-getSummarizedWeather(station_id = 'KTUS', start_date = '2014-01-01',
end_date = '2014-12-31', station_type = "airportCode", opt_temperature_columns
= FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2013<-getSummarizedWeather(station_id = 'KTUS', start_date = '2013-01-01',
end_date = '2013-12-31', station_type = "airportCode",opt_temperature_columns =
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2012<-getSummarizedWeather(station_id = 'KTUS', start_date = '2012-01-01',
end_date = '2012-12-31', station_type = "airportCode", opt_temperature_columns
= FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2011<-getSummarizedWeather(station_id = 'KTUS', start_date = '2011-01-01',
end_date = '2011-12-31', station_type = "airportCode",opt_temperature_columns =
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2010<-getSummarizedWeather(station_id = 'KTUS', start_date = '2010-01-01',
end_date = '2010-12-31', station_type = "airportCode",opt_temperature_columns =
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2009<-getSummarizedWeather(station_id = 'KTUS', start_date = '2009-01-01',
end_date = '2009-12-31', station_type = "airportCode",opt_temperature_columns =
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2008<-getSummarizedWeather(station_id = 'KTUS', start_date = '2008-01-01',
end_date = '2008-12-31', station_type = "airportCode", opt_temperature_columns
= FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2007<-getSummarizedWeather(station_id = 'KTUS', start_date = '2007-01-01',
end_date = '2007-12-31', station_type = "airportCode",opt_temperature_columns =
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
year2006<-getSummarizedWeather(station_id = 'KTUS', start_date = '2006-01-01',
end_date = '2006-12-31', station_type = "airportCode",opt_temperature_columns =
```

```
FALSE, opt_all_columns =FALSE, opt_custom_columns = TRUE, custom_columns =
c(18))
library(rowr)
weather <-cbind.fill(year2016, year2015, year2014, year2013, year2012, year2011,
year2010, year2009, year2008, year2007, year2006)
write.csv(weather, "Tucson.csv")
data <- read.csv("Tucson.csv")
#print(data)
data                <-                data[,!(colnames(data)                %in%
c("Date","Date.1","Date.2","Date.3","Date.4","Date.5","Date.6","Date.7","Date.
8","Date.9","Date.10"))]
write.csv(data, "Tucson.csv")
library(xlsx)
#install.packages('plyr')
library(plyr)
dat<-read.csv("Tucson.csv")
y16 = xtabs(~ Week + Year2016, dat)
y15 = xtabs(~ Week + Year2015, dat)
y14 = xtabs(~ Week + Year2014, dat)
y13 = xtabs(~ Week + Year2013, dat)
y12 = xtabs(~ Week + Year2012, dat)
y11 = xtabs(~Week + Year2011, dat)
y10 = xtabs(~ Week + Year2010, dat)
y9 = xtabs(~ Week + Year2009, dat)
y8 = xtabs(~ Week + Year2008, dat)
y7 = xtabs(~ Week + Year2007, dat)
y6 = xtabs(~ Week + Year2006, dat)

weather<-cbind(y16,y15,y14,y13,y12,y11,y10,y9,y8,y7,y6)
write.csv (weather, "Tucson_sun.csv")
```

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