DESIGN OF PROSUMER MICROGRID AND VIRTUAL POWER PLANTS FOR MULTI-TIER MANUFACTURING SUPPLY CHAINS

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 Engineering
December 2020

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DEDICATION

I express my sincere gratitude to my family, and to my friends for providing their support, guidance, and encouragement throughout my time of study, research and writing this Thesis. This accomplishment would not have been possible without them.

ACKNOWLEDGEMENT

I would first like to thank my thesis advisor Dr. Tongdan Jin of the Ingram School of Engineering at Texas State University for his enormous support and guidance throughout my research. He also provided me with moral support and motivation that could help me in my future career.

I would also like to extend my gratitude to Dr. Clara Novoa of the Ingram School of Engineering at Texas State University for her insightful comments and valuable suggestions during the thesis research.

I would also like to express my gratitude to my thesis committee members Dr. Eduardo Pérez and Dr. Zhijie Sasha Dong for their ideas and remarks on this work.

I am grateful to Dr. Vishu Viswanathan, Graduate Advisor of Ingram School of Engineering for all his valuable advices during my time at Texas State University also extend my wishes to all the professors at the Ingram School.

Finally, I am extending my appreciations to the United States National Science Foundation for partially funding this thesis research under ME-GREEN CBET project (grant # 1704933).

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LIST OF ABBREVIATION

Abbreviation	**Description**
AMPL	Advance Mathematical Programming Language
ASOS	Automated Surface Observing System
BSS	Battery Storage Systems
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
DER	Distributed Energy Resource
DG	Distributed Generation
ES	Electrical Storage
EV	Electric Vehicle
F	Factory
IoE	Internet of Energy
kWh	kilowatt-hour
LA	Los Angeles
LCOE	Levelized Cost of Energy
LOU	Level of Use
LV	Las Vegas
MW	Megawatt

MWh	Megawatt-hour
PV	Photovoltaic
RTP	Real Time Pricing
S	Store
SF	San Francisco
SJ	San Jose
SL	Salt Lake
TOU	Time of Use
TS	Thermal Storage
VPP	Virtual Power Plant
W	Warehouse
WT	Wind Turbine
WU	Weather Underground

ABSTRACT

Production, warehousing and logistics activities consume one-third of global electricity. Generation and integration of cleaner energy is an effective way to achieve higher power efficiency and to mitigate greenhouse gas emissions. This research focuses on siting and sizing wind- and solar-based microgrid system in manufacturing supply chain under demand and supply uncertainty. The study treats two-way energy flow as a new feature along with material, information and cash flows in supply chain operations. First, we design a three-tier manufacturing infrastructure for net zero energy performance by integrating wind turbine, photovoltaics, and energy storage under cost minimization. Second, we combined prosumer microgrid and combined heat and power to form virtual power plants (VPP) in pursuit of profit maximization. The proposed method can guide the manufacturing industry in harnessing onsite renewable sources to attain environmental sustainability. The mixed integer linear programming models are solved with A Mathematical Programming Language using CPLEX solver. The feasibility of the energy solution is further examined through numerical experiments in ten US cities based on 11-year hourly meteorological data. The study shows that integrating onsite renewable energy is a key to mitigating environmental impacts, improving energy reliability and manufacturing sustainability. The research also indicates that the adoption of a feed-in tariff, time-of-use rate, prosumer energy trading, and VPP scheme can reduce the utility bills and accelerate the achievement of 100% renewables integration.

1.INTRODUCTION AND LITERATURE REVIEW

1.1 Research Motivation and Background

Climate change has become one of the most important topics that have attracted a lot of academic researchers, policy makers and industry professionals. Climate change has caused a lot of environmental issues. Increase in carbon emissions is considered as a major cause of this issue. Thus, reducing carbon emissions has become a primary goal of many countries. Everyday human activities such as transportation, power generation, construction and industrial activities emit large amounts of carbons and pollutants. It is important to develop methodologies which aid world governments to come up with policies that can reduce carbon emissions. Sustainability practices are a key element in avoiding the depletion of natural resources to maintain ecological balance in the environment. Such sustainability practices can be implemented in global manufacturing sectors. Implementing sustainable manufacturing is important for many reasons. Firstly, it helps fight climate change and enhance the safety of the facility, products, and community. Sustainable manufacturing can help reduce operation cost, increase efficiency, and can help lower energy consumption. The major segments around manufacturing are: 1) the physical facility itself used to carry out the daily operations, 2) the materials which aids the production process, 3) the equipment used in the process, 4) the workers involved in day to day activities, 5) the storage space where the products are stored, and 5) most importantly the logistics to transport goods to places. All these focus areas can be addressed in manufacturing sustainability. This research focuses on integrating renewable energy technologies which can help achieve sustainable and eco-friendly manufacturing practices.

1.2 The Start-of-the-art of Industry Practices

Many major companies have started to implement eco-friendly operations across their facilities. This section reviews the current implementation of such technologies and their start-of-the-art.

IKEA, a Scandinavian company which sells ready-to-assemble furniture and household appliances in various countries have started to implement sustainability throughout their everyday business activities. The store has concentrated on using third party electrical vehicles (EV) for their logistics. IKEA has installed 700,000 solar photovoltaic (PV) panels which are used to power their stores. They have also entered the net energy market where they can produce energy through PV and wind turbine (WT) and sell to it the utility companies as a clean source of energy (The Guardian, 2020).

UNILIVER a consumer goods manufacturing company, has been actively upgrading their businesses towards green operations. Earlier in 2015 the company pledged that their operations will be net zero carbon by 2030. In 2019, 45.8% of their total electrical and thermal energy use was through renewable resources compared to 15% in 2008. The company constantly invests in the areas of heat pumps, solar power and wind energy. Currently, 85% of their grid electricity usage comes from renewable energy sources (Uniliver, 2020).

IBM is an early adopter of sustainable and eco-friendly business. Their initiatives include cognitive buildings, green data centers, sustainability management. In 2018, 19.3% of its electricity use via the grid coming from green energy sources and 37.9% from its own renewable energy sources thereby avoiding 151,000 MWh of conventional energy associated with 53,000 metric tons of carbon emissions.

NIKE a leading world manufacture of sports goods has a warehouse in Ham, Belgium which operates 100% on renewables. The site also achieves net zero carbon which means they produce their own clean source of energy through renewable energy generators. Nike has pledged to operate more of their facilities as net zero carbon by 2030.

APPLE has invested in 484 MW of renewable energy projects to address upstream supply chain emissions. Apple uses 100% renewable electricity across all their facilities in 43 different countries. Its new corporate headquarters in Cupertino, California obtains 75% of its power from the solar panels placed on its roof.

Several semiconductor manufacturers have turned into using renewables to power their operations. Semiconductor manufacturing sector consumes more energy compared to any other industry. A wafer fab typically consumes about 300-400 MWh/day on average which is equivalent to power 10,000 homes. Energy cost can account up to 30% of the operations cost. The amount of CO_2 released to the atmosphere also stands in a very large quantity. Thus, integrating renewables into manufacturing operations is a key to lowering carbon emissions.

1.3 Literature Review

The literature review is divided into four parts. Firstly, the current state of the production planning models is reviewed. Secondly, renewable energy integration into manufacturing operations is studied. Thirdly, the concept of energy prosumers and its benefit of reducing the production cost are examined. Finally, the rise of virtual power plants and their potential applications are elaborated.

1.3.1 Production planning. This review is classified on the basis of mathematical modelling approaches such as linear programming, nonlinear programming, stochastic programming, single and multi-objective programs.

Ramezanian et al. (2012) develop a mixed integer linear programming model for solving an aggregate production planning which involves determining the production and inventory quantity over a planning horizon. The paper concentrates on multi-period, multi-product and includes machine setups for each period. They propose a generic algorithm to tackle this problem with an objective to minimize the production cost.

The introduction of government incentives for incorporating carbon emissions control has prompted researchers to develop mathematical models to curb carbon emissions. Zhang and Xu (2013) investigate a multi-product production planning with an objective to maximize the profit by including carbon trading decisions, such as carbon cap on the production activities. The problem decides the amounts of production and carbon trading so as to maximize the profit.

Gholamian et al. (2015) develops and solves a supply chain problem comprising different multiple suppliers, manufacturers, and customers with an objective to reduce the total cost of the supply chain activities. They develop a mixed integer nonlinear programming model considering supply and demand uncertainty. The costs include production, inventory, shipping and procurement costs. The model is implemented on a real supply chain as case studies.

Jin et al. (2015) develop a stochastic production-inventory planning model which includes production, inventory, and backorders. Renewable energy sources are also considered to power the manufacturing sites for operation under intermittent power. Their objective is to minimize the total cost of the system including energy. Production, inventory and backorder quantity are determined by using stochastic demands and variable resource availability. The linear programming model is implemented in C++ using CPLEX solver to develop a solution algorithm. Numerical experiments show the cost benefits for attaining the green energy coefficient target.

Han et al. (2019) consider a two-level supply chain comprising of multiple suppliers and a manufacturing facility. In this model, products are manufactured in the plant and are shipped to different suppliers. They present a mixed integer programming model and develop a two-step heuristic algorithm to solve the problem. Production, setup and transportation costs are considered to minimize the total system cost.

1.3.2 Microgrid siting and sizing. Microgrid siting and sizing problem focuses on developing models to determine the location and capacity of installing heterogenous microgrid comprising of various distributed energy resources (DER), such as wind turbine (WT), solar photovoltaics (PV), and battery storage systems (BSS), and combined heat and power (CHP). Researchers such as Roy et al. (2009) explores this concept.

Nojavan et al. (2017) propose a multi-objective optimization model for optimizing the siting and sizing of storage systems in a microgrid incorporating demand response program. The objective is to minimize the installation and operations cost of the storage systems and to lower the loss of load expectation. They develop a mixed integer nonlinear programming model and solve it using GAMS software. Numerical studies are conducted using different distributed generation (DG) units and loads. They compare the results with and without demand response initiatives.

Golari et al. (2017) investigate a multi-period, production-inventory planning model in a multi-facility setting considering onsite and offsite renewables. The facilities are powered by integrating onsite renewable microgrid in conjunction with grid renewables. Implementation of renewables comes with uncertainties. The paper tackles the problem by introducing a multistage stochastic optimization model. Scenario tree approach is carried out for characterizing renewables availability for each period. The first stage is to determine the production, inventory and backorder quantity and use them in different scenarios to allocate renewable energy use in subsequent stages. Numerical experiments prove that carbon neutral operations can be achieved at low cost through onsite and grid connected renewables.

Scalfati et al. (2017) presents a mixed linear programing formulation for optimal sizing of DER units in a smart microgrid. The model aims to minimize the total cost of microgrid ownership given location and load characteristics. The model is applied to a grid connected microgrid with PV and energy storage units. Various parameters are taken into consideration, such as PV and storage system costs, maximum and minimum capacity of the system to be installed, and cost and amount of power purchased from the grid.

Pham et al. (2019) model and design a multi-facility, production-inventory logistics system with energy supply uncertainty. This paper explores the economic feasibility to achieve net-zero carbon operations through siting and sizing of renewable microgrid. Given the location of the facilities, the study models the behavior of WT and PV systems by considering uncertain capacity factors during a year. Climate data analytics approach is developed to model the wind and solar generation of various locations. The research objective is to minimize the cost of two-tier supply chain systems which includes installation and operations cost of various DER units in the factories and warehouses.

Golpira et al. (2018) introduce a smart energy efficient production planning model in a manufacturing facility which includes a grid-tied WT microgrid. They develop a mixed integer linear programming model to minimize the total day ahead cost of the system considering the peak demand charge. The model is computed on the assumption that the main grid provides insufficient energy requirement during the peak hours. This problem is experimented under a multi-product, multi-period, and multi-resource environment.

Subramanyam et al. (2020) propose a method to integrate microgrid in a flow shop production system application. This paper develops a two-stage mixed integer programing model to minimize the levelized cost of energy of the flow shop powered by onsite wind and solar power. The proposed model minimizes the annual energy use of the flow shop in the first stage, and the second stage determines the size of WT, PV, and BSS to meet the hourly electricity demand. The model is solved based on the hourly WT and

PV capacity factor over a one-year period. Net-metering and time of use programs are explored to optimize the two-stage planning model further.

1.3.3 Energy prosumer models. This section explores the literature pertaining to the concept of energy prosumers. An energy prosumer is an entity who can produce and consume energy at the same time. That is, prosumers can sell or buy energy to and from the main grid.

Perković et al. (2016) study the concept of the day-ahead electricity market and its potential benefits when applied to a production facility consisting of combined heat and power (CHP) units, PV, and energy storage devices. The objective of the study is to develop a cost minimization problem with a non-linear programming model. Cost analysis is performed to analyze the impact of PV capacity cost on production cost. Study (NREL, 2018) shows that the PV capacity cost might significantly decline in the next 5-10 years. Hence, it is important to conduct sensitivity analysis on PV cost and how it affects the overall costs.

Perković et al. (2017) explore the concept of prosumers by developing a multi-objective cost minimization model under one facility setup. The study deals with two objectives: minimizing the cost of operations and minimizing the investment cost. The authors discuss the model for a hypothetical factory that operates as prosumer in the energy market. The model considers the power outputs from the CHP unit and PV system. The problem is solved from the energy efficiency perspective over a one-year period.

Wongwut et al. (2017) propose a mixed integer programming model for generation scheduling of a prosumer with the objective to minimize the daily operations cost. The problem is formulated and solved as an individual prosumer entity from the point of view of the utility company. The model includes BSS unit which can store excess energy and sell to a utility company under time-of-use (TOU) contract. The solution finds the optimal BSS size, and the schedules of energy charge and discharge.

Ziarnetzky et al. (2016) present a simulation optimization model considering distributed generation in a semiconductor wafer fab. The model includes an electrical substation with grid connected WT and PV system. Excess energy can be returned to the grid using net metering policies. The model determines the required number of WT and PV for various demand scenarios. The objective is to minimize the operations cost of the facility.

Many measures of improving the energy efficiency of a prosumer are based on energy markets, price trading, single DER unit and presented from utility business perspective. Such measures usually include participating in energy metering or demand response programs, installing energy efficient equipment, managing the energy storage devices, distributed frequency regulations, peer-to-peer distribution, energy contracts. While ample works relating to such applications are published, including Brusco et al. (2014), Liu et al. (2017), Mengelkamp et al. (2018), Park et al. (2019), at the time of this review to the best of our knowledge there are no studies directly associated with manufacturing and supply chain industries. The number of industrial firms striving to move their operations to clean, green and less energy use is growing over the last ten years. Hence it is necessary to study the concept of prosumer from manufacturer and supply chain operator's viewpoint. The main obstacle of using wind- and solar-based DER units is relatively high installation cost and variable power. Therefore, to reliably operate a facility using renewables, prosumer microgrid must be carefully modeled and designed to ease the flow of operations without any power shortage and interruption.

1.3.4 Virtual power plant networks. A virtual power plant (VPP) is a web-based infrastructure of a distributed power plant that combines the capacities of heterogenous DER units to enrich power generation as well as selling energy in the day-ahead market (Asmus (2010), Pudjianto et al. (2008), Pandzic et al. (2017), Othman et al. (2015), Nosratabadi et al. (2017). Multiple entities of the same or different organizational structure can participate in and forming a VPP. The network usually has a central control system used to distribute the load demand based on the availability and requirements of the participants within the network. VPP is an efficient way to implement renewable energy integration as this can aggregate and engage various resources of multiple stakeholders while avoiding huge upfront capital investment.

Researchers have leveraged the VPP for commercial purpose, and intend to maximize the revue or profit to the VPP ownership. Vasirani et al. (2013) take an agent-based approach to study the VPP operations under uncertain demand. A linear programming model is built to maximize the profit margin of a VPP system comprised of WT units and EV fleet. The uncertainty of wind generation motivates the authors to consider EV as a storage device. Energy charge and discharge is considered as a means to control the supply of energy to the grid during low and high demand. By doing so, the VPP owner can sell energy when the demand is high, hence creating a lucrative revenue stream.

The core capability of a VPP is that it can bid to sell excess power to the nearby grid, thus making VPP to function as an independent operator in grid-connected mode. VPP typically engages in a day-ahead price market which means the owner can commit to selling certain amounts of power to the utility company one day in advance. To that end, the VPP's central control system should be able to forecast the demand and supply one day in advance. Hooshmand et al. (2017) discuss the framework for day ahead and intraday generation schedule by choosing a demand response program. They consider stochastic parameters for wind generation and electricity market prices. An optimization model is devised with an objective to maximize the profit of the VPP network.

Behi et al. (2020) analyze the costs and benefits of employing a VPP which is designed to integrate rooftop solar PV, batteries, and heat pump systems. The authors compare various electrical loads and usage trends to develop a profit maximization mathematical model. They perform case studies with different scenarios and the result shows that the cost of energy is reduced by 24% when a VPP is engaged. It is important to study different load conditions and analyze how system behaves. In a manufacturing supply chain network not all the facilities operate with the same load. For example, a production site might require more energy than a warehouse where the products are just stored. Thus, it is important to analyze different load profiles.

Moreover, in some cases DG plays a vital role in making sure that the main power plant is sufficient to satisfy the growing power demand. Stable power source is a crucial element of normal industry operations. With the increase in usage of variable DG units around the manufacturing and supply chain industry, it is necessary to have proper channels to control them. VPP can regulate and govern such DG or DER units associated with power intermittency. At the time of this thesis, we are not aware of any published literature related to VPP integration in multi-tier manufacturing supply chains.

1.4 Estimating the Wind Turbine Capacity Factor

A WT operates in four phases based on the wind speeds. An Automated Surface Observing Systems (ASOS) usually is installed 8-10 meters above the ground to track the wind speed. This thesis uses the wind speeds of various cities collected from the portal of Weather Underground (WU, 2019). Assume h_g is the ground-level to measure wind speed v_g (m/s). Heier (2005) estimates the wind speed at height h as follow,

$$v_h = v_g \left(\frac{h}{h_g} \right)^k \quad ; \qquad \text{for } h \geq h_g \tag{1.1}$$

Where 'k' is the Hellman exponent whose value depends on the terrain and geographical location. A value of 0.27 to 0.34 is assumed for k in populated areas (Blackadar and Tennekes, 1968; Heier, 2005).

Let $P_w(v)$ be the output of the wind turbine at wind speed v. Then according to Thiringer and Linders (1993), the cubic power curve is given as

$$P_w(v) = \begin{cases} 0 & v < v_c, v > v_s \\ P_m \left(v / v_r \right)^3 & v_c \leq v \leq v_r \\ P_m & v_r \leq v \leq v_s \end{cases} \tag{1.2}$$

Where v_c, v_r, and v_s are the cut-in speed, the rated speed and, the cut-off speed, respectively. P_m is the power capacity of the wind turbine in Megawatt (MW) or Kilowatt (kW) depending on the size of the wind turbine. Figure 1.1 shows the typical operational characteristics of a WT based on various wind speeds. From cut-in speeds, v_c, between 2 m/s to 11 m/s, the power output increases. At rated speed, v_r =12 m/s, the power output reaches the maximum and remain stable until 25 m/s. WT is shut down for protection if the wind speed exceeds v_s.

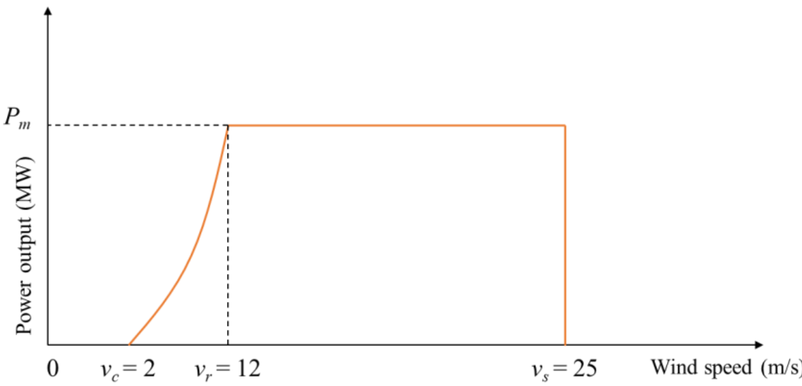

Figure 1.1: Wind turbine power curve

Using these parameters, the WT capacity factor can be calculated. The capacity factor of a WT is the actual output over a given period of time to the maximum possible output over the same period of time and can be expressed as,

$$\lambda_w = \frac{E[P_w(V) \times T]}{P_w \times T} = \frac{1}{v_r^3} \int_{v_c}^{v_r} v^3 f_w(v) dv + (F_w(v_s) - F_w(v_r)) \tag{1.3}$$

The capacity factor λ_w is in the range [0,1]. Note that wind speed usually follows the Weibull distribution Justus et al. (1978), Seguro and Lambert (2000), Dorvlo (2002), Yeh and Wang (2008) . The probability distribution function $f_w(v)$ and the cumulative distribution function $F_w(v)$ is as follows.

$$f_w(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad ; \qquad \text{for } v \geq 0 \tag{1.4}$$

$$F_w(v) = e^{-\left(\frac{v}{c}\right)^k} \tag{1.5}$$

1.5 Estimating the Solar PV Capacity Factor

Let P_t be the actual power output of a PV system which is calculated with uncertain weather conditions and is denoted by,

$$P_t = W_t \eta A I_t [1 - 0.005(T_0 - 25)] \tag{1.6}$$

Where W_t is the weather coefficient and it ranges between 0 and 1. A is the size of the PV and T_o is the operating temperature of the PV. I_t is the solar irradiance (W/m^2) incident on the PV surface at a given time t. The solar irradiance is calculated by Bishop and Rossow (1991),,

$$I_t = 1370(0.7^{(\cos\phi)^{0.678}})\left(1 + 0.034\cos\left(\frac{2\pi(d-4)}{365}\right)\right)\left(\cos\theta + 0.1\left(1 - \frac{\beta}{\pi}\right)\right) \tag{1.7}$$

Where,

$$\begin{aligned} \cos\phi &= \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \\ \cos\theta &= \cos\delta\cos\omega \end{aligned} \tag{1.8}$$

Note that ϕ is the latitude at which the PV is placed, δ is the declination angle, ω is the solar hour. d is the date, β is the PV tilt angle. The capacity factor of the solar PV is given by,

$$\lambda_{PV} = \frac{1}{P_{PV}^{\max} \times T} \sum_{t=1}^{T} P_t \ . \qquad (1.9)$$

Where $P_{PV}^{\max}$ is the PV systems rated capacity factor and T is the operating hours of the PV system.

1.6 Levelized Cost of Energy

Levelized cost of energy (LCOE) is the measure of the net present value of the electricity cost per MWh or kWh over the lifetime of power generating unit. Key inputs for calculating the LCOE includes investment, operations and maintenance costs, carbon credits or government subsidies, or other financing costs. The LCOE is given by,

$$\text{LCOE}(\$ / \text{MWh}) = \frac{\text{Total Energy Cost } (\$)}{\text{Total Energy Consumed (MWh)}} \qquad (1.10)$$

1.7 Electrical Vehicle Energy Intensity Rate

As defined by Pham et al. (2019), EV energy intensity rate is defined as the amount of battery energy necessary to move one-kilogram object over one-kilometer distance at a specific speed. It is given by,

$$q_v = \frac{E_{EV}}{m \times d_{\max}} \qquad (1.11)$$

Where E_{EV} is the battery capacity, m is the EV's gross weight in kg and d_{max} is the driving range of the EV in km. The unit of q_v is MWh/kg/km or kWh/kg/km.

1.8 The Research Contributions

This thesis takes an early attempt to incorporate prosumer energy as an indispensable feature in the design and operation of manufacturing supply chains along with materials, information and cash flows. The study aims at answering two key questions: First, is it economically feasible to implement onsite renewable energy technologies to achieve zero energy use in multi-tier manufacturing and supply chain operations? Second, is it profitable to utilize the concepts of prosumer microgrid and virtual power plants in a manufacturing supply chain? These questions are answered by,

- Developing mathematical model to size and site microgrid systems for minimizing the cost of the production-logistics system in grid-tied and island modes.
- Designing a zero-carbon energy use manufacturing supply chain that minimizes the total system cost through implementing the concept of wind- and solar-based prosumer microgrid.
- Implementation of power trading concepts to maximize the profits of the manufacturing supply chain with the engagement of virtual power plants.

1.9 Thesis Outline

The remainder of the thesis is organized as follows: Chapter 2 explores the simulation-based modelling of WT and PV systems. Chapter 3 investigates production planning and energy scheduling in different granularity. Chapter 4 presents the use of prosumers in three-tier manufacturing supply chains. Chapter 5 develops virtual power plan network with energy trading capabilities in supply chain setting. Chapter 6 concludes the thesis, highlights the managerial insights, and discusses future research.

2.PRODUCTION-LOGISTICS PLANNING UNDER GRID-TIED MICTOGRID

2.1 Problem Description

In this chapter, we consider a three – tier supply chain network comprised of factories, warehouses, and retail stores. In this setting, electricity is the main source for running the facilities. All the facilities in this network are powered by microgrid of its own, which are placed in the proximity. The microgrid consists of two main distributed energy resource (DER) units, namely wind turbine (WT) and solar photovoltaic (PV). Transportation of materials between the facilities is carried out using electric trucks (EV) and these EVs are charged at the respective locations where it starts its journey from factory, warehouse, or store. If the distance between two facilities is larger than the driving range, charging stations are available along the route so that EV can recharge the battery for extending the range. If the microgrid output cannot meet the load of the facilities, conventional energy can be imported to power the facilities. This amount of imported energy will be offset during a period when surplus energy from onsite generation systems exceeds the actual demand of the local facilities. For testing the model, we assume that the energy exchanged is free of charge. With the use of renewable microgrids and logistic electrification, the goal is to design a supply chain network to attain zero energy objective at the minimum cost. Figure 2.1 describes the above mentioned three – tier supply chain network. The primary goals of most manufacturing firms are to seek a high satisfaction to customer’s demands and to become a low cost and emissions producer. To achieve these goals, the company must be able to effectively schedule the production and transportation and maximize resource utilization.

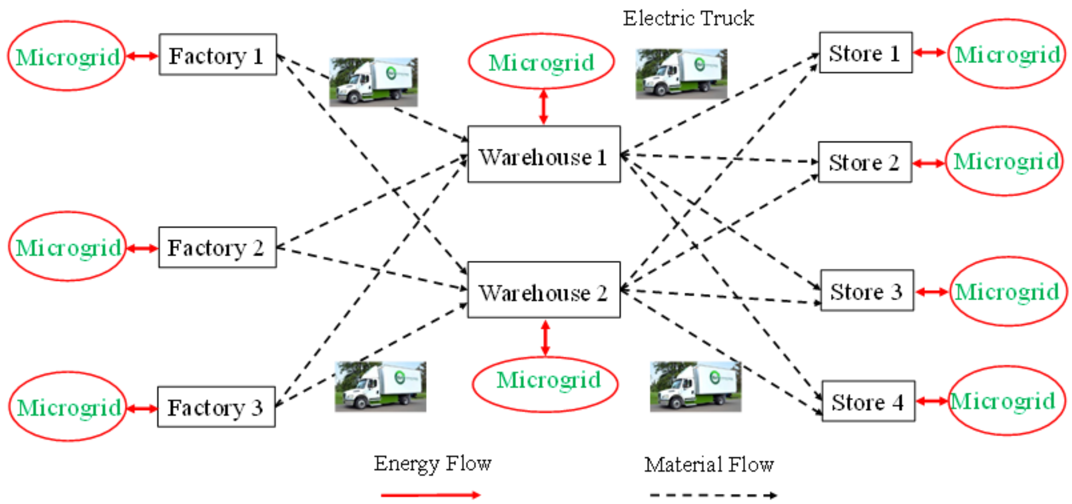

Figure 2.1: Layout of three – tier supply chain with microgrid

2.2 Modeling of a supply chain and production inventory planning

Figure 2.1 describes a three-tier supply chain in which multiple type of products are produced in the factories. These products are then shipped to the warehouse where it is stored and then shipped to the respective stores based on the demand of the store. The objective of this model is to minimize the cost associated with production, inventory, logistics and energy. Table 2.1 is used to formulate the mathematical model.

Table 2.1: Model 2.1 Notation

Notation	Comments
I	number of product type, for i=1, 2, .., I
J	number of production period, for j=1, 2, .., J
K	number of factory, for k=1, 2, .., K
N	number of warehouse, for n=1, 2, .., N
S	number of retail stores, for s=1, 2, .., S
G	number of renewable sources, for g=1, 2, .., G
R	number of resources required in production, for r=1, 2, .., R
p_{ijk}	cost of making one unit of product i in period j in factory k ($/item)
h_{ijn}	unit holding cost of product i in period j warehouse n ($/item/period)
b_{ijn}	unit backorder cost of product i in period j in warehouse n ($/item)
π_{ikn}	cost of shipping a unit of product i from factory k to warehouse n ($/item)

$\tilde{\pi}_{ins}$	cost of shipping one unit of product *i* from warehouse *n* to store *s* ($/item)
v_{ikr}	resource *r* consumed for making one unit of product *i* in factory *k*
w_{jkr}	available production resource of *r* in period *j* in factory *k*
q_v	electric vehicle energy intensity rate (MWh/kg/km)
w_v	vehicle self-weight (kg)
d_{kn}	distance between factory *k* and warehouse *n* (km)
$\tilde{d}_{ns}$	distance between warehouse *n* and store *s* (km)
m_i	unit weight of product type *i* (kg/item)
D_{ijs}	random demand for product *i* in period *j* from store *s*
μ_{ijs}	mean value of D_{ijs}
σ_{ijs}	standard deviation of D_{ijs}
n_{ks}	number of yearly trips between factory *k* and warehouse *n*
$\tilde{n}_{ns}$	number of yearly trips between warehouse *n* and store *s*
t_w	operating hours of warehouse (hours)
$\tilde{t}_s$	operating hours of store (hours)
τ_{gk}	number of generation hours of renewables *g* per period in factory *k*
τ_{gn}	number of generation hours of renewables *g* per period in warehouse *n*
τ_{gs}	number of generation hours of renewables *g* per period in store *s*
a_g	capacity cost for renewable generator *g* ($/MW)
c_g	carbon credits for renewable generator *g* ($/MWh)
e_{ik}	energy consumed for one unit of product *i* in factory *k* (MWh/item)
L_n	electricity demand (load) in warehouse *n* (MW)
$\tilde{L}_s$	electricity demand (load) in store *s* (MW)
γ	probability of meeting the product demand
ϕ_g	capital recovery factor of renewable generator *g*
$P_{gk}(\zeta)$	random power output of renewable generator *g* in factory *k*
$P_{gn}(\zeta)$	random power output of renewable generator *g* in warehouse *n*
$P_{gs}(\zeta)$	random power output of renewable generator *g* in store *s*
$\lambda_{gk}(\zeta)$	capacity factor of renewable generator *g* in factory *k*
$\lambda_{gn}(\zeta)$	capacity factor of renewable generator *g* in warehouse *n*
$\lambda_{gs}(\zeta)$	capacity factor of renewable generator *g* in store *s*
E_ζ	expectation operator with respect to ζ

Table 2.2: Model 2.1 decision variables

Decision Variables	**Comments**
x_{ijkn}	product *i* produced in period *j* in factory *k* shipped to warehouse *n*
$\tilde{x}_{ijkn}$	product *i* in period *j* shipped from warehouse *n* to store *s*
y_{ijn}	inventory of product *i* in period *j* in warehouse *n*
z_{ijn}	backorder of product *i* in period *j* in warehouse *n*
P^c_{gk}	power capacity of generator *g* in factory *k* (unit: MW)
P^c_{gn}	power capacity of generator *g* in warehouse *n* (unit: MW)

P^c_{gs} power capacity of generator g in store s (unit: MW)

2.3 Stochastic planning model

An integrated production-warehouse-retail optimization model is formulated where all facilities including E-trucks are powered by onsite wind and solar energy. The finishing goods are shipped and stored temporally at the central warehouses. These goods are then further distributed to the retail stores to fulfill the random demand. E-trucks are responsible for shipping the goods between these facilities. The objective of the model is to determine the production quantity, inventory level, and backorders such that each store can meet the demand at a required confidence level. To achieve the zero-energy goal, the microgrid portfolio and generation capacity also need to be allocated such that the annual cost of the entire supply chain including production, warehousing and transportation is minimized. Model 2.1 is formulated to incorporate the design goal as well as the system constraints.

Model 2.1:

Minimize

$$\begin{aligned}
f(\mathbf{x},\mathbf{y},\mathbf{z},\mathbf{P}^c) = {} & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}(p_{ijk}+\pi_{ikn})x_{ijkn} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}h_{ijn}y_{ijn} + \sum_{i=1}^{I}\sum_{j=1}^{J-1}\sum_{n=1}^{N}b_{ijn}z_{ijn} \\
& + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{s=1}^{S}\tilde{\pi}_{ins}\tilde{x}_{ijns} \\
& + \sum_{g=1}^{G}\sum_{k=1}^{K}\phi_g a_g P^c_{gk} + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{k=1}^{K}\tau_{gk}(b_g - c_g)P_{jgk}(\zeta) \\
& + \sum_{g=1}^{G}\sum_{n=1}^{N}\phi_g a_g P^c_{gn} + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{N}\tau_{gn}(b_g - c_g)P_{jgn}(\zeta) \\
& + \sum_{g=1}^{G}\sum_{n=1}^{S}\phi_g a_g P^c_{gs} + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{S}\tau_{gs}(b_g - c_g)P_{jgs}(\zeta)
\end{aligned} \tag{2.1}$$

Subject to:

$$\sum_{k=1}^{K} x_{i1kn} + y_{i0n} - y_{i1n} + z_{i1n} = \sum_{s=1}^{S} \tilde{x}_{i1ns} ; \qquad \text{for } j\text{=1, } \forall I\text{, and } \forall n \tag{2.2}$$

$$\sum_{k=1}^{K} x_{ijkn} + y_{ij-1n} - y_{ijn} - z_{ij-1n} + z_{ijn} = \sum_{s=1}^{S} \tilde{x}_{ijns} ; \quad \text{for } j\text{=2, 3, .., } J\text{-1, } \forall I\text{, and } \forall n \tag{2.3}$$

$$\sum_{k=1}^{K} x_{iJkn} + y_{iJ-1n} - y_{iJn} - z_{iJ-1n} = \sum_{s=1}^{S} x_{iJns} ; \qquad \text{for } j\text{=}J\text{, } \forall I\text{, and } \forall n \tag{2.4}$$

$$\Pr\left\{ \sum_{n=1}^{N} \tilde{x}_{ijns} < D_{ijs} \right\} \leq 1-\gamma ; \qquad \text{for } j\text{=1,2, 3, .., } J\text{, } \forall I\text{, and } \forall s \tag{2.5}$$

$$\sum_{i=1}^{I} \sum_{n=1}^{N} v_{ikr} x_{ijkn} \leq w_{jkr} ; \qquad \text{for } \forall j\text{, } \forall r\text{, and } k\text{ =1, 2.., } K \tag{2.6}$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{n=1}^{N} (e_{ik} + q_v d_{kn} m_i) x_{ijkn} + \sum_{n=1}^{N} q_v n_{kn} d_{kn} w_v = \sum_{j=1}^{J} \sum_{g=1}^{G} \tau_{gk} P_{jgk}(\zeta) ;$$

$$\text{for } k\text{=1, 2, …, } K \tag{2.7}$$

$$t_w L_n + + \sum_{k=1}^{K} q_v n_{kn} d_{kn} w_v + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{s=1}^{S} q_v \tilde{d}_{ns} m_i \tilde{x}_{ijns} + \sum_{s=1}^{S} q_v \tilde{n}_{ns} \tilde{d}_{ns} w_v = \sum_{j=1}^{J} \sum_{g=1}^{G} \tau_{gn} P_{jgn}(\zeta) ;$$

$$\text{for } n\text{=1, 2, …, } N \tag{2.8}$$

$$\tilde{t}_s \tilde{L}_s + \sum_{n=1}^{N} q_v \tilde{n}_{ns} \tilde{d}_{ns} w_v = \sum_{j=1}^{J} \sum_{g=1}^{G} \tau_{gs} P_{jgs}(\zeta) ; \quad \text{for } s\text{=1, 2, …, } S \tag{2.9}$$

$$y_{i0n} = 0 ; \qquad \text{for } \forall I \text{ and } \forall n \tag{2.10}$$

$$x_{ijkn}, \tilde{x}_{ijkn}, y_{ijn}, z_{ijn} \in Z^{+} \tag{2.11}$$

$$P_{gk}^{c}, P_{gn}^{c}, P_{gs}^{c} \geq 0 \tag{2.12}$$

Where **x**, **y**, and **z** are respectively the vector representation for decision variables of production, inventory, and backorders. $\mathbf{P}^c$ is the vector for the decision variables of power capacity of WT and PV in each facility. Model 2.1 is a mixed-integer linear programming model in which **x, y**, and **z** are integer decision variables, and P^c is continuous variable. Objective function (2.1) is to minimize the total annual cost comprised of manufacturing, transportation, warehousing, and energy. The first four summation terms represent the production, inventory, backorder costs and shipping costs, respectively. The last three terms capture the costs associated with microgrid installation, maintenance and operations, and carbon credits in factories, warehouse, and stores.

Constraints (2.2) to (2.6) represent the production-inventory constraints. Particularly, constraints (2.2) to (2.4) are the inventory balance condition between the factory and warehouse. Constraint (2.5) the chance constraint stating that the demand in each store must be satisfied with $100\times\gamma\%$. Constraint (2.6) is the manufacturing resource constraint such as machine and labor hours. Constraint (2.7) to (2.9) represent the energy balance equations between the supply and the demand in each facility. Particularly, constraint (2.7) states that the annual electricity consumed by factory k and the forward logistics is fully offset by the onsite generation energy. Q_v is the electric vehicle energy intensity rate at speed v. Constraint (2.8) defines the energy balance of warehouse, stating that the total warehouse energy use including the reverse logistics to the factories and the forward logistics to all stores is fully offset by the onsite generation energy. Note that in reverse logistics, the E-truck is empty with no load of goods. Constraint (2.9) defines that the total energy used by the retail stores including the reverse logistics is fully offset by the onsite generation energy. Constraints (2.10) states that the initial inventory is zero. Finally, constraints (2.11) to (2.12) simply indicate the non-negativity of all the decision variables.

Model 2.1 belongs to the stochastic optimization program with random probability of meeting the demand of retail stores. To tackle Model 2.1, it is further simplified into a two-stage optimization model with deterministic constraints. This is done because of the uncertainty in the wind speeds and weather conditions and the make the problem easily solvable. In stage 1, we allocate the production, inventory, and backorder per period to minimize the annual cost excluding energy expense. In stage 2, we further size the microgrid in each facility to meet the local power demand including transportation during a year. The two-stage problem is given as follows.

Stage 1 for Production-Inventory Planning

Model 2.1.1:

Minimize

$$\begin{aligned} f_1(\mathbf{x},\mathbf{y},\mathbf{z}) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}(p_{ijk}+\pi_{ikn})x_{ijkn} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}h_{ijn}y_{ijn} + \sum_{i=1}^{I}\sum_{j=1}^{J-1}\sum_{n=1}^{N}b_{ijn}z_{ijn} \\ + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{s=1}^{S}\tilde{\pi}_{ins}\tilde{x}_{ijns} \end{aligned} \tag{2.13}$$

Subject to:

$$\sum_{k=1}^{K} x_{i1kn} + y_{i0n} - y_{i1n} + z_{i1n} = \sum_{s=1}^{S}\tilde{x}_{i1ns}\,; \qquad \text{for } j=1,\ \forall I, \text{ and } \forall n \tag{2.14}$$

$$\sum_{k=1}^{K} x_{ijkn} + y_{ij-1n} - y_{ijn} - z_{ij-1n} + z_{ijn} = \sum_{s=1}^{S}\tilde{x}_{ijns}\,; \quad \text{for } j=2, 3, .., J\text{-}1,\ \forall I, \text{ and } \forall n \tag{2.15}$$

$$\sum_{k=1}^{K} x_{iJkn} + y_{iJ-1n} - y_{iJn} - z_{iJ-1n} = \sum_{s=1}^{S} x_{iJns}\,; \qquad \text{for } j=J,\ \forall I, \text{ and } \forall n \tag{2.16}$$

$$\sum_{n=1}^{N}\tilde{x}_{ijns} \ge \mu_{ijs} + z_{\gamma}\sigma_{ijs}\,; \quad \text{for } j=1,2, 3, .., J,\ \forall I \text{ and } \forall s \tag{2.17}$$

$$\sum_{i=1}^{I}\sum_{n=1}^{N} v_{ikr}x_{ijkn} \le w_{jkr}\,; \qquad \text{for } \forall j,\ \forall r, \text{ and } k=1, 2.., K \tag{2.18}$$

$$y_{i0n} = 0\,; \qquad \text{for } \forall I \text{ and } \forall n \tag{2.19}$$

$$x_{ijkn}, \tilde{x}_{ijkn}, y_{ijn}, z_{ijn} \in Z^{+} \tag{2.20}$$

Model 2.1.1 is an integer optimization model to minimize the annual production-inventory cost subject to demand uncertainty. Objective function (2.13) captures all the expenses of the supply chain operations except for the energy cost which is given in Stage 2. Constraint (2.17) is the deterministic counterpart of the chance constraint (2.5). Note that μ_{ijs} and σ_{ijs} are the mean and standard deviation of demand for product *I* in period *j* in store *s*. The resulting decisions on **x**, **y** and **z** become the inputs for the optimization in the second stage.

Stage 2 for Microgrid Siting and Sizing

Model 2.1.2

Minimize

$$\begin{aligned} f_2(\mathbf{P}^c) = & \sum_{g=1}^{G}\sum_{k=1}^{K}\phi_g a_g P_{gk}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{k=1}^{K}\tau_{gk}(b_g - c_g)\lambda_{jgk}P_{gk}^c \\ & + \sum_{g=1}^{G}\sum_{n=1}^{N}\phi_g a_g P_{gn}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{N}\tau_{gn}(b_g - c_g)\lambda_{jgn}P_{gn}^c \\ & + \sum_{g=1}^{G}\sum_{n=1}^{S}\phi_g a_g P_{gs}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{S}\tau_{gs}(b_g - c_g)\lambda_{jgs}P_{gs}^c + f_1(\mathbf{x},\mathbf{y},\mathbf{z}) \end{aligned} \tag{2.21}$$

Subject to:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}(e_{ik} + q_v d_{kn} m_i)x_{ijkn} + \sum_{n=1}^{N} q_v n_{kn} d_{kn} w_v = \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gk}\lambda_{jgk}P_{gk}^c\ ; \qquad \text{for } k=1, 2, \ldots, K \tag{2.22}$$

$$t_w L_n + + \sum_{k=1}^{K} q_v n_{kn} d_{kn} w_v + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S} q_v \tilde{d}_{ns} m_i \tilde{x}_{ijns} + \sum_{s=1}^{S} q_v \tilde{n}_{ns}\tilde{d}_{ns} w_v = \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gn}\lambda_{jgn}P_{gn}^c\ ; \ \text{for } n=1, 2, \ldots, N \tag{2.23}$$

$$\tilde{t}_s \tilde{L}_s + \sum_{n=1}^{N} q_v \tilde{n}_{ns}\tilde{d}_{ns} w_v = \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gs}\lambda_{jgs}P_{gs}^c\ ; \qquad \text{for } s=1, 2, \ldots, S \tag{2.24}$$

$$P_{gk}^c, P_{gn}^c, P_{gs}^c \geq 0 \tag{2.25}$$

Model 2.1.2 is a linear optimization model featured with capacity factor λ_{jgk} for generator *g* in period *j* in factory *k*. This model calculates the power output of the renewable energy generators that should be installed which helps to produce the electricity required for operating the facilities. Mathematically it is equal to the actual power output divided by the capacity. For instance, if a WT capacity is 2 MW, and the actual output in a period is only 0.8 MW due to small wind, the capacity factor is 0.8/2=0.4. In other words, $P_{jgk}(\zeta)$ is connected with P^c_{gk} by $P_{jgk}(\zeta)=\lambda_{jgk}P^c_{gk}$ for $0\leq\lambda_{jgk}\leq1$. Similar connection can be made for P^c_{gn} with $P_{jgn}(\zeta)=\lambda_{jgn}P^c_{gn}$, and for P^c_{gs} with $P_{jgs}(\zeta)=\lambda_{jgs}P^c_{gn}$.

2.4. Numerical Experiments

2.4.1 Weekly planning horizon. The values of the capacity factor to solve the Model 2.1.2 is simulated in Excel as close as a real value. For better understanding we categorize them as City 1 to 4. This climate data will be used to investigate the feasibility of the two-stage model. Different supply chain and production period scenarios are considered to solve this model. The production planning is done weekly for a year. The network has two factories, one warehouse and two retail stores.

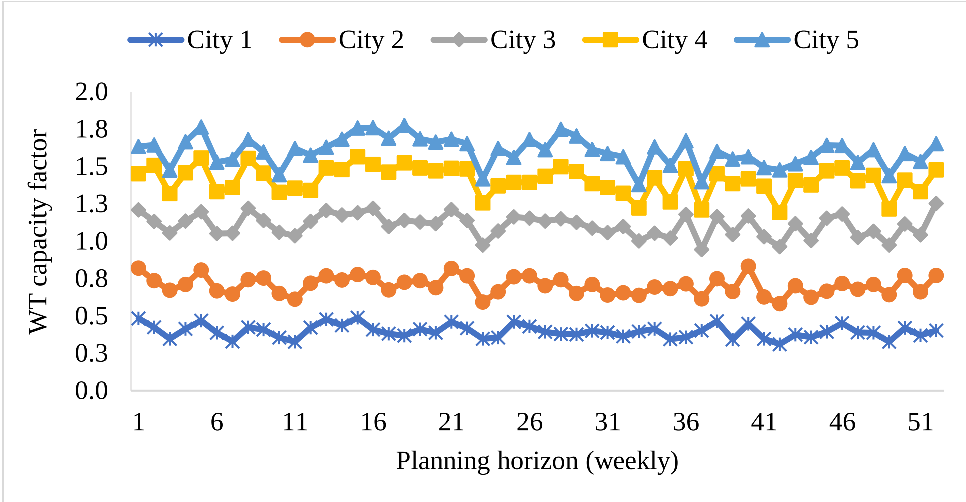

Figure 2.2: Wind turbine capacity factor for weekly planning

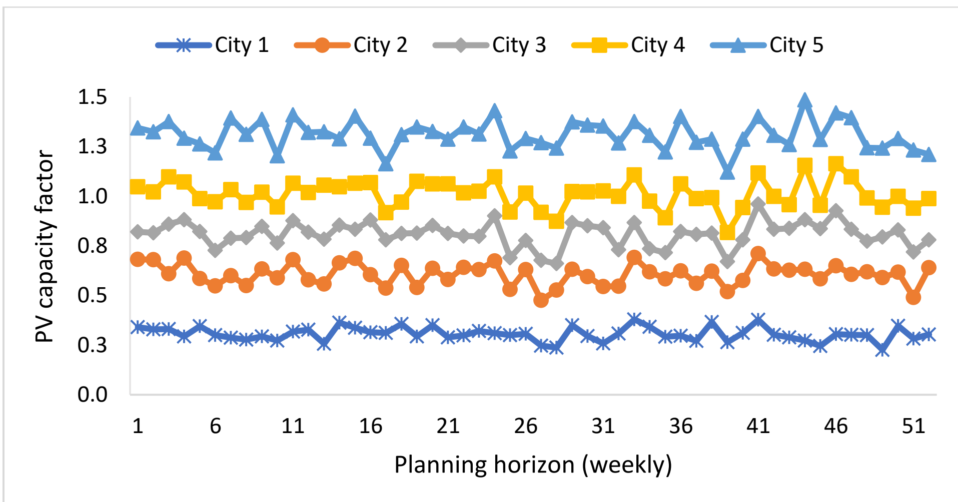

Figure 2.3: Solar PV capacity factor for weekly planning

Figures 2.2 and 2.3 shows the weekly capacity factor of WT and PV, respectively. Assume five facilities are in five different cities. Factories are in City 1 and City 2. The warehouse is in City 3 and two stores are in Cities 4 and 5. The weekly planning horizon is scheduled for 52 weeks over a year. It is assumed that the factory is operated 24 hours a day and 168 hours a week. Tables 2.3 and 2.4 are the parameters used to solve the two-stage optimization model in the weekly planning.

Table 2.3: Parameters for Model 2.1.1 (F=Factory, W=Warehouse, S=Store)

Comments	Notation	Product A (i=1)	Product B (i=2)	Unit
Energy consumed	e_i	0.9	1.2	MWh/item
Production cost (w/o energy)	p_i	400	600	$/item
Holding cost	h_i	8	12	$/period/item
Backlog cost	b_i	150	250	$/item
Shipping cost (F to W)	p_i	10	15	$/item
Shipping cost (W to S)	p_i	14	19	$/ item
Labor hours	v_{i1}	16	24	hours/item
Machine hours	v_{i2}	100	200	hours/item
Product weight	m_i	3	4	Kg/item

Table 2.4: Parameters for Model 2.1.2

WT			PV		
Notation	Value	Unit	Notation	Value	Unit
a_g	1.5×10^6	$/MW	a_g	2×10^6	$/MW
b_g	12	$/MWh	b_g	4	$/MWh
c_g	0	$/MWh	c_g	15	$MWh
τ_g	168	hour/period	τ_g	84	hour/period
v_c	3	m/s	η	0.2	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
ϕ_g	0.08024	n/a	ϕ_g	0.08024	n/a

The two-stage optimization model is solved using AMPL and the CPLEX solver. The software runs in an IntelI Core I i7-8550U processor, which runs at 1.8 GHz 1.99 GHz, and 12 GB DRAM. The weekly planning model has 312 variables and 524 constraints. The optimal production, inventory and backorders are shown in Figures 2.4 and 2.5.

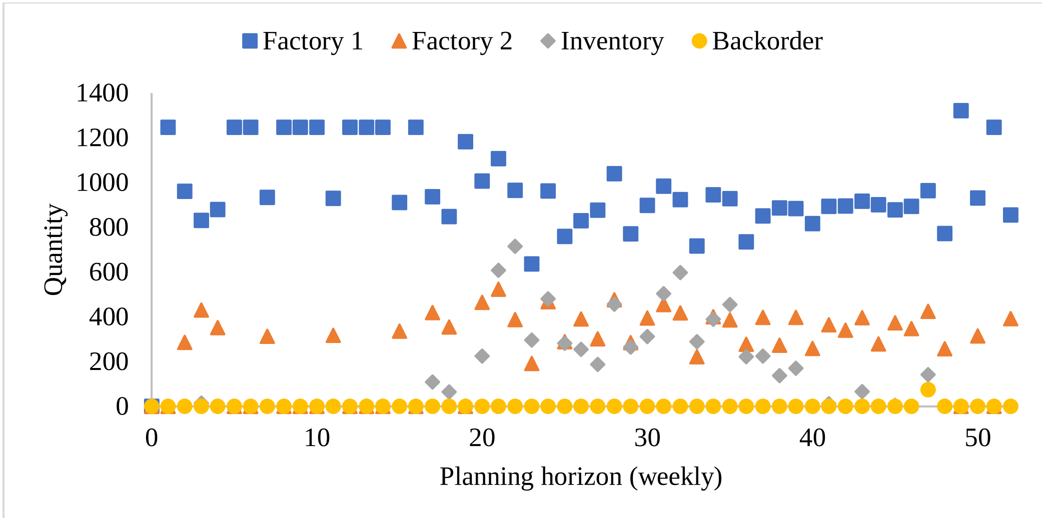

Figure 2.4: Production, inventory, and backorder of Product A

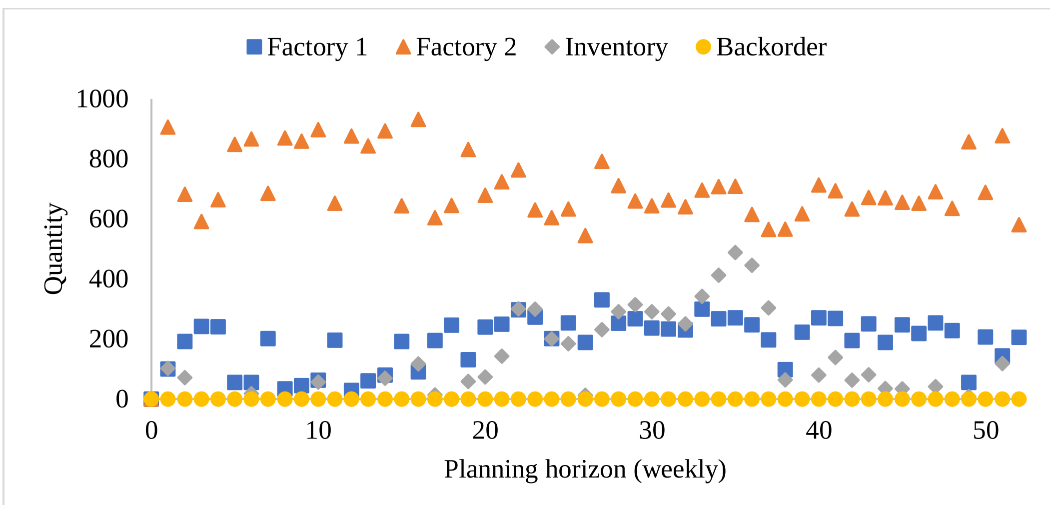

Figure 2.5: Production, inventory, and backorder of Product B

The quantity of inventory and backorder are close to zero in some periods are because of adequate resources available in producing the products. The products are shipped from two different factories in Cities 1 and 2 to the warehouse located in City 3. The products are then shipped to stores in Cities 4 and 5 to meet their demand. The backorders are allowed so that the factories can produce more during periods where the availability of resources become abundant. The annual cost of stage 1 objective in weekly planning is $58 million which includes production, inventory, backorder, and shipping costs. Both x_{ijkn} and $\tilde{x}_{ijkn}$ become the input parameters for the stage 2 microgrid planning model. In conjunction with Table 2.4, Model 2.1.2 is solved in AMPL using CPLEX solver in the same system configuration. The results are given in Table 2.5.

Table 2.5: Model 2.1.2 results in weekly planning

Type	Factory		Warehouse	Store	
	City 1	City 2	City 3	City 4	City 5
WT (MW)	17	21	17.46	13.26	20.98
PV (MW)	0	0	0	0	0

The stage 2 cost includes the microgrid installation, operations and maintenance, electric vehicles charging with total of $13 million. The model chooses to install WT across all the locations because of its lower cost. The capacity factor of the WT and PV has no significant impact on the decision. For example, the capacity factor of WT and PV are similar and although PV system has more operating efficiency than a WT system (20% vs. 15%) the model chooses to install WT because of the lower capacity cost.

2.4.2 Daily Planning Horizon. Next the production planning is carried out daily for 365 days for a year. Figures 2.6 and 2.7 shows the daily WT and PV capacity factor of these cities. Tables 2.6 shows the parameters used in solving Models 2.1.2. Note that Model 2.1.1 is solved using the same parameters as shown in Table 2.3.

Table 2.6: Model 2.1.2 parameters for daily planning

WT			PV		
Notation	Value	Unit	Notation	Value	Unit
a_g	1.5×10^6	\$/MW	a_g	2×10^6	\$/MW
b_g	12	\$/MWh	b_g	4	\$/MWh
c_g	0	\$/MWh	c_g	15	\$MWh
τ_g	24	hour/period	τ_g	12	hour/period
v_c	3	m/s	η	0.2	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
ϕ_g	0.08024	n/a	ϕ_g	0.08024	n/a

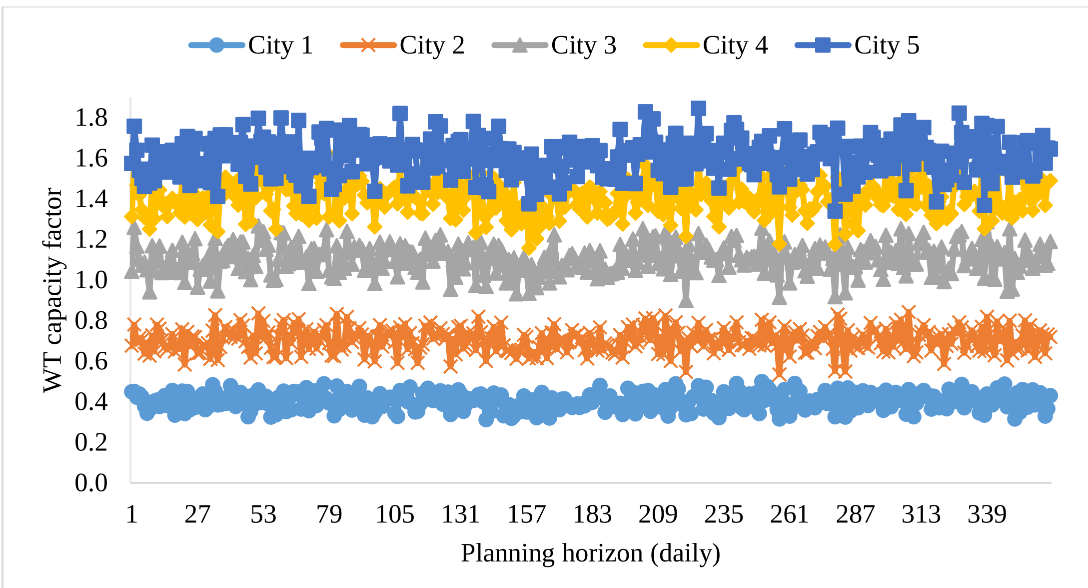

Figure 2.6: Wind turbine capacity factor for daily planning

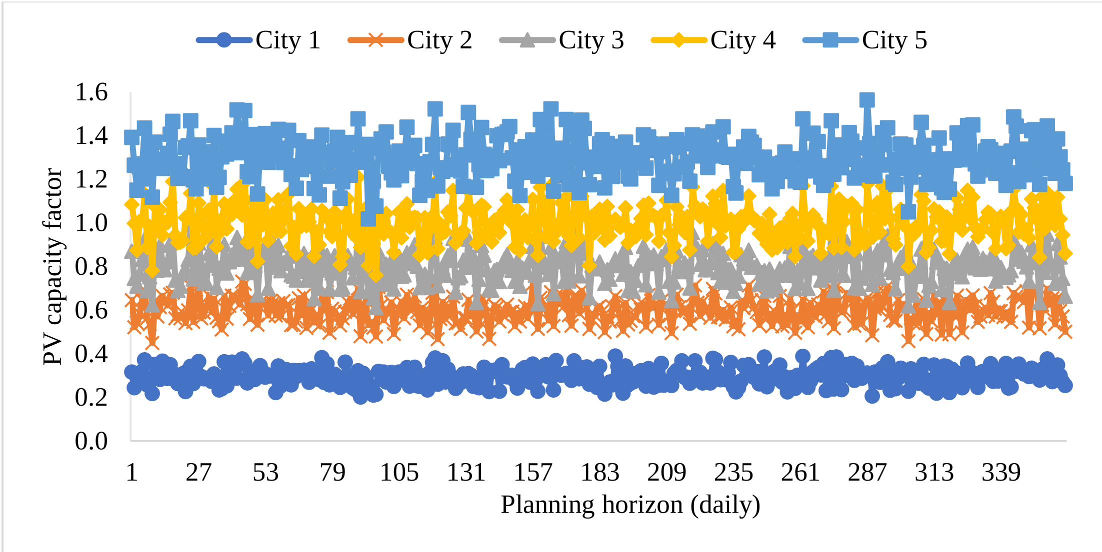

Figure 2.7: Wind turbine capacity factor for daily planning

The daily planning model has 2184 decision variables and 3644 constraints. The model is solved in AMPL using CPLEX solver. The results of production, inventory and backorders are given in Figures 2.8 and 2.9.

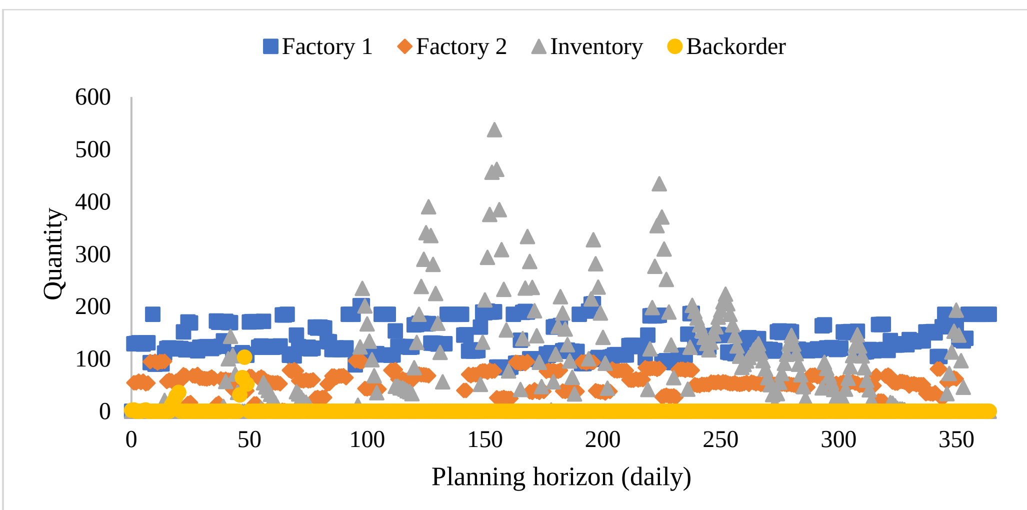

Figure 2.8: Daily production, inventory, and backorder of Product A

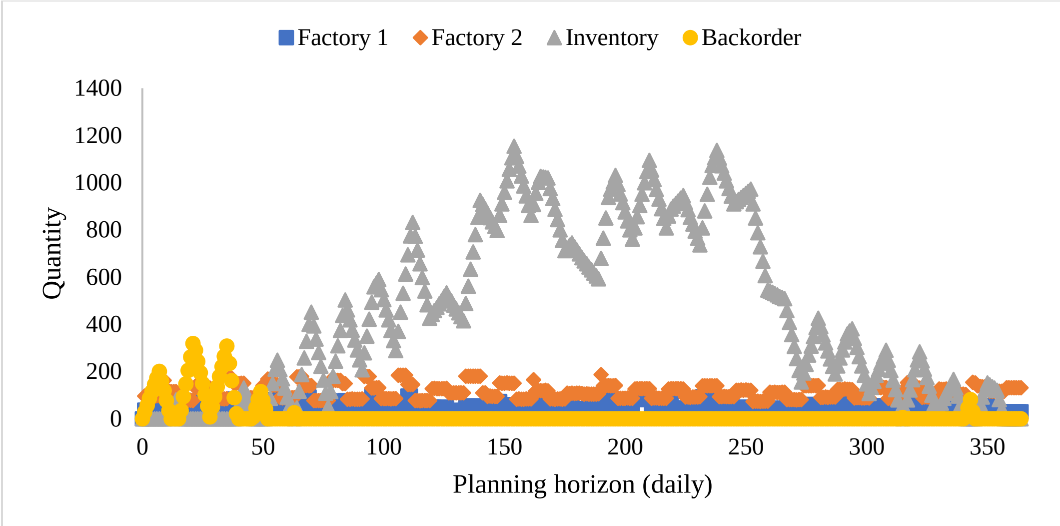

Figure 2.9: Daily production, inventory, and backorder of Product B

Table 2.7: Model 2.1.2 results in daily planning

Type	Factory		Warehouse	Store	
	City 1	City 2	City 3	City 4	City 5
WT (MW)	18	25	17.56	13.35	20.06
PV (MW)	0	0	0	0	0

The weekly available resources are spread equally over 7 days in the daily planning model. The daily production quantity is based on the resource availability, such as machine and labor hours. In Figure 2.8, the inventory increases as the model chooses to produce more units during the periods where the resources are abundant. The is due to the fact that the inventory holding cost is relatively cheaper than the production cost. The production quantity for a period is affected by the inventory cost. Similar trend is seen for Product B as shown in Figure 2.9. The daily production quantity is used as the input for solving the stage 2 optimization and results are recorded in Table 2.7. The first stage cost is $67 million, and the second stage cost is $14 million. It is interesting to see that daily planning is more costly than the weekly planning.

3.PRODUCTION-LOGISTICS PLANNING WITH ISLAND MICROGRID

3.1 Problem Description

In this chapter, a three-tier production planning model with island microgrid operations is considered. An island microgrid operates independently and is not connected to the main power grid. The microgrid is comprised of heterogeneous distributed energy resources (DER), such as wind turbines (WT), solar photovoltaics (PV) and battery storage systems (BSS). Hence, the model allocates the size of WT, PV and BSS to be installed in each of the facilities. For energy storage, the model needs to determine the amount of energy stored in the BSS in each period. Electric vehicles (EV) are employed to transport the goods between the upper stream and downstream facilities. Other conditions remain the same as these in Chapter 2. This problem is solved in two stages, the first stage is a production inventory planning model and the second stage implements the results from the first phase to size the capacity of WT, PV, and BSS units. Figure 3.1 illustrates the operational principle of a multi-tier supply chain network with island microgrid systems.

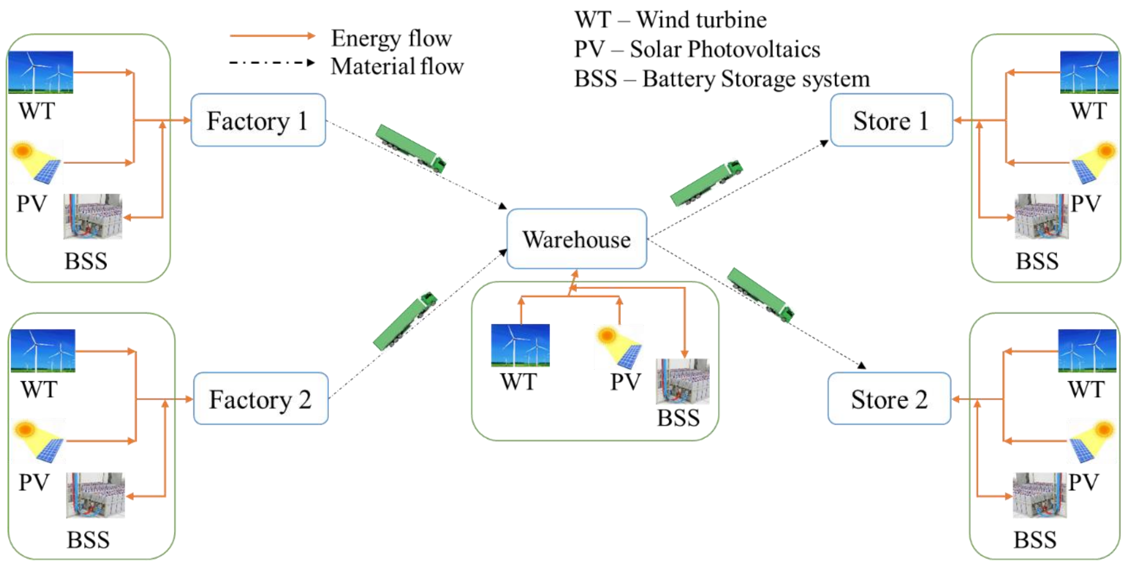

Figure 3.1: A Three-tier supply chain network with island microgrid systems

3.2 An Integrated Production and Island Microgrid Planning Model

This section proposes an integrated decision model for production planning and microgrid sizing under island operation. The model makes decisions on production, inventory, backorder, and the size of WT, PV and BSS. The multi-tier system is comprised of *k* factories, *n* warehouses and *s* retail stores. Let *I* be the types of product manufactured in each of the factories. A detailed description of the model notation are listed in Table 3.1, and

Table 3.2 shows the decision variables.

Table 3.1: Notation for Model 3.1

Notation	Comments
I	number of product type, for i=1, 2, .., I
J	number of production period, for j=1, 2, .., J
K	number of factory, for k=1, 2, .., K
N	number of warehouse, for n=1, 2, .., N
S	number of retail stores, for s=1, 2, .., S

G	type of renewable generator, for g=1, 2, .., G
R	number of resources required in production, for r=1, 2, .., R
p_{ijk}	cost of making one unit of product I in period j in factory k (\$/item)
h_{ijn}	unit holding cost of product I in period j warehouse n (\$/item/period)
b_{ijn}	unit backorder cost of product I in period j in warehouse n (\$/item)
π_{ikn}	cost of shipping one unit of product I from factory k to warehouse n (\$/item)
$\tilde{\pi}_{ins}$	cost of shipping a unit of product I from warehouse n to store s (\$/item)
v_{ikr}	resource r consumed for making one unit of product I in factory k
w_{jkr}	available production resource of r in period j in factory k
q_v	electric vehicle energy intensity rate (MWh/kg/km)
w_v	vehicle self-weight (kg)
d_{kn}	distance between factory k and warehouse n (km)
$\tilde{d}_{ns}$	distance between warehouse n and store s (km)
m_i	unit weight of product type I (kg/item)
D_{ijs}	random demand for product I in period j from store s
μ_{ijs}	mean value of D_{ijs}
σ_{ijs}	standard deviation of D_{ijs}
n_{ks}	number of yearly trips between factory k and warehouse n
$\tilde{n}_{ns}$	number of yearly trips between warehouse n and store s
t_w	operating hours of warehouse (hours)
$\tilde{t}_s$	operating hours of store (hours)
τ_{gk}	generation hours of renewable generator g per period in factory k
τ_{gn}	generation hours of renewable generator g per period in warehouse n
τ_{gs}	number of generation hours of renewables g per period in store s
a_g	capacity cost for renewable generator g (\$/MW)
a_b	capacity cost for battery storage system (\$/MWh)
b_g	operation and maintenance cost for renewable generator g (\$/MWh)
c_g	carbon credits for renewable generator g (\$/MWh)
e_{ik}	energy used for producing a unit of product I in factory k (MWh/item)
L_n	electricity demand (load) in warehouse n (MW)

$\tilde{L}_s$	electricity demand (load) in store *s* (MW)
γ	probability of meeting the product demand
ϕ_g	capital recovery factor of renewable generator *g*
ϕ_b	capital recovery factor of battery storage system
ζ	random wind or weather condition in a period
$P_{gk}(\zeta)$	random power output of renewable generator *g* in factory *k*
$P_{gn}(\zeta)$	random power output of renewable generator *g* in warehouse *n*
$P_{gs}(\zeta)$	random power output of renewable generator *g* in store *s*
$\lambda_{gk}(\zeta)$	capacity factor of renewable generator *g* in factory *k*
$\lambda_{gn}(\zeta)$	capacity factor of renewable generator *g* in warehouse *n*
$\lambda_{gs}(\zeta)$	capacity factor of renewable generator *g* in store *s*

Table 3.2: Model 3.1 Decision variables

Decision Variable	**Comments**
x_{ijkn}	amount of product *I* in period *j* made by factory *k* shipped to warehouse *n*
$\tilde{x}_{ijkn}$	amount of product *I* in period *j* shipped from warehouse *n* to store *s*
y_{ijn}	inventory of product *I* in period *j* in warehouse *n*
z_{ijn}	backorder of product *I* in period *j* in warehouse *n*
$P^c{}_{gk}$	power capacity of generator *g* in factory *k* (unit: MW)
$P^c{}_{gn}$	power capacity of generator *g* in warehouse *n* (unit: MW)
$P^c{}_{gs}$	power capacity of generator *g* in store *s* (unit: MW)
$B^c{}_k$	BSS capacity at factory *k*
$B^c{}_n$	BSS capacity at warehouse *n*
$B^c{}_s$	BSS capacity at store *s*

Model 3.1:

Minimize

$$
\begin{aligned}
f(\mathbf{x},\mathbf{y},\mathbf{z},\mathbf{P}^c) = {} & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}(p_{ijk}+\pi_{ikn})x_{ijkn} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N} h_{ijn}y_{ijn} + \sum_{i=1}^{I}\sum_{j=1}^{J-1}\sum_{n=1}^{N} b_{ijn}z_{ijn} \\
& + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{s=1}^{S}\tilde{\pi}_{ins}\tilde{x}_{ijns} \\
& + \sum_{g=1}^{G}\sum_{k=1}^{K}\phi_g a_g P_{gk}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{k=1}^{K}\tau_{gk}(b_g - c_g)P_{jgk}(\zeta) + \varphi_B d_B \sum_{k=1}^{K} B_k^c \\
& + \sum_{g=1}^{G}\sum_{n=1}^{N}\phi_g a_g P_{gn}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{N}\tau_{gn}(b_g - c_g)P_{jgn}(\zeta) + \varphi_B d_B \sum_{n=1}^{N} B_n^c \\
& + \sum_{g=1}^{G}\sum_{n=1}^{S}\phi_g a_g P_{gs}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{S}\tau_{gs}(b_g - c_g)P_{jgs}(\zeta) + \varphi_B d_B \sum_{s=1}^{S} B_s^c
\end{aligned} \tag{3.1}
$$

Subject to:

$$\sum_{k=1}^{K} x_{i1kn} + y_{i0n} - y_{i1n} + z_{i1n} = \sum_{s=1}^{S}\tilde{x}_{i1ns}\,; \qquad \text{for } j=1,\ \forall I, \text{ and } \forall n \tag{3.2}$$

$$\sum_{k=1}^{K} x_{ijkn} + y_{ij-1n} - y_{ijn} - z_{ij-1n} + z_{ijn} = \sum_{s=1}^{S}\tilde{x}_{ijns}\,; \text{ for } j=2, 3, .., J\text{-}1,\ \forall I, \text{ and } \forall n \tag{3.3}$$

$$\sum_{k=1}^{K} x_{iJkn} + y_{iJ-1n} - y_{iJn} - z_{iJ-1n} = \sum_{s=1}^{S} x_{iJns}\,; \qquad \text{for } j=J,\ \forall I, \text{ and } \forall n \tag{3.4}$$

$$\Pr\left\{\sum_{n=1}^{N}\tilde{x}_{ijns} < D_{ijs}\right\} \le 1-\gamma\,; \qquad \text{for } j=1,2, 3, .., J,\ \forall I, \text{ and } \forall s \tag{3.5}$$

$$\sum_{i=1}^{I}\sum_{n=1}^{N} v_{ikr}x_{ijkn} \le w_{jkr}\,; \qquad \text{for } \forall j,\ \forall r, \text{ and } k=1, 2.., K \tag{3.6}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}(e_{ik} + q_v d_{kn} m_i)x_{ijkn} + \sum_{n=1}^{N} q_v n_{kn} d_{kn} w_v + B_{tn} - B_{t-1n} \le \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gk}P_{jgk}(\zeta)\,;$$

$$\text{for } k=1,2,..k \tag{3.7}$$

$$t_w L_n + + \sum_{k=1}^{K} q_v n_{kn} d_{kn} w_v + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S} q_v \tilde{d}_{ns} m_i \tilde{x}_{ijns} + \sum_{s=1}^{S} q_v \tilde{n}_{ns}\tilde{d}_{ns} w_v + B_{tn} - B_{t-1n} \le \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gn}P_{jgn}(\zeta)$$

$$\text{for } n=1,2,\ldots,N \tag{3.8}$$

$$\tilde{t}_s\tilde{L}_s + \sum_{n=1}^{N} q_v \tilde{n}_{ns}\tilde{d}_{ns} w_v + B_{ts} - B_{t-1s} \le \sum_{j=1}^{J}\sum_{g=1}^{G}\tau_{gs}P_{jgs}(\zeta)\,;$$

$$\text{for } s=1, 2, \ldots, S \tag{3.9}$$

$$y_{i0n} = 0; \quad \text{for } \forall I \text{ and } \forall n \tag{3.10}$$

$$0 \le B_{tk} \le B_k^c; \quad \text{for } k=1, 2, \ldots, K \tag{3.11}$$

$$0 \le B_{tn} \le B_n^c; \quad \text{for } n=1, 2, \ldots, N \tag{3.12}$$

$$0 \le B_{ts} \le B_s^c; \quad \text{for } s=1, 2, \ldots, S \tag{3.13}$$

$$P_{gk}^c, P_{gn}^c, P_{gs}^c \ge 0 \tag{3.14}$$

$$B_k^c, B_n^c, B_s^c \ge 0 \tag{3.15}$$

$$B_{jk}, B_{jn}, B_{js} \ge 0 \tag{3.16}$$

$$x_{ijkn}, \tilde{x}_{ijkn}, y_{ijn}, z_{ijn} \ge 0 \tag{3.17}$$

Objective function (3.1) is to minimize the total cost comprised of manufacturing, transportation, warehousing, and energy. The cost items are similar to Model 2.1. Note that **x**, **y**, and **z** are respectively the vector representation for decision variables of production, inventory, and backorders. $\mathbf{P}^c$ is the vector for the decision variables of power capacity of the WT and PV in each facility and $\mathbf{B}^c$ is the vector representation for the decision variables of energy capacity of BSS at each facility. Model 3.1 is a mixed-integer linear programming model in which **x**, **y**, and **z** are integer decision variables, and $\mathbf{P}^c$ and $\mathbf{B}^c$ are continuous variables.

Constraints (3.2) to (3.6) represent the production-inventory constraints. Constraints (3.2) to (3.4) are the inventory balance condition between the factory and warehouse. Constraint (3.5) is the chance constraint stating that the demand in each retail store must be satisfied with $100\gamma\%$ (e.g. γ=0.9 or 0.95). Constraint (3.6) is the manufacturing resource constraint at each of the factories. Constraint (3.10) states that no initial inventory is available at each of the warehouses.

Constraint (3.7) to (3.9) represents the energy balance equations between the supply and the demand in each facility. Particularly, constraint (3.7) states that the annual electricity consumed by factory k during production and transportation of goods is fully offset by the onsite microgrid generation. Also q_v is the electric vehicle energy intensity rate at speed v. Constraint (3.8) defines the energy balance of the warehouse, stating that the total warehouse energy use including the base load and the return of electric trucks back to the factories and the transportation of goods to all stores is fully offset by the microgrid energy. Note that the electric trucks returning to the factory are empty with no load of goods, hence less electricity is consumed. Constraint (3.9) defines that the total energy used by the retail stores including the store base load and the reverse logistics of empty trucks back to the warehouse is fully offset by the onsite microgrid generation. Constraints (3.11) to (3.13) stipulate that the battery storage level at time t in factories, warehouses and stores, denoted as B_{tk}, B_{tn}, and B_{ts}, respectively, is always non-negative, but not to exceed their capacity. Finally, constraints (3.14) to (3.17) simply define the non-negativity condition of all the decision variables.

3.3 A two-stage Optimization Model with Deterministic Constraints

Since Model 3.1 involves chance constraints and the uncertain generation, a direct solution is difficult to compute. To make the problem tractable, Model 3.1 is reformulated into a two-stage problem. In the first stage, the model is solved as a production-inventory model where the production, inventory and backorders are determined. In the second stage, using the stage 1 results, the power capacity of the WT and PV and the energy capacity of BSS units at each of the facility are further allocated. For convenience, we use Model 3.2.1 to represent the first stage decision, and Model 3.2.2 stands for the second stage decision.

Model 3.2.1 (Production Planning)

Minimize

$$f_1(\mathbf{x},\mathbf{y},\mathbf{z}) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{n=1}^{N}(p_{ijk}+\pi_{ikn})x_{ijkn} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}h_{ijn}y_{ijn} + \sum_{i=1}^{I}\sum_{j=1}^{J-1}\sum_{n=1}^{N}b_{ijn}z_{ijn} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{n=1}^{N}\sum_{s=1}^{S}\tilde{\pi}_{ins}\tilde{x}_{ijns} \tag{3.18}$$

Subject to:

$\sum_{k=1}^{K} x_{i1kn} + y_{i0n} - y_{i1n} + z_{i1n} = \sum_{s=1}^{S}\tilde{x}_{i1ns}$; for j=1, $\forall I$, and $\forall n$ (3.19)

$\sum_{k=1}^{K} x_{ijkn} + y_{ij-1n} - y_{ijn} - z_{ij-1n} + z_{ijn} = \sum_{s=1}^{S}\tilde{x}_{ijns}$; for j=2, 3, .., J-1, $\forall I$, and $\forall n$ (3.20)

$\sum_{k=1}^{K} x_{iJkn} + y_{iJ-1n} - y_{iJn} - z_{iJ-1n} = \sum_{s=1}^{S} x_{iJns}$; for j=J, $\forall I$, and $\forall n$ (3.21)

$\Pr\left\{\sum_{n=1}^{N}\tilde{x}_{ijns} < D_{ijs}\right\} \le 1-\gamma$; for j=1,2, 3, .., J, $\forall I$, and $\forall s$ (3.22)

$\sum_{i=1}^{I}\sum_{n=1}^{N} v_{ikr}x_{ijkn} \le w_{jkr}$; for $\forall j$, $\forall r$, and k =1, 2.., K (3.23)

$y_{i0n} = 0$; for $\forall I$ and $\forall n$ (3.24)

$x_{ijkn}, \tilde{x}_{ijkn}, y_{ijn}, z_{ijn} \ge 0$ (3.25)

Model 3.2.1 is a linear integer programming model. To solve the original stochastic model, constraint (3.5) is converted into its deterministic counterpart shown in constraint (3.22). All the other constraints remain the same.

Model 3.2.2 (Microgrid Sizing)

Minimize

$$\begin{aligned} f_2(\mathbf{P}^c, \mathbf{B}^c, x, y, z) = & \sum_{g=1}^{G}\sum_{k=1}^{K}\phi_g a_g P_{gk}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{k=1}^{K}\tau_{gk}(b_g - c_g)\lambda_{jgk}P_{gk}^c + \varphi_B d_B \sum_{k=1}^{K} B_k^c \\ & + \sum_{g=1}^{G}\sum_{n=1}^{N}\phi_g a_g P_{gn}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{N}\tau_{gn}(b_g - c_g)\lambda_{jgn}P_{gn}^c + \varphi_B d_B \sum_{n=1}^{N} B_n^c \\ & + \sum_{g=1}^{G}\sum_{n=1}^{S}\phi_g a_g P_{gs}^c + \sum_{j=1}^{J}\sum_{g=1}^{G}\sum_{n=1}^{S}\tau_{gs}(b_g - c_g)\lambda_{jgs}P_{gs}^c + \varphi_B d_B \sum_{s=1}^{S} B_s^c + f_1(\mathbf{x}, \mathbf{y}, \mathbf{z}) \end{aligned} \tag{3.26}$$

Subject to:

$$\sum_{i=1}^{I}\sum_{n=1}^{N}(e_{ik} + q_v d_{kn} m_i)x_{itkn} + \sum_{n=1}^{N} q_v n_{tkn} d_{kn} w_v + B_{tk} - B_{t-1,k} \le \sum_{g=1}^{G}\tau_{gk}\lambda_{tgk}P_{gk}^c\ ;$$

for t=1, 2, ..., T, and for k=1, 2, …, K (3.27)

$$\tau_m L_n + \sum_{k=1}^{K} q_v n_{tkn} d_{kn} w_v + \sum_{i=1}^{I}\sum_{s=1}^{S} q_v \tilde{d}_{tns} m_i \tilde{x}_{itns} + \sum_{s=1}^{S} q_v \tilde{n}_{tns}\tilde{d}_{ns} w_v + B_{tn} - B_{t-1n} \le \sum_{g=1}^{G}\tau_{gn}\lambda_{tgn}P_{gn}^c\ ;$$

for t=1, 2, ..., T, and for n=1, 2, …, N (3.28)

$$\tilde{\tau}_m \tilde{L}_s + \sum_{n=1}^{N} q_v \tilde{n}_{tns}\tilde{d}_{ns} w_v + B_{ts} - B_{t-1s} \le \sum_{g=1}^{G}\tau_{gs}\lambda_{tgs}P_{gs}^c\ ;$$

for t=1, 2, ..., T, for s=1, 2, …, S (3.29)

$0 \le B_k \le B_k^c$; for k=1, 2, …, K (3.30)

$0 \le B_n \le B_n^c$; for n=1, 2, …, N (3.31)

$0 \le B_s \le B_s^c$; for s=1, 2, …, S (3.32)

$P_{gk}^c, P_{gn}^c, P_{gs}^c \ge 0$ (3.33)

$$B_k^c, B_n^c, B_s^c \geq 0 \tag{3.34}$$

$$B_{jk}, B_{jn}, B_{js} \geq 0 \tag{3.35}$$

Model 3.2.2 is the second stage decision in which the capacity of WT and PV and BSS are to be optimized. Here *t* is the scheduling granularity e.g. weekly, daily, or hourly. All the other constrains are the same as those in Model 3.1. In the next three sections, the two-stage model is implemented in three different supply chain network settings, each being solved in weekly, daily, and hourly basis.

3.4 Weekly Planning

3.4.1 Two-factory, one-warehouse, and two-store setting. In this section, the model is experimented for weekly planning, that is, the stage 1 production-inventory decision and the stage-two energy scheduling decision are planned in weekly basis over one year. There are 52 weeks in a year. Using the wind speeds and weather conditions of ten cities in the U.S, the capacity factor of the WT and PV are estimated based on historical meteorological data. Model 3.2.1 is tested on a two-factory, one-warehouse, and two-store network as shown in Figure 3.2 and 3.3. In Network 1, the two factories are in Phoenix, AZ and Reno, NV. The products are shipped to a central warehouse which is in Las Vegas, NV and then shipped to the retail stores in Salt Lake City, UT and San Jose, CA.

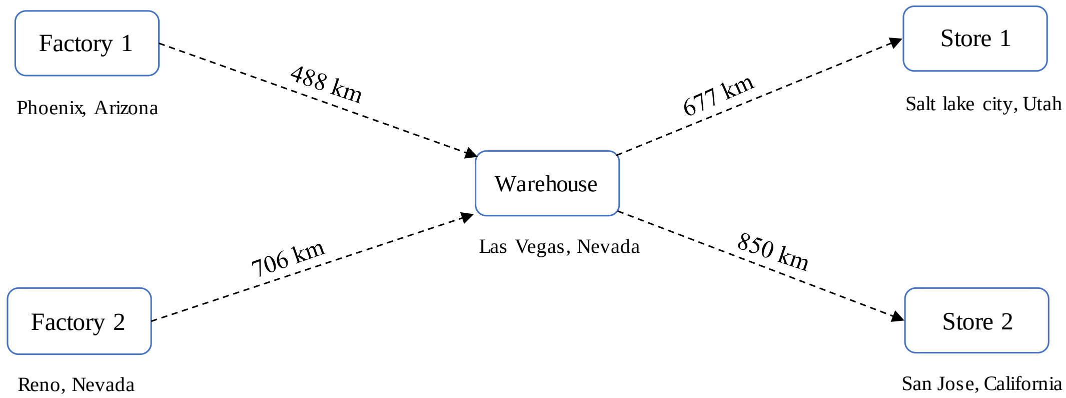

Figure 3.2: Supply chain layout for Network 1

Similarly, in Network 2 there are two factories which are located in Yuma and Tucson in AZ, the products are shipped to a central warehouse in Los Angeles, CA and then shipped to two retail stores in Sacramento and San Francisco in CA.

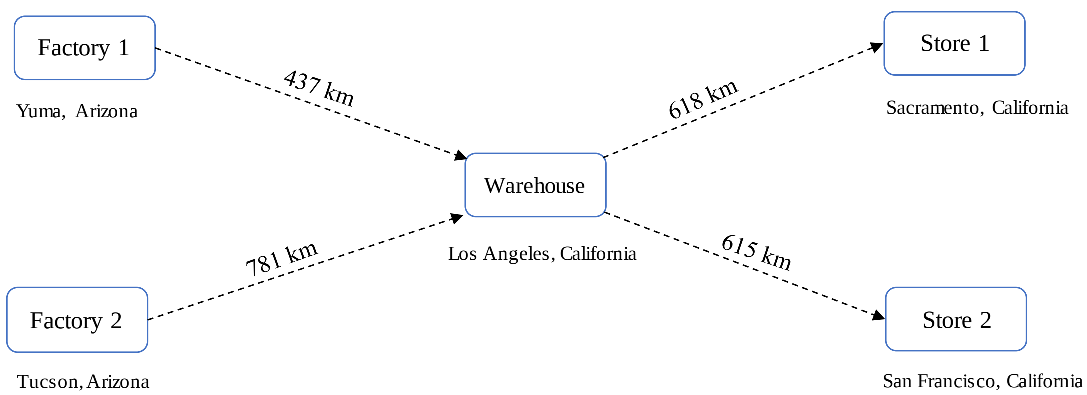

Figure 3.3: Supply chain layout for Network 2

Table 3.3: Summary of twelve experimental cases

Cases	Value of factor changes
1	Benchmark
2	holding cost of Products A and B increase by 50%
3	holding cost of Products A and B decrease by 50%
4	backorder cost of Products A and B increase by 50%
5	backorder cost of Products A and B decrease by 50%
6	PV capacity cost decrease by 50%
7	PV carbon credits is $30/MWh

8	PV carbon credits is $0/MWh (no carbon credits)
9	Discount rate is 7%
10	Battery cost decrease by 50%
11	Battery cost increase by 50%
12	Battery capacity cost is $0.5M/MWh

In these experiments, we consider power intense manufacturing facilities such as a semiconductor wafer fab or a seawater desalination factory that operates 24 hours a day and 7 days a week. The warehouses under consideration are assumed to operate 24 hours a day with base load of 7 MW. The retail stores are operated 12 hours a day with a base load of 4 MW each. The granularity of production planning and energy scheduling is one week in each facility over a 52-week horizon. The results were analyzed in 12 cases shown in Table 3.3 with each case being a change in the critical parameters of the model. All other parameters are provided in Tables 3.4 and 3.5.

Table 3.4: Experimental data for model 3.2.1 in weekly planning

Comments	Notation	Product A (i=1)	Product B (i=2)	Unit
Energy consumed	e_i	0.9	1.2	MWh/item
Production cost (w/o energy)	p_i	400	600	$/item
Holding cost	h_i	8	12	$/period/item
Backlog cost	b_i	75	100	$/item
Shipping cost (F to W)	p_i	0.05	0.08	$/item/km
Shipping cost (W to S)	p_i	0.05	0.08	$/ item/km
Labor hours	v_{i1}	16	24	hours/item
Machine hours	v_{i2}	100	200	hours/item
Product weight	m_i	3	4	Kg/item

*(Note: F- Factory, W – Warehouse, S – Store, w/o - without) *

Table 3.5: Experimental data for model 3.2.2 in weekly planning

WT	PV	BSS

Notation	Value	Unit	Notation	Value	Unit	Notation	Value	Unit
a_g	1.5	$M/MW	a_g	2	$M/MW	a_b	0.02	$M/MW
b_g	12	$/MWh	b_g	4	$/MWh	b_g	n/a	$/MWh
c_g	0	$/MWh	c_g	15	$MWh	c_g	n/a	$/MWh
τ_g	168	hours	τ_g	84	hours	τ_g	168	hours
v_c	3	m/s	η	0.2	N/A	v_c	n/a	m/s
v_r	12	m/s	T_o	45	^{o}C	v_r	n/a	m/s
v_s	25	m/s	α	0	rad	v_s	n/a	m/s
n_e	20	year	n_e	20	years	n_e	n/a	year
i_e	0.05	n/a	i_e	0.05	n/a	i_e	0.05	n/a
ϕ_g	0.0802	n/a	ϕ_g	0.0802	n/a	ϕ_b	0.129	n/a

The WT and PV capacity factors of the ten cities used to solve this model are shown Figure 3.4: Weekly WT capacity factor for ten testing U.S. citiesFigures 3.4 and 3.5.

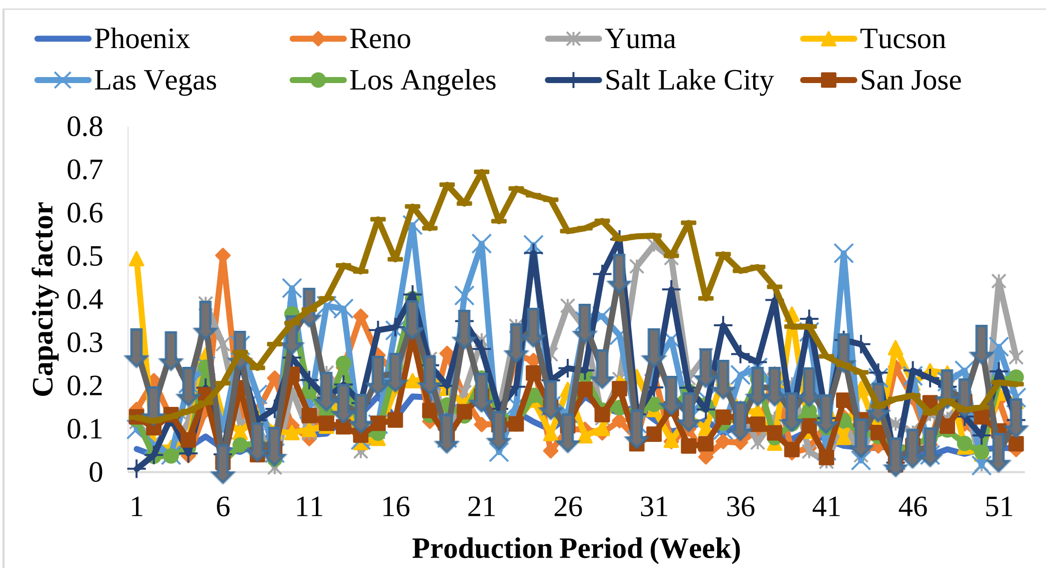

Figure 3.4: Weekly WT capacity factor for ten testing U.S. cities

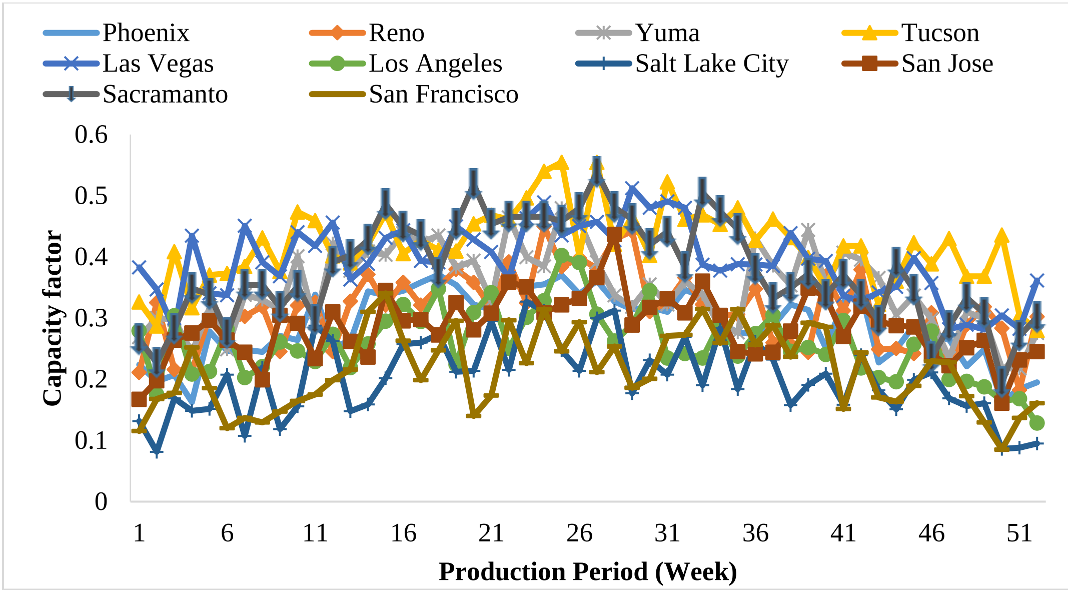

Figure 3.5: Weekly PV capacity factor for ten testing U.S. cities

3.4.2 Results analysis of Network 1. Model 3.2.1 is solved using AMathematical Programming Language (AMPL) software using CPLEX solver in Intel(R) Core(TM) i5-6500 CPU @ 3.20GHz, 3192 Mhz, 4 Core(s), 4 Logical Processor with running time of abouttwo seconds. The weekly production planning model in Network 1 has 624 variables and 834 constraints. Figure 3.6 shows the production quantity in Phoenix and Reno factories for Case 1.

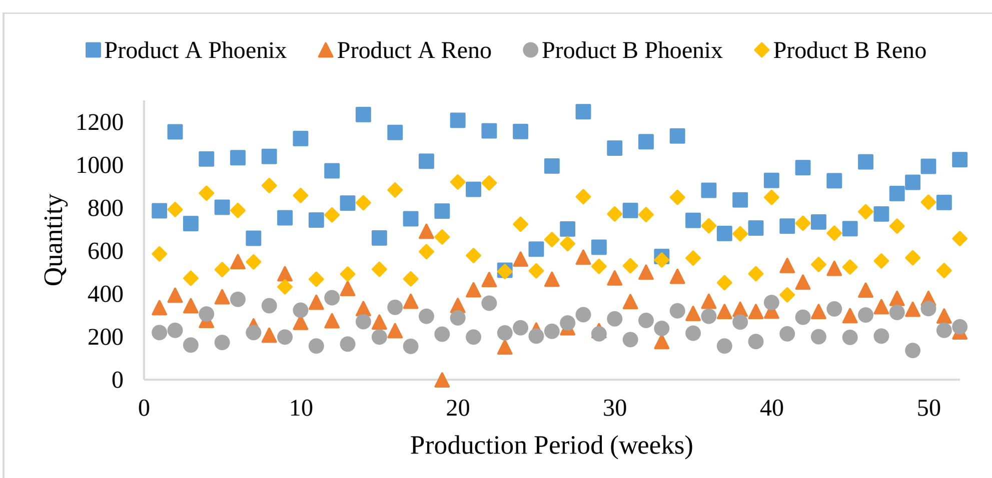

Figure 3.6: Weekly production quantity at Phoenix and Reno factories

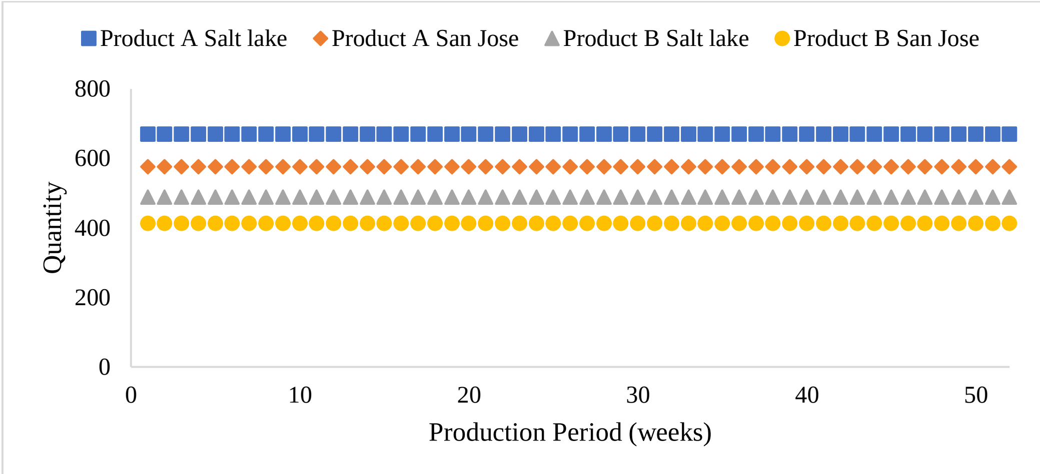

Figure 3.7: Weekly production quantity from warehouse to Salt Lake and San Jose Stores

Figure 3.7 shows the quantity of products shipped from the central warehouse at Las Vegas to the retail stores at Salt Lake and San Jose for case 1. The quantity of products are constant for each of the 52 weeks as the demand at the store has to be met with 90% confidence. The production quantity shipped from factory to warehouse and the quantity shipped from the warehouse to to the store remains the same for all the cases. However variation is observed in the inventory and backorders in each of the cases.

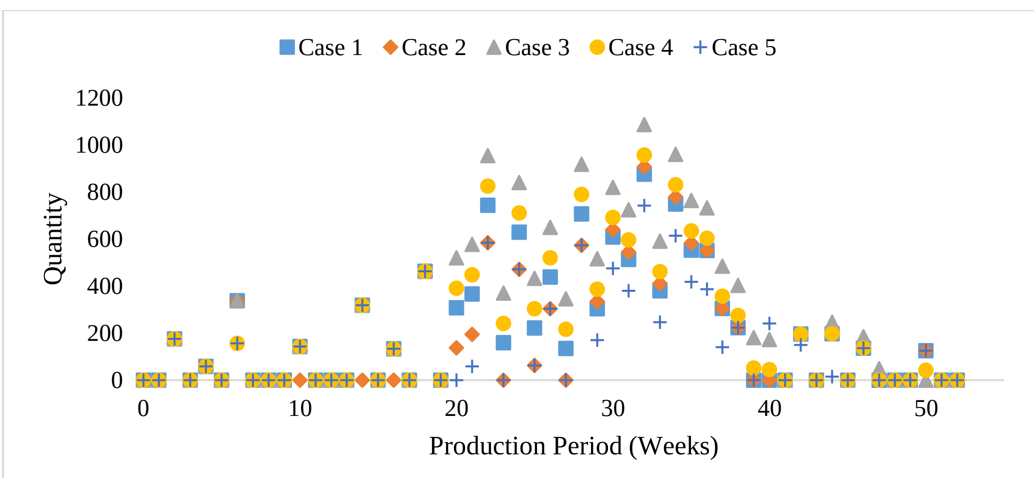

Figure 3.8: Weekly inventory of Product A in cases 1-5

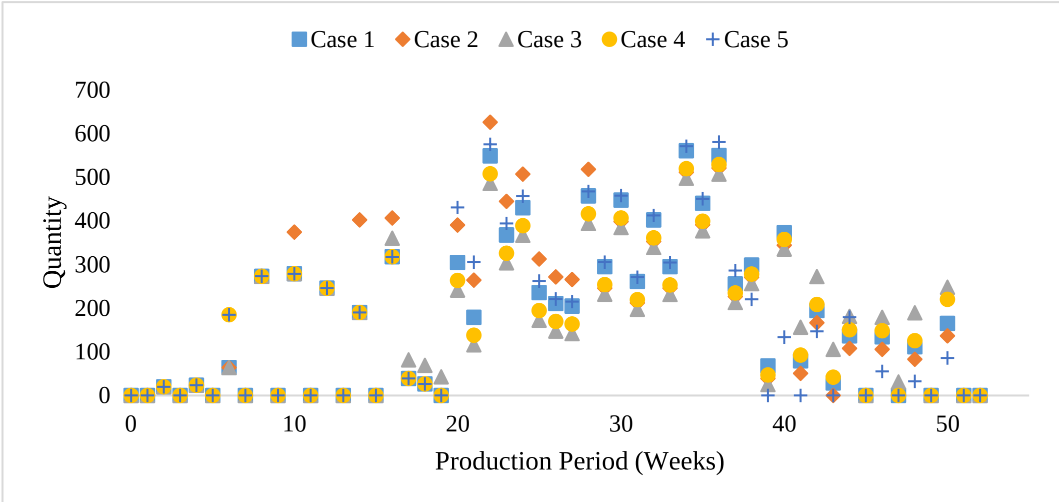

Figure 3.9: Weekly inventory of product B in cases 1-5

Figures 3.8 and 3.9 show the inventory quantities of Products A and B at each period for Cases 1 to 5. The inevntory level trends to increase and remain high between Weeks 20 and 40. The available machine hours in these periods are relatively large so the model chooses to produce more products and store them in the inventory to make sure the demand at each store is met from Weeks 41 to 52.

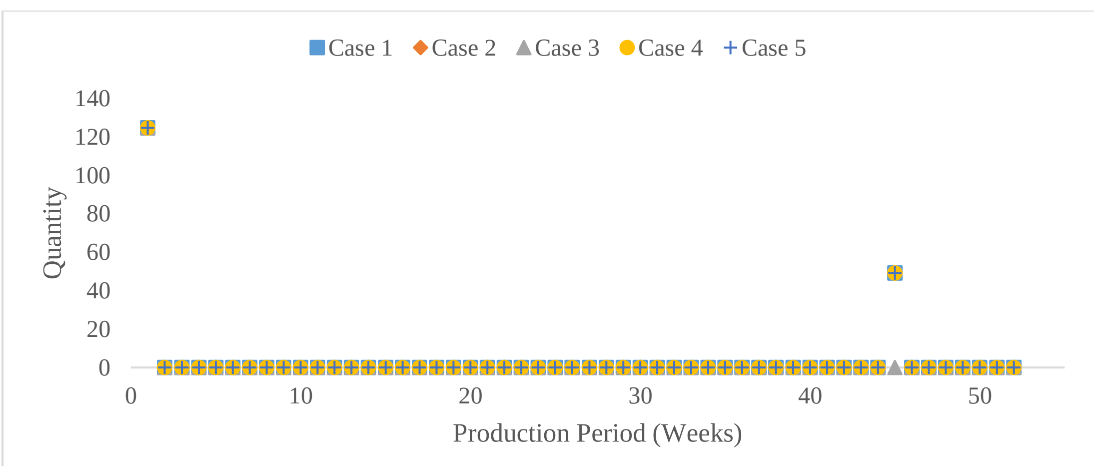

Figure 3.10: Weekly backorders of Product A in cases 1-5

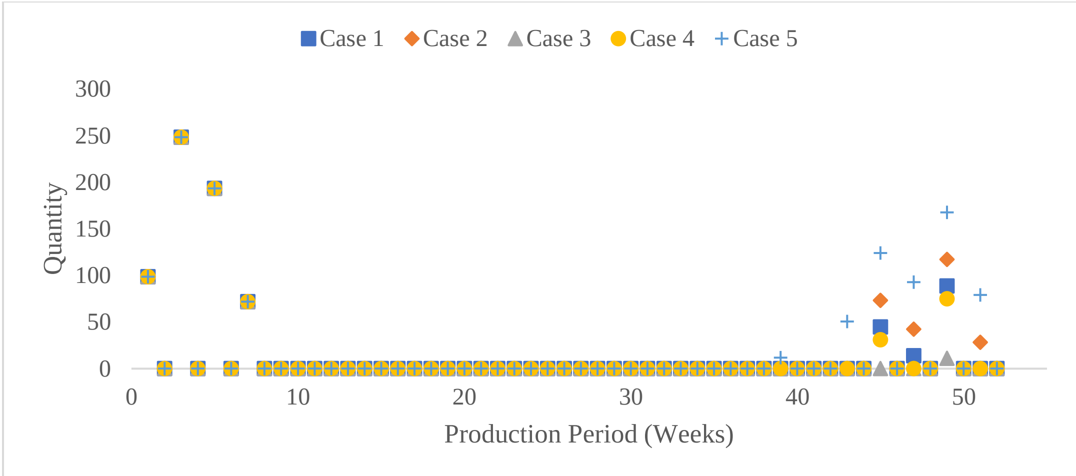

Figure 3.11:Weekly backorders of Product B in cases 1-5

Figures 3.10 and 3.11 show the backorder quantities of Product A and B at the end of each period for 52 weeks. The quantities turn out to be low due to adequate availability of resources in the factory at each period, and products are either made or stored in the inventory. The inventory and backorders for various cases describe the way how the model responds to the change in the key parameters. The production quantities in the factories and the shipping quantites from the warehouse to the store becomes the inputs for the second stage model which determines the capacity of WT, PV and BSS units. The results from the second stage for all the cases are tabulated for easy comparison. Tables 3.6 to 3.17 show the results of the microgrid and battery sizing for each case, the production and shippment as the input parameter remains the same for each case. However, the total system cost and the microgrid sizing may change for each case.

Table 3.6: Results of Case 1 for setup 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)

Phoenix	0.0	78.4	236.0	210.7	12,098,424	57428
Reno	1.8	49.2	422.2	147.6	8,492,401	57526
Las Vegas	0.0	52.5	26.5	122.1	7,498,580	61390
Salt Lake	17.4	0.8	57.9	158.9	2,776,058	17472
San Jose	4.2	16.5	760.4	282.7	4,947,339	17498
Total Cost	$99,758,071					

Table 3.7: Results of Case 2 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	235.5	210.6	12,097,161	57428
Reno	0.8	50.5	404.7	147.7	8,498,072	57526
LV	0.0	52.5	26.5	122.1	7,498,580	61390
SL	17.4	0.8	57.9	158.9	2,776,062	17472
SJ	4.2	16.5	760.4	282.7	4,947,339	17498
Total Cost	$99,764,775					

Table 3.8: Results of Case 3 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	236.0	210.7	12,098,424	57428
Reno	1.8	49.2	422.2	147.6	8,492,401	57526
LV	0.0	52.5	26.5	122.1	7,498,580	61390
SL	17.4	0.8	57.9	158.9	2,776,058	17472
SJ	4.2	16.5	760.4	282.7	4,947,339	17498
Total Cost	$99,758,071					

Table 3.9: Results of Case 4 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	236.0	210.7	12,098,424	57428
Reno	1.8	49.2	422.2	147.6	8,492,401	57526
L V	0.0	52.5	26.5	122.1	7,498,580	61390
S L	17.4	0.8	57.9	158.9	2,776,058	17472
S J	4.2	16.5	760.4	282.7	4,947,339	17498
Total Cost	$99,800,836					

Table 3.10: Results of Case 5 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	236.0	210.7	12,098,424	57428
Reno	1.8	49.2	422.2	147.6	8,492,401	57526
L V	0.0	52.5	26.5	122.1	7,498,580	61390
S L	17.4	0.8	57.9	158.9	2,776,058	17472

S J	4.2	16.5	760.4	282.7	4,947,339	17498
Total Cost		$99,706,680				

Table 3.11: Results of Case 6 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	235.5	101.2	5,809,337	57428
Reno	0.0	52.1	382.3	76.2	4,380,734	57526
L V	0.0	52.5	26.5	53.5	3,287,312	61390
S L	5.2	31.6	75.0	181.6	3,172,603	17472
S J	0.0	21.2	105.0	96.3	1,685,923	17498
Total Cost		$82,282,113				

Table 3.12: Results of Case 7 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.3	235.5	184.8	10,612,869	57428
Reno	0.0	52.0	382.2	130.1	7,485,005	57526
L V	0.0	52.4	26.4	100.1	6,145,218	61390
S L	17.8	0.8	760.4	262.4	4,584,657	17472
S J	4.2	16.4	57.9	161.1	2,820,279	17498
Total Cost		$95,595,554				

Table 3.13: Results of Case 8 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	235.5	236.5	13,581,451	57428
Reno	0.0	52.1	382.3	167.5	9,632,896	57526
L V	2.2	49.0	93.4	137.5	8,441,272	61390
S L	18.0	0.0	774.4	263.2	4,597,774	17472
S J	4.2	16.5	57.9	179.9	3,435,478	17498
Total Cost		$103,957,861				

Table 3.14: Results of Case 9 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	235.5	275.6	15,828,474	57428
Reno	0.0	52.1	382.3	193.9	11,152,669	57526
L V	2.2	49.0	93.4	160.3	9,839,774	61390

S L	18.0	0.0	774.4	290.3	5,071,595	17472
S J	4.2	16.5	57.9	228.5	3,998,401	17498
Total Cost		$106,078,863				

Table 3.15: Results of Case 10 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	235.5	231.2	13,276,454	57428
Reno	0.0	52.1	382.3	158.8	9,137,858	57526
L V	2.0	49.0	108.2	135.9	8,342,672	61390
S L	17.7	0.0	797.2	205.0	3,581,245	17472
S J	4.2	16.5	57.9	192.0	3,360,486	17498
Total Cost		$97,809,528				

Table 3.16: Results of Case 11 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	78.4	235.5	241.8	13,886,448	57428
Reno	0.0	52.1	382.3	176.1	10,127,935	57526
L V	0.0	52.5	26.5	144.8	8,886,197	61390
S L	12.3	13.6	374.4	312.4	5,457,485	17472
S J	4.2	16.5	57.9	200.6	3,510,470	17498
Total Cost		$101,417,498				

Table 3.17: Results of Case 12 for Network 1 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Phoenix	0.0	95.6	0.0	275.5	15,821,388	57428
Reno	0.0	73.4	0.0	211.9	12,189,046	57526
L V	0.0	53.6	0.0	146.1	8,971,658	61390
S L	0.0	51.8	0.0	486.4	8,498,740	17472
S J	4.3	19.9	0.0	221.0	3,866,548	17498
Total Cost		$107,529,705				

The microgrid sizing is greatly influenced by the capacity factors of WT and PV at each facility site. Case 1 serves as the benchmark study, and shows the capacities of the wind turbine, PV and battery systems to be installed. Cities such as Phoenix, Reno, Las Vegas and San Jose has higer PV capacity factor and the model opts to install PV, whereas the WT capacity factor is high in Salt Lake City, thus the model chooses to install more WT capacity. The capacities of the battery systmes depends on the power load of each of the facility. In Phoenix the installation of PV is higher, thus the power produced is directly consumed for the factory's daily operation. Hence there is less battery capacity to be installed. In Reno, the installation of WT and PV capacities are less compared to Phoenix, hence istallation of a larger battery is required so that the energy can be stored and used in the periods when the generation is small. Las Vegas is the site of the central warehouse, and a base load of 7 MW is required for its 24/7 warehousing operation. Thus the wind turbine and battery installation is low. The stores in Salt Lake city and San Jose consume a base load of 4 MW for 12 hours during the daytime.

In Case 2 the installation at Reno has been altered slightly but the overall combained capacity still remains the same. This is due to an increase in inventory costs of the first stage decison, hence increasing the objective function value to $64,043,381. To counter this high costs, in the second stage the model chooses to install more battery capacity. Since Reno is sunny and the PV capacity factor is high, larger installation of PV means more energy can be generated and stored in the BSS.

Results of Case 3 remains the same of the benchmark case. The model chooses to install WT and PV systems based on the climate condition. The cost of first stage in Case 3 is $63, 840, 546 which is less than Case 2 because of the reduced inventory holding cost.

Case 4 is also similar to the benchmark case. The total cost of production, shipping and storage in the first stage cost is $63,987,876.

For Case 5, the total cost in the first stage is $63,893,720. This reduced cost is due to the low backorder cost. The backorder quantities of each of the cases can be viewed in

Figures 3.12 and 3.13. The WT, PV and battery installation remains same as the benchmark case.

In Case 6 where the PV capacity cost is reduced by 50% of the benchmark case, as expected the model chooses to install more PV across all the facilities. Particularly, in Salt Lake city although the WT capacity factor is much better than that of PV, the model chooses to install more PV because of the low PV capacity cost.

Case 7 investigate how carbon credits influence the adoption of PV generation. Carbon credits are an intensive program carried out by government agencies in various countries to stimulate the adoption and integration of PV systems. Currently, in the US a carbon credits between $12 to $15 per MWh are given to every PV installation. As a benchmarck value we used $15/MWh. Here we increase the value to $35/MWh to test how to model behaves. As anticipated the model chooses to install more PV. In Salt Lake city, although a carbon credit of $35/MWh is applied the model still prefer to install WT due to good wind profile and excessive energy is stored in the battery.

In Case 8, we tested the model by applying $0/MWh carbon credit. At facilities in Las Vegas, Salt Lake city the model chooses to install less PV. This reduced PV installation in Salt Lake city means more WT installation which in turn increases the battery capacity as more energy is required to be stored.

In Case 9, the model is tested by increasing the discounted rate from 5% to 7% which means that the installation costs of WT and PV systems are increased. Thus, the installation capacity changes in Reno, Las Vegas and Salt Lake city compared to the benchmark case. The model chooses to install more WT as its capacity cost is less.

In Case 10 the battery cost is reduced by 50%, and as anticpated the model chooses to install more battery at each of the facilities. In facilities at Reno and San Jose the model directly uses the required energy from WT and PV systems to meet the demand, thus less battery capacity is needed at those facilities.

Case 11 sees the battery cost to increase by 50% which forces the model to decrease the battery size. In Salt Lake city there is more battery installed because of the increased WT and PV capacities.

In Case 12, the battery cost is increased to $\$0.5\times10^6$/MWh. At this cost level there is no installation of battery at any of these facilities.

3.4.3 Analysis of Network 2. The production-inventory results remain the same as Network 1 because the same parameters and resources were used. However, the sizing of DER units are found to change because the climate conditions of the cities in Network 2 changes. The results for all 12 cases are summerized in Table 3.18 to 3.29.

Table 3.18: Results of Case 1 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	12.2	35.0	628.9	145.8	8,892,813	57411
Tucson	0.0	47.1	194.7	123.6	7,112,805	57530
Los Angeles	21.3	56.2	433.5	200.7	12,312,114	61360
Sacramento	1.4	14.8	49.7	139.7	2,441,358	17472
San Francisco	16.4	0.0	38.5	156.4	2,735,900	17491
Total System Cost		$96,035,656				

Table 3.19: Results of Case 2 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	12.1	35.0	628.5	145.8	8,371,944	57411
Tucson	0.0	44.5	257.4	120.1	7,112,805	57534
LA	21.3	56.2	433.5	200.7	12,312,114	61360
Sacramento	1.4	14.8	49.7	139.7	2,441,358	17472
SF	16.4	0.0	38.5	156.4	2,735,900	17491
Total Cost		$95,929,952				

Table 3.20: Results of Case 3 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	12.1	35.0	628.5	145.8	8,370,163	57411
Tucson	0.0	43.1	291.9	118.2	6,799,345	57530
LA	21.3	56.2	433.5	200.7	12,312,115	61360
Sacramento	1.4	14.8	49.7	139.7	2,441,358	17472
SF	16.4	0.0	38.5	156.4	2,735,901	17491
Total Cost		$95,615,717				

Table 3.21: Results of Case 4 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	12.1	35.0	628.5	145.8	8,370,163	57411
Tucson	0.0	43.1	291.9	118.2	6,799,345	57530
LA	21.3	56.2	433.5	200.7	12,312,115	61360
Sacramento	1.4	14.8	49.7	139.7	2,441,358	17472
SF	16.4	0.0	38.5	156.4	2,735,901	17491
Total Cost		$95,763,046				

Table 3.22: Results of Case 5 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	12.1	35.0	628.5	145.8	8,892,813	57411
Tucson	0.0	47.1	194.7	123.6	7,112,806	57530
LA	21.3	56.2	433.5	200.7	12,312,115	61360
Sacramento	1.4	14.8	49.7	139.7	2,441,358	17472
SF	16.4	0.0	38.5	156.4	2,735,901	17491
Total Cost		$95,984,265				

Table 3.23: Results of Case 6 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	0.0	59.8	210.4	75.6	4,338,008	57411
Tucson	0.0	55.2	0.0	57.6	3,316,225	57530
LA	9.2	85.1	0.0	114.2	7,006,390	61360
Sacramento	1.1	15.3	53.0	70.8	1,236,349	17472
SF	7.5	12.4	116.7	135.6	2,371,681	17491
Total Cost		$81,328,829				

Table 3.24: Results of Case 7 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)

Yuma	12.2	35.0	628.9	131.9	7,570,106	57411
Tucson	0.0	47.1	194.7	101.2	5,821,159	57530
LA	21.3	56.2	433.5	185.2	11,360,820	61360
Sacramento	1.4	14.8	49.7	118.6	2,072,697	17472
SF	0.0	16.4	38.5	133.0	2,326,794	17491
Total Cost		$92,624,436				

Table 3.25: Results of Case 8 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	12.2	35.0	628.9	159.8	9,173,782	57411
Tucson	13.0	31.9	436.8	143.4	8,248,661	57530
LA	21.3	56.2	433.5	215.4	13,263,410	61360
Sacramento	2.2	13.9	61.1	159.9	2,793,983	17472
SF	16.4	0.0	38.5	156.4	2,735,901	17491
Total Cost		$99,275,267				

Table 3.26: Results of Case 9 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	12.2	35.0	628.9	168.9	9,696,295	57411
Tucson	0.0	47.1	194.7	147.2	8,469,143	57530
LA	21.3	56.2	433.5	235.0	14,407,811	61360
Sacramento	2.2	13.9	61.1	165.8	2,896,292	17472
SF	15.0	0.0	125.9	175.6	3,071,024	17491
Total Cost		$101,602,091				

Table 3.27: Results of Case 10 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	12.2	35.0	628.9	131.6	7,557,566	57411
Tucson	13.0	31.9	436.8	118.3	6,808,190	57530
LA	28.6	46.2	709.0	189.3	11,607,520	61360
Sacramento	2.2	13.9	61.1	135.6	2,368,982	17472
SF	12.6	0.0	343.2	141.8	2,479,402	17491
Total Cost		$93,832,164				

Table 3.28: Results of Case 11 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	12.2	35.0	628.9	160.0	9,186,322	57411
Tucson	0.0	47.1	194.7	128.0	7,364,952	57530
LA	14.1	68.4	210.8	209.3	12,831,801	61360
Sacramento	1.4	14.8	49.7	143.4	2,505,703	17472
SF	16.4	0.0	38.5	150.0	2,785,798	17491
Total Cost		$97,735,217				

Table 3.29: Results of Case 12 for Network 2 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	0.0	71.3	0.0	178.4	10,240,518	57411
Tucson	0.0	55.2	0.0	134.6	7,742,143	57530
LA	9.2	85.1	0.0	225.7	13,838,160	61360
Sacramento	1.5	17.3	0.0	153.0	2,673,865	17472
SF	17.9	0.0	0.0	164.8	2,881,842	17491
Total Cost		$100,436,790				

In stage 2 of the model, the power capacity of WT and solar PV systems and energy capacity of battery are determined. Similar to Setup 1 the capacity decision is hugely dependent on the wind speed and weather condition of the local city. The model is first tested on the benchmark case (i.e. Case 1). Cities like Tucson and Sacramento possess high PV capacity factor,and thus the model chooses to install more PV at these facilities; whereas cities like Yuma and Los Angeles have a mix of strong sunshine and moderate wind, the model prefers a generation mix of WT and PV at these facilities. San Francisco has very high wind profile, hence the model chooses to install more WT at this facility.

In Case 2 the model is tested by increasing the inventory holding cost by 50%. As a result the total system cost goes up in the first stage production decision with $63,155,405. To compensate the cost increase, the model in the second stage chooses to install less PV capacity and more battery capacity in Tucson. This tends to balance out the cost increase in the previous stage.

In Case 3, we can observe a small change in PV and battery capacity in Tucson. This change occurs because of the change in the objective function value for this case. Due to this decrease, the model chooses to install more battery with a slightly reduced PV capacity. Case 4 remains the same as Case 3 with the total cost of the first stage production being $63,099,900.

The capacity for WT, PV and BSS in Case 5 remains the same as that of the benchmark case. The objective function value decreases to $63,005,745 in this case.

Case 6 sees a decrease in the capacity cost of the PV systems. The model opts to expand and install more PV in all the facilities. For the facilities in Tucson and Los Angeles the PV installation is higher compared to the benchmark case.

Case 7 examines the impct of carbon credits on the microgrid design. The model in this case is tested by increasing the carbon credits from baseline $15/MWh to $30/MWh. The model automatically chooses to install more PV across all the facilities. Particularly, in San Francisco where the wind turbine capacity factor is high, $35/MWh carbon credit become competive and the model chooses to install PV in San Francisco.

Government-based incentive policies keep changing over the years and renewable carbon credits generally is decreasing. In case 8 we test the model by applying zero carbon credits to PV. As expected the overall cost of the system increases and the model chooses to install generation systems that leads to the least expense based on the wind and weather profiles of the cities.

3.4.4 Four-factory, two-warehouse, and four-store setting. Model 3.2 is further applied to an expaneded supply chain network comprised of four factories, two warehouses and, four stores as shown in Figure 3.12. The factories are located in Phoenix, Reno, Yuma and Tucson, respectively. The products are shipped to two warehouses located at Las Vegas and Los Angeles from which they are distributed to stores in Salt Lake, San Jose, Sacramento and San Francisco.

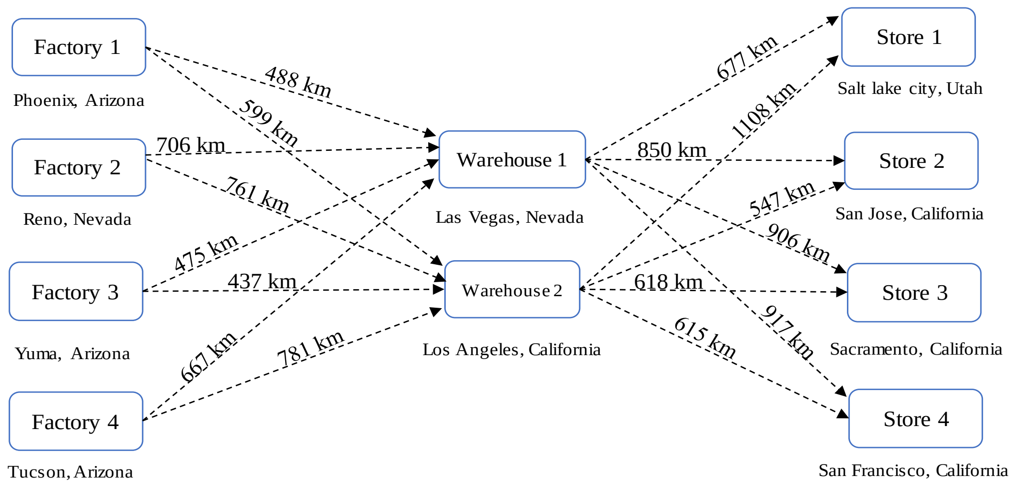

Figure 3.12: Supply chain layout for Network 3

3.4.5 Results and discussion of Network 3. Similar to the previous networks, Model 3.2.1 is solved for a expanded setting using AMPL software and CPLEX solver. The model parameters for the two-stage optimization remain the same as of the previous two networks. The expanded model has 1,248 decision variables and 3,332 constraints. The results of the second stage decision are summerized in Tables 3.30 to 3.41,

Table 3.30: Results of Case 1 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	224.9	6,392,538	28426
Reno	0.0	34.5	169.3	161.1	5,450,934	33836
Yuma	4.4	17.9	274.5	150.3	3,895,376	25913
Tucson	0.4	23.9	247.7	120.5	4,055,913	33669
Las Vegas	0.0	53.2	26.8	122.8	7,602,621	61895
Los Angeles	22.1	58.2	449.2	206.0	12,758,496	61934
Salt Lake	17.2	0.8	754.0	259.2	4,556,882.	17582
San Jose	4.1	16.1	56.5	173.9	3,053,077	17558
Sacramento	1.4	14.8	49.4	138.2	2,426,895	17566
San Francisco	16.4	0.0	38.5	155.8	2,737,086	17567
Total Cost		$120,100,154				

Table 3.31: Results of Case 2 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	224.9	6,392,538	28426
Reno	0.0	34.5	169.3	161.1	5,450,934	33836
Yuma	4.4	17.9	274.5	150.3	3,895,376	25913
Tucson	0.4	23.9	247.7	120.5	4,055,913.21	33669
LV	0.0	53.2	26.8	122.8	7,602,621	61895
LA	22.1	58.2	449.2	206.0	12,758,496	61934
SL	17.2	0.8	754.0	259.2	4,556,882.	17582
San Jose	4.1	16.1	56.5	173.9	3,053,077	17558
Sacramento	1.4	14.8	49.4	138.2	2,426,895	17566
SF	16.4	0.0	38.5	155.8	2,737,086	17567
Total Cost	$120,157,921					

Table 3.32: Results of Case 3 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	224.9	6,392,538	28426
Reno	0.0	34.5	169.3	161.1	5,450,934	33836
Yuma	4.4	17.9	274.5	150.3	3,895,376	25913
Tucson	0.4	23.9	247.7	120.5	4,055,913.21	33669
LV	0.0	53.2	26.8	122.8	7,602,621	61895
LA	22.1	58.2	449.2	206.0	12,758,496	61934
SL	17.2	0.8	754.0	259.2	4,556,882.	17582
San Jose	4.1	16.1	56.5	173.9	3,053,077	17558
Sacramento	1.4	14.8	49.4	138.2	2,426,895	17566
SF	16.4	0.0	38.5	155.8	2,737,086	17567
Total Cost	$120,100,154					

Table 3.33: Results of Case 4 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	224.9	6,392,538	28426
Reno	0.0	34.5	169.3	161.1	5,450,934	33836

Yuma	4.4	17.9	274.5	150.3	3,895,376	25913
Tucson	0.4	23.9	247.7	120.5	4,055,913	33669
LV	0.0	53.2	26.8	122.8	7,602,621	61895
LA	22.1	58.2	449.2	206.0	12,758,496	61934
SL	17.2	0.8	754.0	259.2	4,556,882	17582
San Jose	4.1	16.1	56.5	173.9	3,053,077	17558
Sacramento	1.4	14.8	49.4	138.2	2,426,895	17566
SF	16.4	0.0	38.5	155.8	2,737,086	17567
Total Cost		$120,124,189				

Table 3.34: Results of Case 5 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	224.9	6,392,538	28426
Reno	0.0	34.5	169.3	161.1	5,450,934	33836
Yuma	4.4	17.9	274.5	150.3	3,895,376	25913
Tucson	0.4	23.9	247.7	120.5	4,055,913.21	33669
LV	0.0	53.2	26.8	122.8	7,602,621	61895
LA	22.1	58.2	449.2	206.0	12,758,496	61934
SL	17.2	0.8	754.0	259.2	4,556,882.	17582
San Jose	4.1	16.1	56.5	173.9	3,053,077	17558
Sacramento	1.4	14.8	49.4	138.2	2,426,895	17566
SF	16.4	0.0	38.5	155.8	2,737,086	17567
Total Cost		$120,072,731				

Table 3.35: Results of Case 6 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0	40.5	175	110.5	3,141,438	28426
Reno	0	34.5	169.3	79.3	2,683,866	33836
Yuma	0	26.8	124.6	78	2,020,954	25913
Tucson	0	34.4	0	61.4	2,066,523	33669
LV	0	53.2	26.8	53.8	3,332,923	61895
LA	9.5	88.2	0	117.2	7,260,412	61934
SL	5.1	31.4	104.2	183.3	3,223,200	17582
San Jose	0	20.7	73.2	89.4	1,569,542	17558
Sacramento	1.1	15.2	52.7	70	1,229,022	17566
SF	7.5	12.4	116.8	135.1	2,372,714	17567
Total Cost		$96,069,537				

Table 3.36: Results of Case 7 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	197.9	5,625,090	28426
Reno	0.0	34.5	169.3	140.1	4,739,703	33836
Yuma	4.4	17.9	274.5	134.5	3,485,642	25913
Tucson	0.4	23.9	247.7	101.0	3,399,086	33669
LV	0.0	53.2	26.8	100.7	6,230,482	61895
LA	22.1	58.2	449.2	190.1	11,772,712	61934
SL	17.2	0.8	754.0	258.6	4,546,113	17582
San Jose	4.1	16.1	56.5	156.8	2,752,834	17558
Sacramento	1.4	14.8	49.4	117.3	2,060,418	17566
SF	16.4	0.0	38.5	155.8	2,737,087	17567
Total Cost		$114,574,833				

Table 3.37: Results of Case 8 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	5.2	37.4	113.6	251.8	7,156,238	28426
Reno	0.0	34.5	169.3	182.1	6,162,166	33836
Yuma	4.4	17.9	274.5	166.1	4,305,110	25913
Tucson	0.4	23.9	247.7	140.1	4,712,740	33669
LV	2.3	49.7	94.7	143.5	8,884,192	61895
LA	22.1	58.2	449.2	221.9	13,744,281	61934
SL	17.2	0.0	767.9	254.2	4,469,788	17582
SJ	4.1	16.1	56.5	191.0	3,353,320	17558
Sacramento	2.2	13.8	60.8	158.1	2,777,425	17566
SF	16.4	0.0	38.5	155.8	2,737,087	17567
Total Cost		$125,507,850				

Table 3.38: Results of Case 9 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	266.0	7,560,630	28426
Reno	0.0	34.5	169.3	190.6	6,447,519	33836
Yuma	4.4	17.9	274.5	174.7	4,527,142	25913
Tucson	0.4	23.9	247.7	141.8	4,771,585	33669
LV	2.3	49.7	94.7	146.5	9,069,637	61895
LA	22.1	58.2	449.2	241.1	14,930,173	61934
SL	17.2	0.0	767.9	280.2	4,926,446	17582
SJ	4.1	16.1	56.5	205.2	3,602,538	17558
Sacramento	2.2	13.8	60.8	163.9	2,879,127	17566

SF	15.0	0.0	126.0	174.9	3,072,357	17567
Total Cost		$129,060,016				

Table 3.39: Results of Case 10 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	113.6	216.9	6,086,486	28426
Reno	0.0	34.5	169.3	154.6	5,231,751	33836
Yuma	4.4	17.9	274.5	136.6	3,539,936	25913
Tucson	0.4	23.9	247.7	111.0	3,735,192	33669
LV	0.0	53.2	26.8	120.8	7,567,892	61895
LA	14.6	70.8	218.4	194.2	12,731,278	61934
SL	12.2	13.5	371.2	202.0	4,272,292	17582
SJ	4.1	16.1	56.5	169.7	2,979,878	17558
Sacramento	1.4	14.8	49.4	133.2	2,362,932	17566
SF	16.4	0.0	38.5	141.2	2,687,169	17567
Total Cost		$116,712,891				

Table 3.40: Results of Case 11 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	37.4	113.6	208.2	5,918,758	28426
Reno	0.0	34.5	169.3	167.6	5,670,119	33836
Yuma	4.4	17.9	274.5	164.0	4,250,816	25913
Tucson	0.4	23.9	247.7	130.1	4,376,634	33669
LV	0.0	53.2	26.8	123.4	7,637,352	61895
LA	14.6	70.8	218.4	214.7	13,297,017	61934
SL	12.2	13.5	371.2	297.7	5,233,737	17582
SJ	4.1	16.1	56.5	178.0	3,126,276	17558
Sacramento	1.4	14.8	49.4	141.8	2,490,859	17566
SF	16.4	0.0	38.5	158.7	2,787,005	17567
Total Cost		$122,631,687				

Table 3.41: Results of Case 12 for Network 3 in weekly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	5.2	45.7	0.0	259.3	7,370,286	28426

Reno	0.0	43.9	0.0	188.8	6,387,600	33836
Yuma	0.0	33.6	0.0	186.1	4,823,409	25913
Tucson	0.0	34.4	0.0	143.4	4,824,556	33669
LV	0.0	54.4	0.0	124.3	7,694,580	61895
LA	9.5	88.2	0.0	231.5	14,339,875	61934
SL	0.0	51.4	0.0	440.7	7,748,940	17582
SJ	4.2	19.4	0.0	194.3	3,411,606	17558
Sacramento	1.5	17.2	0.0	151.3	2,658,011	17566
SF	17.9	0.0	0.0	164.1	2,883,097	17567
Total Cost		$129,315,998				

In Setup 3 for weekly planning, similar results as those of Networks 1 and 2 are observed. As the key parameters changes, small variation in WT, PV and BSS capacity occur in certain cases. The total system cost is higher as this decision involves ten facilities. The model while solved in setup 3 has more combinations for shipping the quantities, the model has the option of shipping to a closer location. For example, the factory in Phoenix is much closer to the warehouse in Las Vegas compared to the warehouse in Los Angeles. The model chooses to ship products from Phoenix to Las Vegas rather than to Los Angeles. The transportation distance is taken into cosideration as it has an effect in the total cost of the system. The results of each sensitivity analysis shows that change in parameter may not hugely affect the decision. For example, in Case 6 where the model is tested by decresing thr PV capacitiy cost to $1M/MW, it shows more WT is installed at locations like Los Angeles, Salt Lake and San Francisco because of their strong wind profile. In fact San Francisco does not install PV in all cases.

3.5 Daily Planning

3.5.1 Conversion of weekly production to daily production. In an attempt to improve the granularity of Model 3.2, the length of a planning period is reduced from one week to one day. First, it is attempted on two-factory, one-warehouse, and two-store setting. It means the number of planning periods incresaes from 52 to 364 over a year. In order to achieve this we convert the weekly production of the two products to daily production by diving by seven for each day of the weeks and the result is equally distributed in a week. Figures 3.13 and 3.14 shows the daily production for Network 1 as opposed to the weekly production shown in Figure 3.6. The conversion is similar for both the networks.

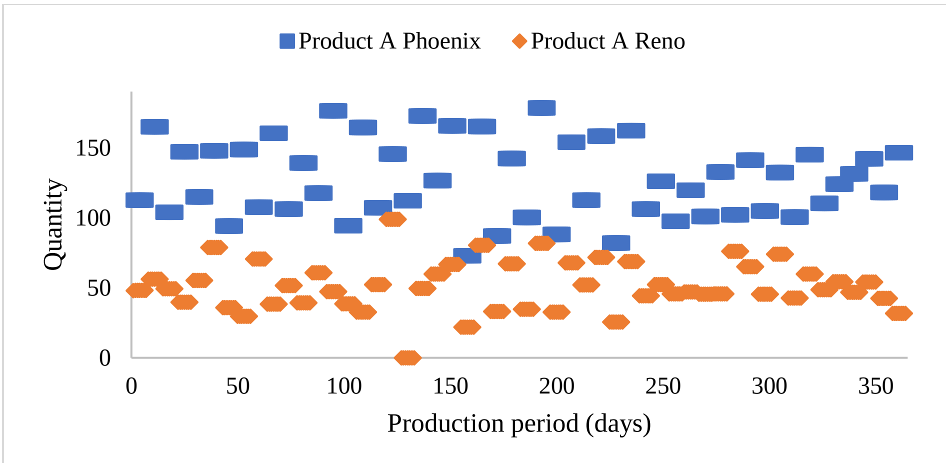

Figure 3.13: Daily production of Product A in the factories

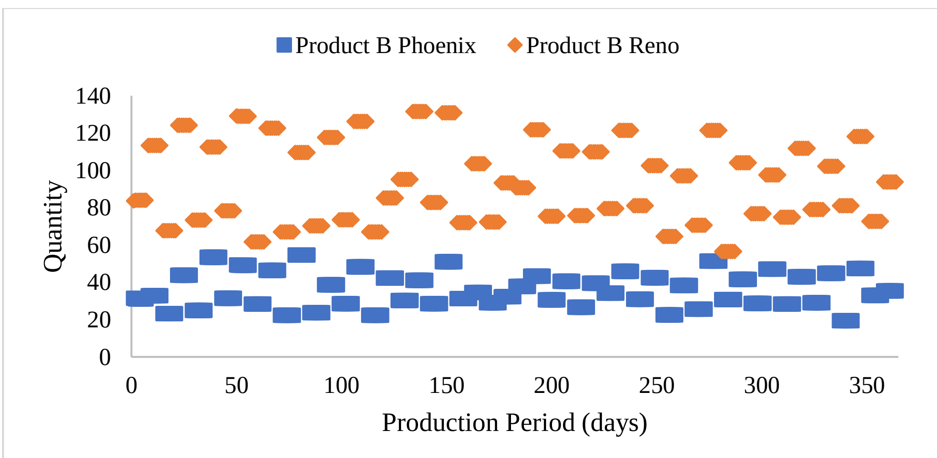

Figure 3.14: Daily production of Product B in the factories

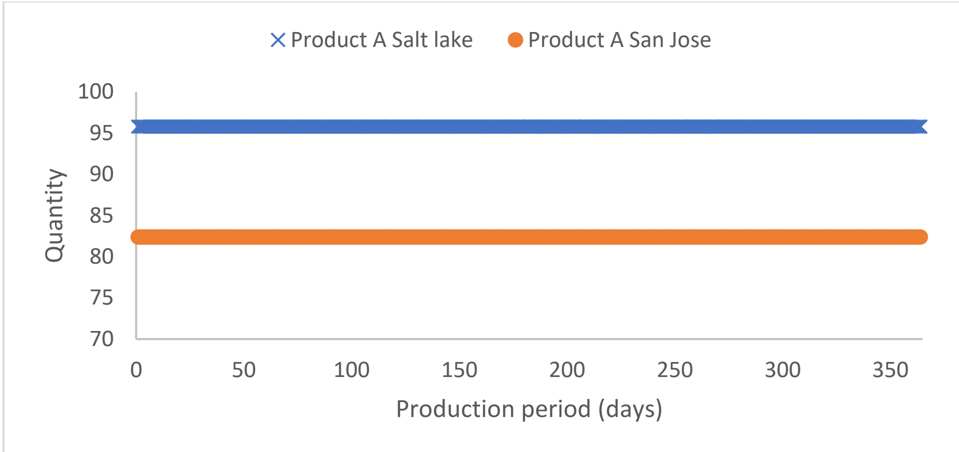

Figure 3.15: Daily shipping quantity of Product A from warehouse to stores

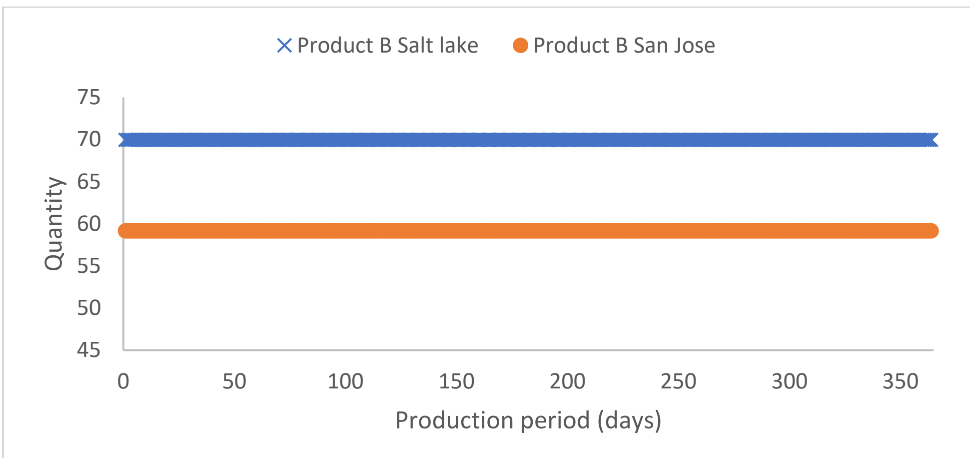

Figure 3.16: Daily shipping quantity of Product B from warehouse to stores

3.5.2 Two-factory, one-warehouse, and two-store setting. The daily planning model is tested on Networks 1 and 2, each comprised of two factories, one warehouse, and two stores as shown in Figure 3.2 and Figure 3.3. The model has 4,368 variables and 5,830 constraints.

3.5.3 Analysis of Network 1. The results of the production planning model are still in weekly basis, but the energy scheduling is carried out in daily basis. The WT, PV, and

BSS capacity along with the levelized cost of energy and total cost of 12 cases are summarized in Tables 3.42 to 3.53.

Table 3.42: Results of Case 1 for Network 1 in daily planning

City	**WT (MW)**	**PV (MW)**	**BS (MWh)**	**LCOE ($/MWh)**	**Energy Cost ($/MWh)**	**Energy use (MWh)**
Phoenix	0.0	77.1	248.5	208.10	11,949,825.02	57422
Reno	1.7	48.0	423.5	144.53	8,314,743.47	57528
Las Vegas	0.9	47.9	48.4	114.46	7,026,416.09	61390
Salt Lake	0.0	44.3	38.0	387.56	6,771,403.18	17472
San Jose	1.8	17.5	76.9	171.56	3,001,994.00	17498
Total Cost		$110,957,895				

Table 3.43: Results of Case 2 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	208.10	11,949,825.02	57422
Reno	1.7	48.0	423.5	144.53	8,314,743.47	57528
LV	0.9	47.9	48.4	114.46	7,026,416.09	61390
SL	0.0	44.3	38.0	387.56	6,771,403.18	17472
SJ	1.8	17.5	76.9	171.56	3,001,994.00	17498
Total Cost		$111,105,540				

Table 3.44: Results of Case 3 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	208.10	11,949,825.02	57422
Reno	1.7	48.0	423.5	144.53	8,314,743.47	57528
LV	0.9	47.9	48.4	114.46	7,026,416.09	61390
SL	0.0	44.3	38.0	387.56	6,771,403.18	17472
SJ	1.8	17.5	76.9	171.56	3,001,994.00	17498
Total Cost		$100,465,914				

Table 3.45: Results of Case 4 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	208.10	11,949,825.02	57422
Reno	1.7	48.0	423.5	144.53	8,314,743.47	57528
LV	0.9	47.9	48.4	114.46	7,026,416.09	61390
SL	0.0	44.3	38.0	387.56	6,771,403.18	17472
SJ	1.8	17.5	76.9	171.56	3,001,994.00	17498
Total Cost		$111,251,920				

Table 3.46: Results of Case 5 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	208.10	11,949,825.02	57422
Reno	1.7	48.0	423.5	144.53	8,314,743.47	57528
LV	0.9	47.9	48.4	114.46	7,026,416.09	61390
SL	0.0	44.3	38.0	387.56	6,771,403.18	17472
SJ	1.8	17.5	76.9	171.56	3,001,994.00	17498
Total Cost		$110,658,184				

Table 3.47: Results of Case 6 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	100.33	5,761,098.37	57428
Reno	0.0	50.2	394.9	74.68	4,296,018.11	57526
LV	0.0	49.4	13.4	49.96	3,067,015.42	61390
SL	0.0	44.3	38.0	184.33	3,220,630.72	17472
SJ	0.0	19.8	77.1	86.64	1,516,036.37	17498
Total Cost		$91,753,801				

Table 3.48: Results of Case 7 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	182.66	10,488,904.52	57428
Reno	0.0	50.2	394.9	126.78	7,293,543.41	57526
LV	0.0	49.4	13.4	93.82	5,759,608.55	61390
SL	0.0	44.3	38.0	354.12	6,187,113.48	17472
SJ	1.8	17.5	77.1	152.96	2,676,474.60	17498
Total Cost		$95,595,554				

Table 3.49: Results of Case 8 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	233.55	13,410,745.52	57428
Reno	1.7	48.0	423.5	161.71	9,302,737.78	57526
LV	1.9	46.1	87.5	133.95	8,223,379.89	61390
SL	0.0	44.3	38.0	421.00	7,355,692.88	17472
SJ	3.1	16.3	78.5	189.03	3,307,784.50	17498
Total Cost		$115,495,224				

Table 3.50: Results of Case 9 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)

Phoenix	0.0	77.1	248.5	246.65	14,163,408.96	57428
Reno	1.7	48.0	423.5	169.69	9,761,800.17	57526
LV	1.9	46.1	87.5	136.71	8,392,626.56	61390
SL	0.0	44.3	38.0	459.54	8,029,097.22	17472
SJ	3.1	16.3	78.5	202.30	3,539,851.09	17498
Total Cost		$117,780,931				

Table 3.51: Results of Case 10 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	77.1	248.5	202.50	11,627,968.31	57428
Reno	1.7	48.0	423.5	135.00	7,766,317.45	57526
LV	1.4	46.2	123.7	112.45	6,903,404.19	61390
SL	0.0	44.3	38.0	384.74	6,722,234.49	17472
SJ	3.1	16.3	78.5	165.85	2,902,095.09	17498
Total Cost		$109,815,879				

Table 3.52: Results of Case 11 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	73.0	138.2	195.74	11,239,697.67	57428
Reno	0.0	53.1	360.4	158.65	9,127,122.03	57526
LV	0.0	49.4	13.4	114.85	7,050,771.41	61390
SL	0.0	44.3	38.0	390.37	6,820,571.87	17472
SJ	1.8	17.5	76.9	177.25	3,101,606.95	17498
Total Cost		$111,232,781				

Table 3.53: Results of Case 12 for Network 1 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	73.0	138.2	195.74	11,239,697.67	57428
Reno	0.0	53.1	360.4	158.65	9,127,122.03	57526
LV	0.0	49.4	13.4	114.85	7,050,771.41	61390
SL	0.0	44.3	38.0	390.37	6,820,571.87	17472
SJ	1.8	17.5	76.9	177.25	3,101,606.95	17498
Total Cost		$111,653,358				

The expected total system cost of the daily planning increases compared with the weekly planning. The behavior of the model to changes in key parameters remains the same. LCOE is high compared to the networks in the weekly planning. The second stage decision on WT and PV are dependent on the climate profile of the location. If a location has a high PV capacity factor the model chooses to install more PV at that location, for example Phoenix, Reno. If the WT capacity factor is higher the model chooses to install more WT at the location, such as San Francisco.

3.5.4 Analysis of Network 2. Network 2 is also solved in a similar way as network 1in the AMPL computational environment, and the results are documented in Tables 3.54 to 3.65.

Table 3.54: Results of Case 1 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	11.0	36.1	590.1	143.7	8,250,228.44	57411
Tucson	0.0	42.6	287.4	117.0	6,731,768.04	57530
Los Angeles	2.6	105.1	12.4	259.8	15,942,253.12	1384
Sacramento	1.5	14.0	55.2	133.7	2,335,564.83	336
San Francisco	14.1	0.0	134.0	149.5	2,615,503.82	355
Total Cost		$108,756,251				

Table 3.55: Results of Case 2 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	11.0	36.1	590.1	143.7	8,250,228.44	57411
Tucson	0.0	42.6	287.4	117.0	6,731,768.04	57530
Los Angeles	2.6	105.1	12.4	259.8	15,942,253.12	1384
Sacramento	1.5	14.0	55.2	133.7	2,335,564.83	336
San Francisco	14.1	0.0	134.0	149.5	2,615,503.82	355
Total Cost		$108,903,908				

Table 3.56: Results of Case 3 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	11.0	36.1	590.1	143.7	8,250,228.44	57411
Tucson	0.0	42.6	287.4	117.0	6,731,768.04	57530
Los Angeles	2.6	105.1	12.4	259.8	15,942,253.12	1384
Sacramento	1.5	14.0	55.2	133.7	2,335,564.83	336
San Francisco	14.1	0.0	134.0	149.5	2,615,503.82	355
Total Cost		$108,602,701				

Table 3.57: Results of Case 4 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	11.0	36.1	590.1	143.7	8,250,228.44	57411
Tucson	0.0	42.6	287.4	117.0	6,731,768.04	57530
Los Angeles	2.6	105.1	12.4	259.8	15,942,253.12	1384
Sacramento	1.5	14.0	55.2	133.7	2,335,564.83	336
San Francisco	14.1	0.0	134.0	149.5	2,615,503.82	355
Total Cost		$109,050,277				

Table 3.58: Results of Case 5 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	11.0	36.1	590.1	143.7	8,250,228.44	57411
Tucson	0.0	42.6	287.4	117.0	6,731,768.04	57530
Los Angeles	2.6	105.1	12.4	259.8	15,942,253.12	1384
Sacramento	1.5	14.0	55.2	133.7	2,335,564.83	336
San Francisco	14.1	0.0	134.0	149.5	2,615,503.82	355
Total Cost		$109,050,277				

Table 3.59: Results of Case 6 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	0.0	58.1	213.8	73.9	4,242,169.75	57411
Tucson	0.0	53.1	37.6	57.3	3,295,335.86	57530
Los Angeles	0.8	107.4	13.4	121.0	7,424,846.06	1384
Sacramento	0.5	15.1	62.9	67.2	1,174,394.16	336
San Francisco	6.9	12.3	113.5	129.9	2,271,426.15	355
Total Cost		$91,288,870				

Table 3.60: Results of Case 7 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	11.0	36.1	590.1	129.4	7,425,503.87	57411
Tucson	0.0	42.6	287.4	96.8	5,567,018.47	57530
Los Angeles	2.6	105.1	12.4	230.8	14,159,193.11	1384
Sacramento	1.5	14.0	55.2	113.8	1,988,370.91	336
San Francisco	14.1	0.0	134.0	149.5	2,615,503.82	355
Total Cost		$104,635,738				

Table 3.61: Results of Case 8 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	12.3	33.9	652.8	157.8	9,061,445.76	57411
Tucson	0.0	42.6	287.4	137.3	7,896,517.61	57530
Los Angeles	56.4	56.4	62.0	278.0	17,059,197.57	1384
Sacramento	1.5	13.7	56.6	151.5	2,647,759.57	336

San Francisco	14.1	0.0	134.0	149.5	2,615,503.82	355
Total Cost	$112,196,994					

Table 3.62: Results of Case 9 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	12.3	33.9	590.1	164.0	9,413,899.57	57411
Tucson	0.0	42.6	287.4	138.6	7,973,026.44	57530
Los Angeles	42.7	68.8	22.2	307.2	18,850,299.72	1328
Sacramento	1.5	13.7	55.2	156.2	2,729,462.85	336
San Francisco	14.1	0.0	139.4	168.4	2,945,381.45	355
Total Cost	$114,977,854					

Table 3.63: Results of Case 10 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	12.3	33.9	652.8	129.6	7,440,236.92	57411
Tucson	0.0	42.6	287.4	110.5	6,359,632.95	57530
Los Angeles	2.6	105.1	12.4	259.6	15,926,251.19	1328
Sacramento	1.5	13.7	55.2	127.7	2,231,306.86	336
San Francisco	12.0	0.0	334.2	134.8	2,357,750.47	355
Total Cost	$107,228,866					

Table 3.64: Results of Case 11 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	11.0	36.1	590.1	157.0	9,014,396.29	57411
Tucson	0.0	42.6	287.4	123.5	7,103,903.12	57530
Los Angeles	2.6	105.1	12.4	260.1	15,958,255.05	1328
Sacramento	1.5	14.0	55.2	137.8	2,407,062.17	336
San Francisco	14.1	0.0	20.8	134.3	2,349,401.65	355
Total Cost	$110,032,818					

Table 3.65: Results of Case 12 for Network 2 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Yuma	0.0	73.1	0.0	183.1	10,508,221.58	57411
Tucson	0.0	57.0	0.0	139.2	8,008,624.60	57530
Los Angeles	2.6	105.1	12.4	272.3	16,710,345.59	1328
Sacramento	0.0	20.5	55.2	371.4	6,488,571.72	336
San Francisco	19.3	0.0	20.8	254.2	4,446,801.68	355
Total Cost	$114,365,598					

3.5.5 Four-factory, two-warehouse and four-store setting. For this setting, the model has 14,560 variables and 13,332 constraints. The model is coded in AMPL and CPLEX solver is used as the serach. The results are given in Tables 3.66 to 3.77.

Table 3.66: Results of case 1 for Network 3 in daily planning

City	**WT (MW)**	**PV (MW)**	**BS (MWh)**	**LCOE ($/MWh)**	**Energy Cost ($/MWh)**	**Energy use (MWh)**
Phoenix	0.0	53.5	150.0	224.9	6,392,538	28426
Reno	0.1	47.7	205.5	161.1	5,450,934	33836
Yuma	5.2	24.3	320.6	150.3	3,895,376	25913
Tucson	0.0	35.0	265.1	120.5	4,055,913	33669
Las Vegas	1.5	77.0	82.8	122.8	7,602,621	61895
Los Angeles	63.5	127.0	30.5	206.0	12,758,496	61934
Salt Lake	0.0	61.1	58.6	259.2	4,556,882	17582
San Jose	4.1	22.4	105.8	173.9	3,053,077	17558
Sacramento	2.0	18.8	75.1	138.2	2,426,895	17566
San Francisco	21.5	0.0	72.4	155.8	2,737,086	17567
Total Cost		$153,685,679				

Table 3.67: Results of case 2 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	224.9	6,392,538	28426
Reno	0.1	47.7	205.5	161.1	5,450,935	33836
Yuma	5.2	24.3	320.6	150.3	3,895,376	25913
Tucson	0.0	35.0	265.1	120.5	4,055,913	33669
Las Vegas	1.5	77.0	82.8	122.8	7,602,622	61895
Los Angeles	63.5	127.0	30.5	206.0	12,758,497	61934
Salt Lake	0.0	61.1	58.6	259.2	4,556,883	17582
San Jose	4.1	22.4	105.8	173.9	3,053,077	17558
Sacramento	2.0	18.8	75.1	138.2	2,426,896	17566
San Francisco	21.5	0.0	72.4	155.8	2,737,087	17567
Total Cost		$153,755,548				

Table 3.68: Results of case 3 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	224.9	6,392,538	28426
Reno	0.1	47.7	205.5	161.1	5,450,935	33836
Yuma	5.2	24.3	320.6	150.3	3,895,376	25913
Tucson	0.0	35.0	265.1	120.5	4,055,913	33669
Las Vegas	1.5	77.0	82.8	122.8	7,602,622	61895
Los Angeles	63.5	127.0	30.5	206.0	12,758,497	61934
Salt Lake	0.0	61.1	58.6	259.2	4,556,883	17582
San Jose	4.1	22.4	105.8	173.9	3,053,077	17558

Sacramento	2.0	18.8	75.1	138.2	2,426,896	17566
San Francisco	21.5	0.0	72.4	155.8	2,737,087	17567
Total Cost		$153,612,769				

Table 3.69: Results of case 4 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	224.9	6,392,538	28426
Reno	0.1	47.7	205.5	161.1	5,450,935	33836
Yuma	5.2	24.3	320.6	150.3	3,895,376	25913
Tucson	0.0	35.0	265.1	120.5	4,055,913	33669
Las Vegas	1.5	77.0	82.8	122.8	7,602,622	61895
Los Angeles	63.5	127.0	30.5	206.0	12,758,497	61934
Salt Lake	0.0	61.1	58.6	259.2	4,556,883	17582
San Jose	4.1	22.4	105.8	173.9	3,053,077	17558
Sacramento	2.0	18.8	75.1	138.2	2,426,896	17566
San Francisco	21.5	0.0	72.4	155.8	2,737,087	17567
Total Cost		$153,827,287				

Table 3.70: Results of case 5 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	224.9	6,392,538	28426
Reno	0.1	47.7	205.5	161.1	5,450,935	33836
Yuma	5.2	24.3	320.6	150.3	3,895,376	25913
Tucson	0.0	35.0	265.1	120.5	4,055,913	33669
Las Vegas	1.5	77.0	82.8	122.8	7,602,622	61895
Los Angeles	63.5	127.0	30.5	206.0	12,758,497	61934
Salt Lake	0.0	61.1	58.6	259.2	4,556,883	17582
San Jose	4.1	22.4	105.8	173.9	3,053,077	17558
Sacramento	2.0	18.8	75.1	138.2	2,426,896	17566
San Francisco	21.5	0.0	72.4	155.8	2,737,087	17567
Total Cost		$153,540,711				

Table 3.71: Results of case 6 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	110.5	3,141,438	28426
Reno	0.0	47.7	206.6	79.3	2,683,866	33836
Yuma	0.0	34.8	140.4	78.0	2,020,954	25913
Tucson	0.0	45.1	27.0	61.4	2,066,523	33669
Las Vegas	0.0	79.7	21.5	53.8	3,332,923	61895
Los Angeles	1.6	184.1	22.5	117.2	7,260,412	61934
Salt Lake	0.0	61.1	58.6	183.3	3,223,200	17582

San Jose	0.0	26.8	109.2	89.4	1,569,542	17558
Sacramento	0.8	20.3	85.6	70.0	1,229,022	17566
San Francisco	9.9	16.7	158.5	135.1	2,372,714	17567
Total Cost		$110,238,876				

Table 3.72: Results of case 7 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	197.9	5,625,090	28426
Reno	0.1	47.7	205.5	140.1	4,739,703	33836
Yuma	5.2	24.3	320.6	134.5	3,485,642	25913
Tucson	0.0	35.0	265.1	101.0	3,399,086	33669
Las Vegas	0.1	79.7	25.0	100.7	6,230,482	61895
Los Angeles	1.6	184.1	22.5	190.1	11,772,712	61934
Salt Lake	0.0	61.1	58.6	258.6	4,546,113	17582
San Jose	2.2	24.1	104.0	156.8	2,752,834	17558
Sacramento	2.0	18.8	75.1	117.3	2,060,418	17566
San Francisco	21.5	0.0	72.4	155.8	2,737,087	17567
Total Cost		$143,407,767				

Table 3.73: Results of case 8 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	251.8	7,156,238	28426
Reno	0.1	47.7	205.5	182.1	6,162,166	33836
Yuma	5.2	23.6	342.5	166.1	4,305,110	25913
Tucson	0.8	34.0	282.4	140.1	4,712,740	33669
Las Vegas	3.0	74.5	138.1	143.5	8,884,192	61895
Los Angeles	107.7	86.2	206.8	221.9	13,744,281	61934
Salt Lake	0.0	61.1	58.6	254.2	4,469,788	17582
San Jose	4.1	22.4	105.8	191.0	3,353,320	17558
Sacramento	2.3	18.5	76.7	158.1	2,777,425	17566
San Francisco	21.5	0.0	72.4	155.8	2,737,087	17567
Total Cost		$162,624,340				

Table 3.74: Results of case 9 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	266.0	7,560,630	28426
Reno	0.1	47.7	205.5	190.6	6,447,519	33836
Yuma	5.2	24.3	320.6	174.7	4,527,142	25913
Tucson	0.0	35.0	265.1	141.8	4,771,585	33669
Las Vegas	3.0	74.5	138.1	146.5	9,069,637	61895
Los Angeles	79.9	111.9	55.6	241.1	14,930,173	61934

Salt Lake	0.0	61.1	58.6	280.2	4,926,446	17582
San Jose	4.1	22.4	105.8	205.2	3,602,538	17558
Sacramento	2.0	18.5	75.1	163.9	2,879,127	17566
San Francisco	19.8	0.0	183.4	174.9	3,072,357	17567
Total Cost	$162,657,543					

Table 3.75: Results of case 10 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	216.9	6,086,486	28426
Reno	0.1	47.7	205.5	154.6	5,231,751	33836
Yuma	5.2	23.6	342.5	136.6	3,539,936	25913
Tucson	0.8	34.0	282.4	111.0	3,735,192	33669
Las Vegas	1.8	74.5	227.6	120.8	7,567,892	61895
Los Angeles	79.9	111.9	55.6	194.2	12,731,278	61934
Salt Lake	0.0	61.1	58.6	202.0	4,272,292	17582
San Jose	4.1	22.4	105.8	169.7	2,979,878	17558
Sacramento	2.0	18.5	75.1	133.2	2,362,932	17566
San Francisco	16.7	0.0	466.3	141.2	2,687,169	17567
Total Cost		$151,528,272				

Table 3.76: Results of case 11 for Network 3 in daily planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	53.5	150.0	208.2	5,918,758	28426
Reno	0.1	47.7	205.5	167.6	5,670,119	33836
Yuma	5.2	23.6	320.6	164.0	4,250,816	25913
Tucson	0.0	35.0	265.1	130.1	4,376,634	33669
Las Vegas	0.1	79.5	25.0	123.4	7,637,352	61895
Los Angeles	63.5	127.0	30.5	214.7	13,297,017	61934
Salt Lake	0.0	61.1	58.6	297.7	5,233,737	17582
San Jose	2.2	24.1	104.0	178.0	3,126,276	17558
Sacramento	2.0	18.5	75.1	141.8	2,490,859	17566
San Francisco	22.4	0.0	32.2	158.7	2,787,005	17567
Total Cost		$155,373,085				

Table 3.77: Results of case 12 for Network 3 in daily planning

City	**WT (MW)**	**PV (MW)**	**BS (MWh)**	**LCOE ($/MWh)**	**Energy Cost ($/MWh)**	**Energy use (MWh)**
Phoenix	0.0	65.2	7.8	259.3	7,370,286	28426
Reno	0.0	65.4	0.0	188.8	6,387,600	33836
Yuma	0.0	44.4	0.0	186.1	4,823,409	25913
Tucson	0.0	48.4	0.0	143.4	4,824,556	33669
Las Vegas	0.0	83.4	0.0	124.3	7,694,580	61895

Los Angeles	1.6	184.1	22.5	231.5	14,339,875	61934
Salt Lake	0.0	68.7	8.2	440.7	7,748,940	17582
San Jose	0.0	36.5	0.0	194.3	3,411,606	17558
Sacramento	0.0	27.8	5.0	151.3	2,658,011	17566
San Francisco	23.7	0.0	10.2	164.1	2,883,097	17567
Total Cost		$166,798,130				

3.6 Hourly Planning

3.6.1 Two-factory, one-warehouse and two-store setting. The model is further reduced to hourly planning for 8736 hours a year. This hourly planning model is solved only for the benchmark case for all the three networks. The main changes in the experimental data is that the holding cost is on hourly basis for both the products and the operational time for the DER units is one hour per period. The other parameters remain the same. Like the daily planning the production quantity is converted from weekly to hourly by dividing it by 168 hours in a week. The conversion quantity is given in Figures 3.17 and 3.18. The energy scheduling is carried out per hour.

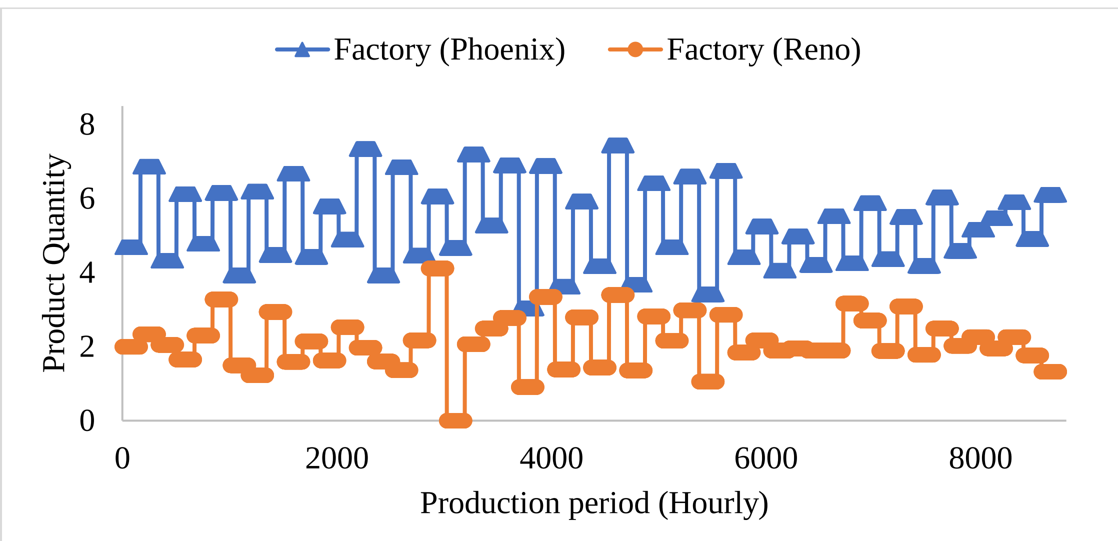

Figure 3.17: Conversion of weekly Production to hourly Production of Product A

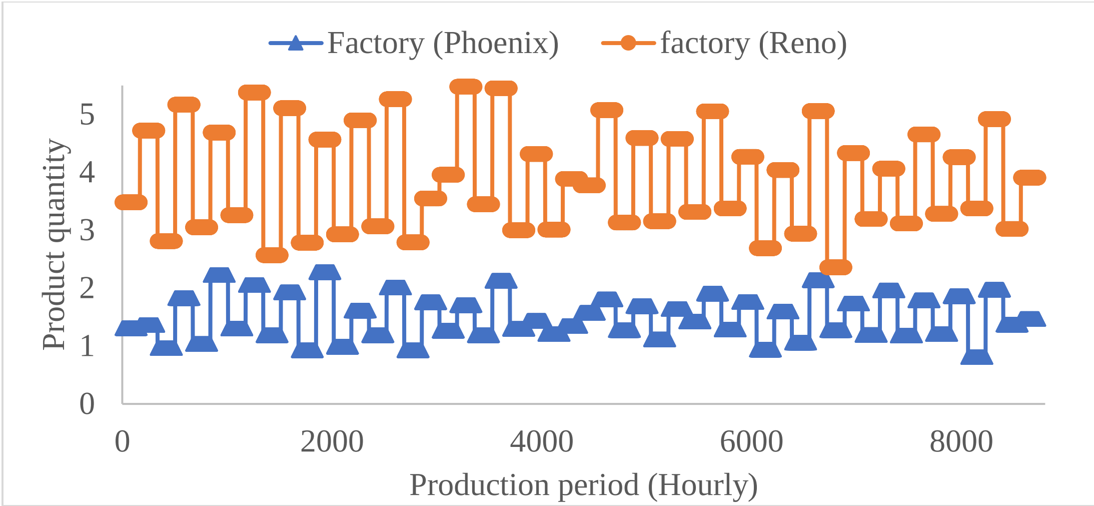

Figure 3.18: Conversion of weekly Production to hourly Production of Product B

3.6.2 Network 1

Table 3.78: Results of Case 1 for Network 1 in hourly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	79.5	214.7	212.8	12,215,974	57399
Reno	1.9	47.8	430.2	144.7	8,326,584	57524
Las Vegas	1.0	47.6	61.5	115.0	7,030,396	61152
Salt Lake	0.0	44.1	40.6	386.9	6,760,650	17472
San Jose	2.0	17.3	76.1	171.2	2,996,221	17498
Total Cost		$110,770,701				

Table 3.78 shows the results of the hourly planning model for Network 1. The total system cost is $110,770,701 and the decision on the DER units depends on the location. The model chooses to install 79.5 MW PV in Phoenix due to large sunny day percentage over the year. Since Reno has a mixed climate profile but mostly sunny, the model chooses to install 1.9 MW WT and 47.8 MW PV there. Similar trend can be seen at the store in San Jose and the warehouse in Las Vegas.

3.6.3 Network 2

Table 3.79: Results of Case 1 for Network 2 in hourly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy Use (MWh)
Yuma	11.0	36.0	592.2	143.8	8,257,375.87	57405
Tucson	0.0	43.0	280.4	117.7	6,770,185.99	57532
Los Angeles	5.5	100.3	14.6	254.8	15,622,928.76	61304
Sacramento	1.5	14.0	54.8	141.5	2,472,258.84	17472
San Francisco	14.5	0.0	107.2	149.4	2,613,953.20	17491
Total Cost		$107,990,355				

3.6.4 Four-factory, two-warehouse and four-store setting

Table 3.80: Results of Case 1 for Network 3 in hourly planning

City	WT (MW)	PV (MW)	BS (MWh)	LCOE ($/MWh)	Energy Cost ($/MWh)	Energy use (MWh)
Phoenix	0.0	40.5	175.0	224.9	6,392,538	28426
Reno	0.0	34.5	169.3	161.1	5,450,934	33836
Yuma	4.4	17.9	274.5	150.3	3,895,376	25913
Tucson	0.4	23.9	247.7	120.5	4,055,913.21	33669
Las Vegas	0.0	53.2	26.8	122.8	7,602,621	61895
Los Angeles	22.1	58.2	449.2	206.0	12,758,496	61934
Salt Lake	17.2	0.8	754.0	259.2	4,556,882.	17582
San Jose	4.1	16.1	56.5	173.9	3,053,077	17558
Sacramento	1.4	14.8	49.4	138.2	2,426,895	17566
San Francisco	16.4	0.0	38.5	155.8	2,737,086	17567
Total Cost		$120,100,154				

The hourly planning is more cost-consuming than the weekly or the daily planning. While, if incentives like time of use (TOU), feed in tariff or the model is able to sell energy to the grid hourly granularity can be utilized to reduce the cost.

4. MODELING OF MULTI-TIER SUPPLY CHAIN AS ENERGY PROSUMERS

4.1 Problem Description

In this chapter, we model a three-tier manufacturing supply chain with energy prosumer participation. An energy prosumer is an entity which both consumes and produces energy. The surplus energy can be traded in the day-ahead transactive market. Hence the concept of prosumer involves both generation and consumption rather than focusing on one or the other. The configuration of the supply chain networks is similar to those in Chapters 3 with the only difference is that all facilities are connected to the same main grid. The goal of this model is to minimize the cost of production, inventory, transportation, and installation of microgrid in the facilities during a year.

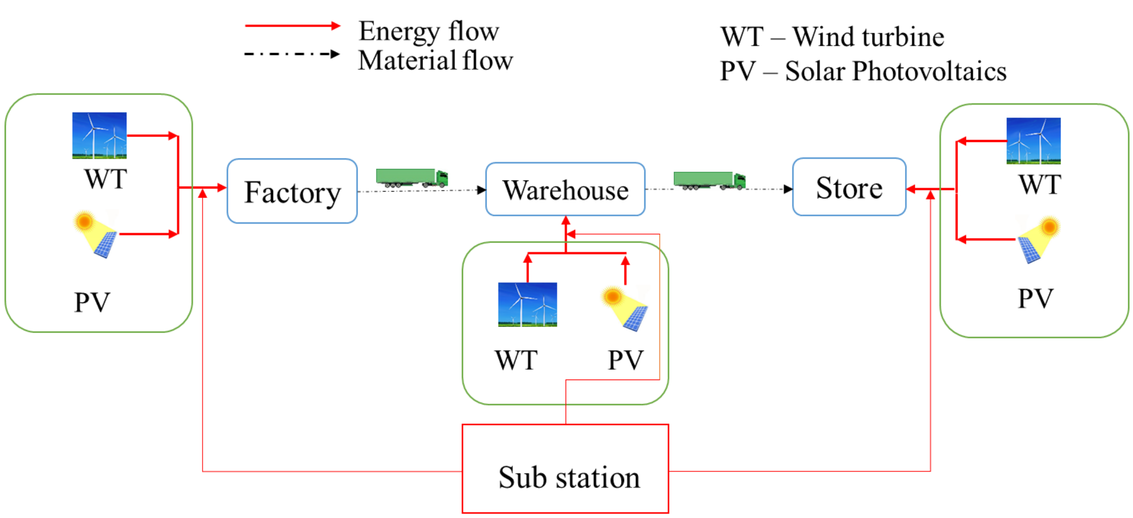

Figure 4.1: Multi-tier supply chain layout with grid connected microgrid

4.2 Two-Stage Production and Microgrid Planning Model

The energy prosumer model is solved as a two -stage optimization model. The first stage in the production planning and the second stage is to determine the portfolio and capacity of the microgrid. The difference between this model and the one in the Chapter 3 is that Model 3.1 is solved as an island microgrid whereas Model 4.1 is solved as grid tied microgrid. The microgrid can actively participate in demand response program such as time of use (TOU), level of use (LOU) and critical peak pricing (CPP) contracts. The first stage comes from Model 3.2.1 in Section 3.3 of Chapter 3. The second stage is given as Model 4.1. The notation of this model is presented in Table 4.1, and the decision variables are listed in Table 4.2.

Table 4.1: Notation for Model 4.1 Parameters

Notation	Comments
G	number of renewable sources, for g=1, 2, .., G
q_v	electric vehicle energy intensity rate (MWh/kg/km)
w_v	vehicle self-weight (kg)
d_{kn}	distance between Factory k and Warehouse n (km)
$\tilde{d}_{ns}$	distance between Warehouse n and Store s (km)
m_i	unit weight of Product type i (kg/item)
D_{ijs}	random demand for Product i in period j from Store s
n_{ks}	number of yearly trips between Factory k and Warehouse n
$\tilde{n}_{ns}$	number of yearly trips between Warehouse n and Store s
t_w	operating hours of Warehouse (hours)
$\tilde{t}_s$	operating hours of Store (hours)
t_{gk}	number of generation hours of renewables g per period in Factory k
t_{gn}	number of generation hours of renewables g per period in Warehouse n
t_{gs}	number of generation hours of renewables g per period in Store s
a_g	capacity cost for renewable generator g ($/MW)
a_b	capacity cost for battery storage system ($/MWh)
b_g	operation and maintenance cost for renewable generator g ($/MWh)
c_g	carbon credits for renewable generator g ($/MWh)
e_{ik}	energy consumed for producing one unit of Product i in Factory k (MWh/item)
L_n	electricity demand or load in Warehouse n (MW)

$\tilde{L}_s$	electricity demand or load in Store *s* (MW)
ϕ_g	capital recovery factor of renewable generator *g*
ϕ_b	capital recovery factor of battery storage system
d_b	Capacity cost of battery storage system ($/MWh)

Table 4.2: Decision Variables for Model 4.1

Decision Variables	**Comments**
$P^c{}_{gk}$	power capacity of generator *g* in Factory *k* (unit: MW)
$P^c{}_{gn}$	power capacity of generator *g* in Warehouse *n* (unit: MW)
$P^c{}_{gs}$	power capacity of generator *g* in Store *s* (unit: MW)
$B^c{}_{gk}$	battery capacity in Factory *k* (unit: MWh)
$B^c{}_{gn}$	battery capacity in Warehouse *n* (unit: MWh)
$B^c{}_{gs}$	battery capacity in Store *s* (unit: MWh)
$E^u{}_{kt}$	Energy imported from the main grid at time *t* in factory *k* (Unit:MWh)
$E^v{}_{kt}$	Energy exported to the main grid at time *t* in factory *k* (Unit:MWh)
$E^u{}_{nt}$	Energy imported from the main grid at time *t* in warehouse (Unit:MWh)
$E^v{}_{nt}$	Energy exported to the main grid at time *t* in warehouse (Unit:MWh)
$E^u{}_{st}$	Energy imported from the main grid at time *t* in store *s* (Unit:MWh)
$E^v{}_{st}$	Energy exported to the main grid at time *t* in store *s* (Unit:MWh)

Model 4.1 Microgrid Sizing on prosumer energy transactions

Minimize

$$
\begin{aligned}
& f_2(\mathbf{P}^c,\mathbf{B}^c,\mathbf{E}^u,\mathbf{E}^v) = \\
& \sum_{g=1}^{G}\sum_{k=1}^{K}\phi_g a_g P_{gk}^c + \sum_{t=1}^{T}\sum_{g=1}^{G}\sum_{k=1}^{K}\tau_{gk}(b_g - c_g)\lambda_{tgk}P_{gk}^c + \varphi_B d_B \sum_{k=1}^{K} B_k^c + \sum_{k=1}^{K}\sum_{t=1}^{T}(\rho_{kt}^u E_{kt}^u - \rho_{kt}^v E_{kt}^v) \\
& + \sum_{g=1}^{G}\sum_{n=1}^{N}\phi_g a_g P_{gn}^c + \sum_{t=1}^{T}\sum_{g=1}^{G}\sum_{n=1}^{N}\tau_{gn}(b_g - c_g)\lambda_{tgn}P_{gn}^c + \varphi_B d_B \sum_{n=1}^{N} B_n^c + \sum_{n=1}^{N}\sum_{t=1}^{T}(\rho_{nt}^u E_{nt}^u - \rho_{nt}^v E_{nt}^v) \\
& + \sum_{g=1}^{G}\sum_{n=1}^{S}\phi_g a_g P_{gs}^c + \sum_{t=1}^{T}\sum_{g=1}^{G}\sum_{n=1}^{S}\tau_{gs}(b_g - c_g)\lambda_{tgs}P_{gs}^c + \varphi_B d_B \sum_{s=1}^{S} B_s^c + \sum_{n=1}^{N}\sum_{t=1}^{T}(\rho_{st}^u E_{st}^u - \rho_{st}^v E_{st}^v) \\
& \quad + f_1(\mathbf{x},\mathbf{y},\mathbf{z})
\end{aligned}
\tag{4.1}
$$

Subject to:

$$\sum_{i=1}^{I}\sum_{n=1}^{N}(e_{ik}+q_v d_{kn} m_i)x_{itkn}+\sum_{n=1}^{N}q_v n_{tkn} d_{kn} w_v + B_{kt} - B_{k,t-1} + (E_{kt}^{v} - E_{kt}^{u}) = \sum_{g=1}^{G}\tau_{gk}\lambda_{tgk}P_{gk}^{c};$$

for t=1, 2, ..., T, and for k=1, 2, …, K (4.2)

$$\tau_w L_n + \sum_{k=1}^{K} q_v n_{tkn} d_{kn} w_v + \sum_{i=1}^{I}\sum_{s=1}^{S} q_v \tilde{d}_{tns} m_i \tilde{x}_{itns} + \sum_{s=1}^{S} q_v \tilde{n}_{tns} \tilde{d}_{ns} w_v + B_{nt} - B_{n,t-1} + (E_{nt}^{v} - E_{nt}^{u}) = \sum_{g=1}^{G}\tau_{gn}\lambda_{tgn}P_{gn}^{c};$$

for t=1, 2, ..., T, and for n=1, 2, …, N (4.3)

$$\tilde{\tau}_s \tilde{L}_s + \sum_{n=1}^{N} q_v \tilde{n}_{tns} \tilde{d}_{ns} w_v + B_{st} - B_{s,t-1} + (E_{st}^{v} - E_{st}^{u}) = \sum_{g=1}^{G}\tau_{gs}\lambda_{tgs}P_{gs}^{c};$$

for t=1, 2, ..., T, for s=1, 2, …, S (4.4)

$P_{gk}^{c}, P_{gn}^{c}, P_{gs}^{c} \geq 0$ for all g, k, n and s (4.5)

$B_{k}^{c}, B_{n}^{c}, B_{s}^{c} \geq 0$ for all k, n and s (4.6)

$B_{kt}, B_{nt}, B_{st} \geq 0$ for all k, n, s and t (4.7)

$E_{kt}^{u}, E_{nt}^{u}, E_{st}^{u} \geq 0$ for all k, n, s and t (4.8)

$E_{kt}^{v}, E_{nt}^{v}, E_{st}^{v} \geq 0$ for all k, n, s and t (4.9)

$B_{k,0} = B_{k,t} = B_{k}^{c}$ for all k and $t = T$ (4.10)

$B_{n,0} = B_{n,t} = B_{n}^{c}$ for all n and $t = T$ (4.11)

$B_{s,0} = B_{s,t} = B_{s}^{c}$ for all s and $t = T$ (4.12)

$0 \leq B_{k,t} \leq B_{k}^{c}$ for all k and t (4.13)

$0 \leq B_{n,t} \leq B_{n}^{c}$ for all n and t (4.14)

$0 \leq B_{s,t} \leq B_{s}^{c}$ for all s and t (4.15)

The objective function (4.1) minimizes the cost of the microgrid system, including installation, operations and maintenance, the expense of purchasing grid energy, and the income of selling surplus electricity. Constraint (4.2) is the energy balance equation for the factory which indicates the amount of energy consumed must be offset by the amount of energy produced from microgrid. Constraint (4.3) and (4.4) define the same energy balance condition for the warehouses and the stores, respectively. Constraints (4.3) to (4.9) depict the non-negativity of the decision variables. Constraints (4.10) to (4.12) indicate that the battery in the initial and final period is full. Constraints (4.13) to (4.15) state that the stored energy at each period should not exceed the battery capacity limit.

In the next two sections, we will discuss the details about the network setting, data for testing the model, and the result analysis. The value of $f_1(\mathbf{x}, \mathbf{y}, \mathbf{z})$ comes from solving Model 3.2.1 on a weekly basis in Chapter 3.

4.3 Two-Factory, One-Warehouse, and Two-Store Network

The prosumer model is tested in a supply chain layout comprised of two factories located in Phoenix, and Reno, a single warehouse in Las Vegas, and two stores located in Salt Lake City and San Jose. Electric vehicles are used to transport goods between the facilities. A representation of the layout in given in Figure 3.2 in Section 3.4 of Chapter 3. As mentioned earlier, the stage one model is as same as Model 3.2.1 and the data used to solve this model is given in Table 3.4 in Section 3.4. It is noted that the production planning is carried out weekly over a year (i.e., 52 weeks). The microgrid sizing problem is tackled on an hourly basis where the energy scheduling is carried out hour by hour for t=1, 2, …, 8736. To do so, the weekly production quantity need to be converted to the hourly rate. x_{ijkn} and x_{ijns} is simply divided by 168 hours assuming the factories operate 7 days a week and 24 hours a day. The hourly production upon the conversion is presented in Figures 3.17 and 3.18, respectively in Section 3.6.1 of Chapter 3. The data to solve the stage two problem comes from Table 3.5 on Section 3.4. The only difference is that τ_g becomes 1 hour. Model 4.1 is tested in 8 cases by changing the key model parameters, including electricity selling price, buying price, battery cost, and PV cost. A summary of the cases in given in Table 4.3. Note that the benchmark cost of selling electricity to the grid is $50/MWh and the buying cost from the grid is $70/MWh.

Table 4.3: Case summary

Case No.	Explanation
1	Benchmark with battery cost $0.4 M/MWh
2	Selling price is $25/MWh
3	Buying price $150/MWh
4	TOU
5	Battery cost $0.05M/MWh
6	Battery cost $0.02M/MWh
7	Battery cost $0.01M/MWh
8	PV capacity cost $ 1 M/MWh and selling price $0/MWh

4.3.1 Results discussion and analysis

Case 1 (Benchmark)

Table 4.4: Results of Case 1 in Network 1

Type	**Factory**		**Warehouse**	**Store**	
	Phoenix	**Reno**	**Las Vegas**	**Salt Lake**	**San Jose**
WT (MW)	0	0	1.63	4.26	0
PV (MW)	0	0	8.76	0	0
BSS (MWh)	0	0	0	0	0

Case 1 is the benchmark study with the battery cost of $0.4M/MWh. The total cost of the supply chain system is $81,073,190. The model chooses to buy electricity from the grid for the factories in Phoenix and Reno as that is a cheaper option than installing WT, PV and BSS units. Figures 4.2 and 4.3 show the amount of hourly energy purchased from the grid during a year. The factories have a base load of 8 MW, respectively.

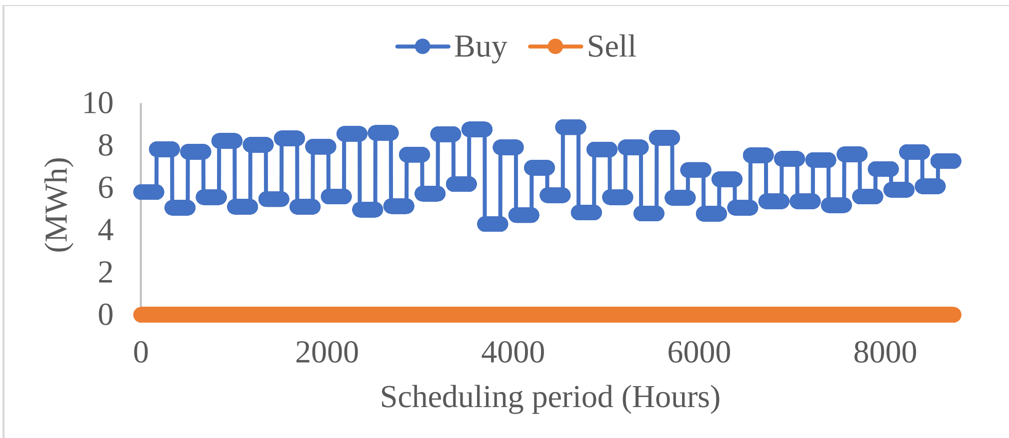

Figure 4.2: Energy purchased from the grid in Phoenix Factory

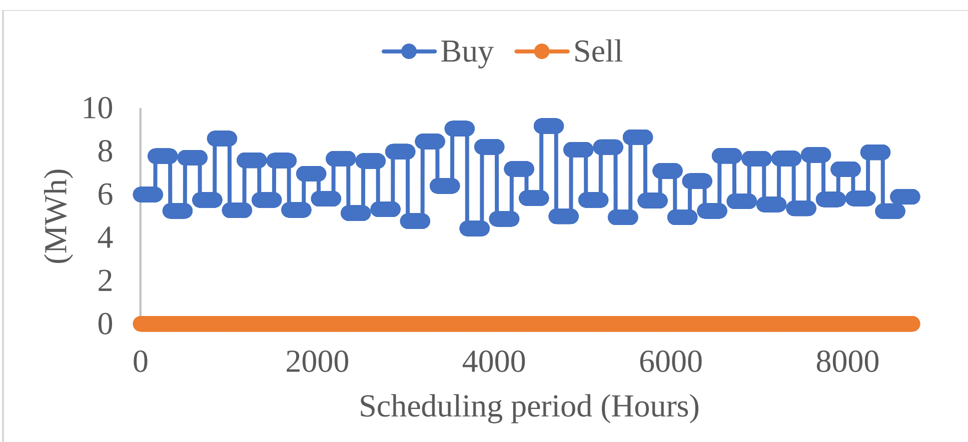

Figure 4.3: Energy purchased from the grid in Reno Factory

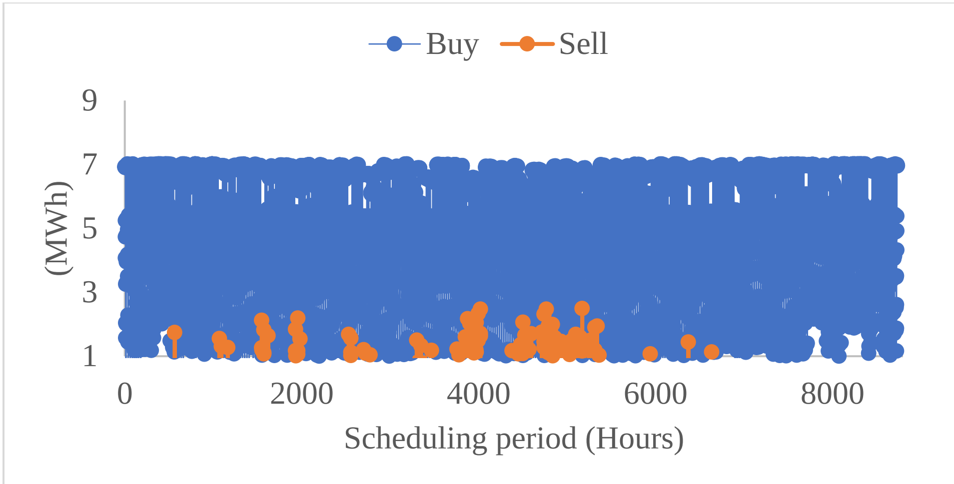

Figure 4.4: Energy purchased and sold in Las Vegas Warehouse

The warehouse in Las Vegas has a base load of 7 MW. The model chooses to install some WT and PV to meet the load. Figure 4.4 shows the amount of energy purchased from the grid and sold to the grid on an hourly basis. The model opts to install WT and PV so that it can generate revenue by selling electricity to the grid, indicating that the warehouse can behave as an energy prosumer.

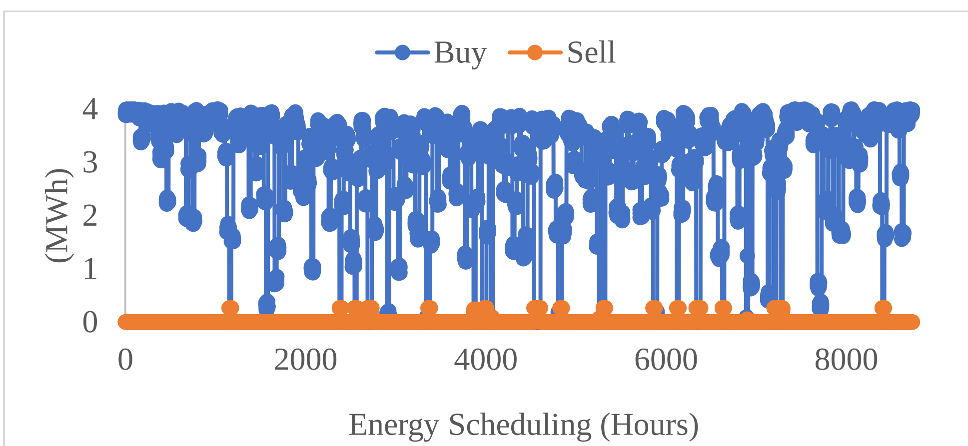

Figure 4.5: Energy purchased and sold in Salt Lake Store

Figure 4.5 shows the amount of energy purchased and sold in Salt Lake store. The store has a baseload of 4 MW. The model chooses to install WT as the location has a high wind capacity factor. The remaining electricity is purchased from the grid. Since WT is installed, during the days of higher power production the excess electricity is sold to the gird to generate income to the store.

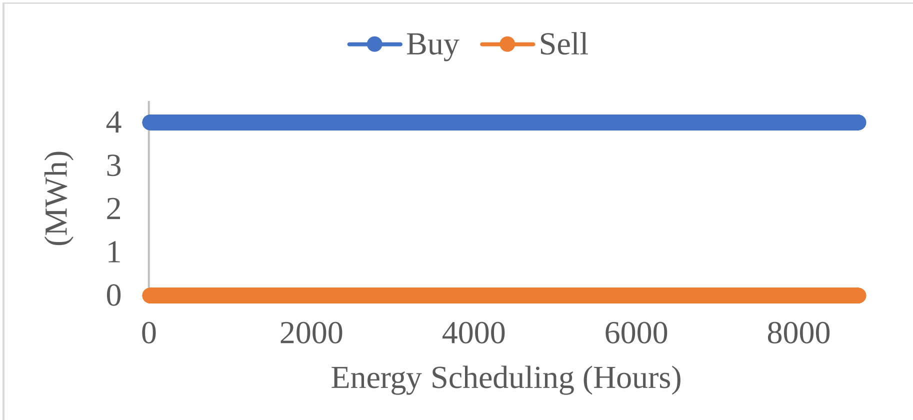

Figure 4.6: Energy purchased and sold in San Jose Store

Figure 4.6 shows the amount of energy purchased and sold in San Jose store. There is no installation of WT or PV systems, rather the model simply chooses to buy the required electricity from the main grid.

Case 2

Table 4.5: Results summary of Case 2 in Network 1

Type	Factory		Warehouse	Store	
	Phoenix	Reno	Las Vegas	Salt Lake	San Jose
WT (MW)	0	0	1.24	4	0
PV (MW)	0	0	8.11	0	0
BSS (MWh)	0	0	0	0	0

In Case 2, the model is tested by decreasing the selling price from $50/MWh to $25/MWh. Since the system is making less money from sales, the model chooses to install less microgrid capacity than Case 1. The cost is $81,076,385. As a result of making less revenue the total system cost is higher than that of Case 1. The amount of energy purchased from the grid by the factories in Phoenix and Reno remains the same as Case 1. The intermediate results for factories are shown in Figures 4.2 and 4.3.

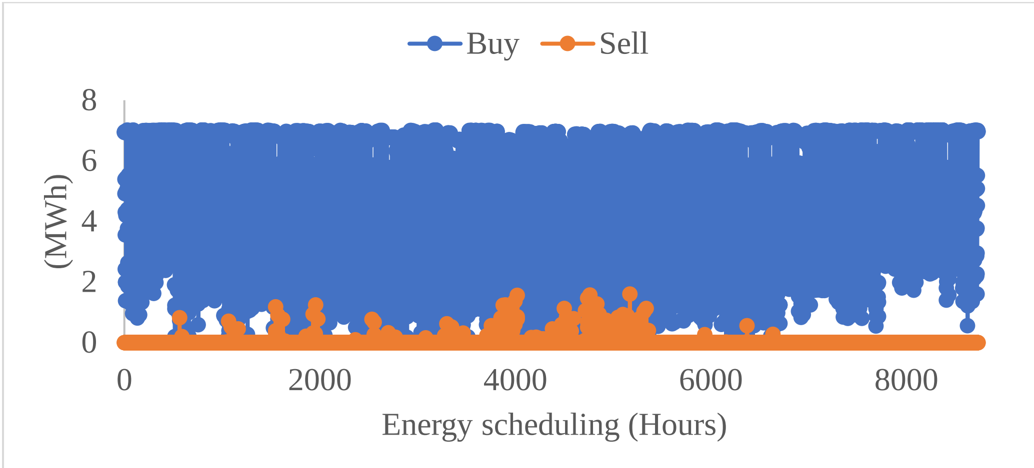

Figure 4.7: Energy purchased and sold for Case 2 in Las Vegas Warehouse

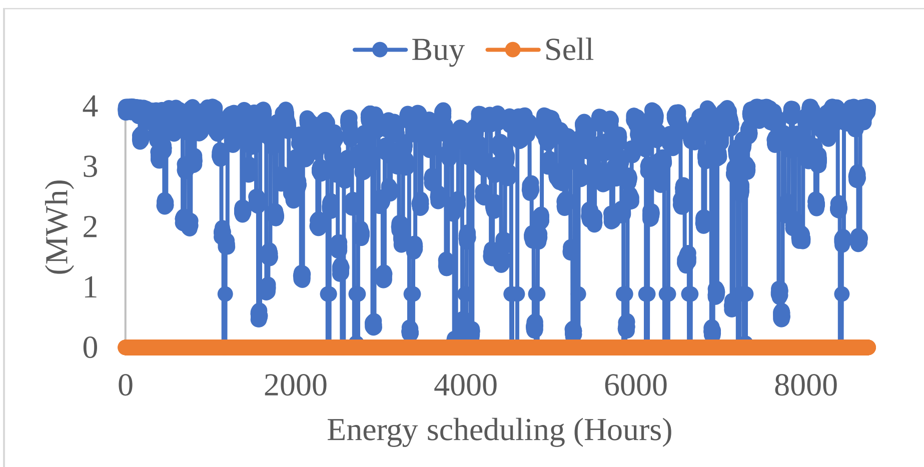

Figure 4.8: Energy purchased and sold for Case 3 in Salt Lake Store

Figures 4.7 and 4.8 show the amount of energy purchased by the warehouse in Las Vegas and the store in Salt Lake City, respectively. Similarly, the model opts to install less WT and PV in Las Vegas and Salt Lake facilities. There is no change in the amount of energy purchased in San Jose store as it remains the same shown in Figure 4.6.

Case 3

Table 4.6: Results summary of Case 3 in Network 1

Type	Factory		Warehouse	Store	
	Phoenix	**Reno**	**Las Vegas**	**Salt Lake**	**San Jose**
WT (MW)	0	11.12	19.19	24.72	7.36
PV (MW)	18	14.7	15.69	0	8.45
BSS (MWh)	0	0	0	0	0

In Case 3 we test the model by increasing the purchasing price from \$70/MWh to \$150/MWh. This is the price that makes all the facilities to install WT or PV systems on site. In fact, more WT and PV are installed in the facilities as it can help to power the facilities as well as sell the excess energy to the grid and make money. The total system cost is \$92,824,355. The amount of energy purchased and sold is given in Figures 4.9 to 4.13.

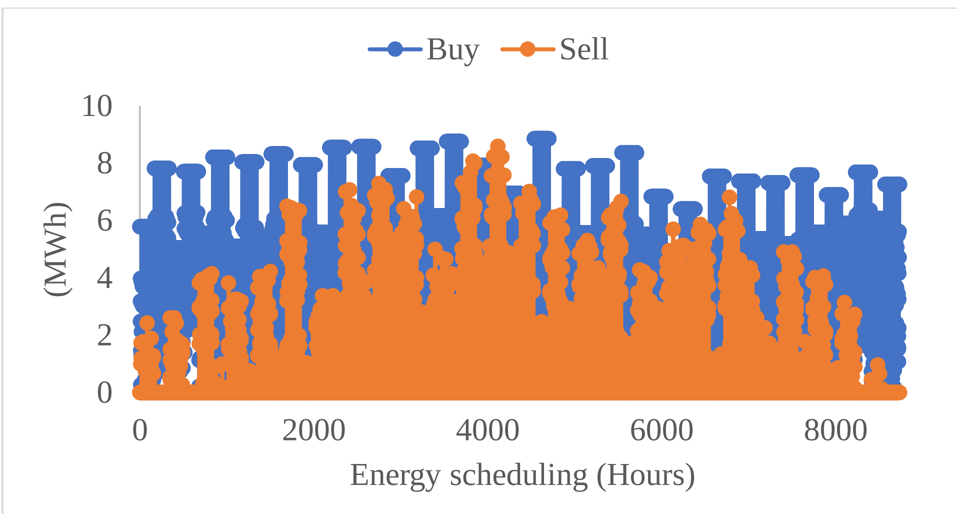

Figure 4.9: Energy purchased and sold for Case 3 in Phoenix Factory

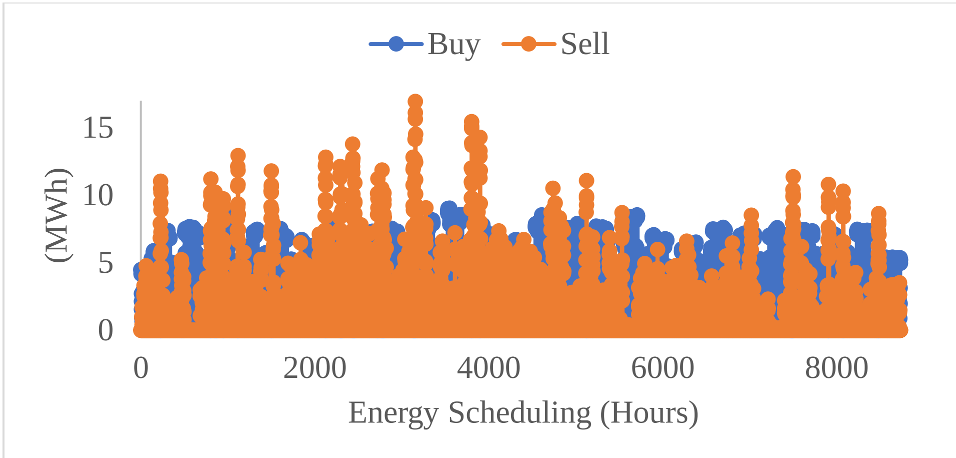

Figure 4.10: Energy purchased and sold for Case 3 in Reno Factory

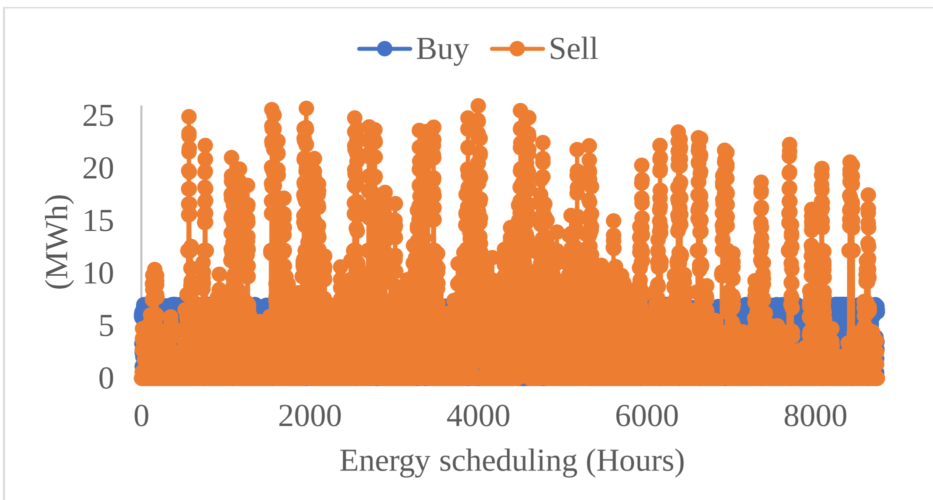

Figure 4.11: Energy purchased and sold for Case 3 in Las Vegas Warehouse

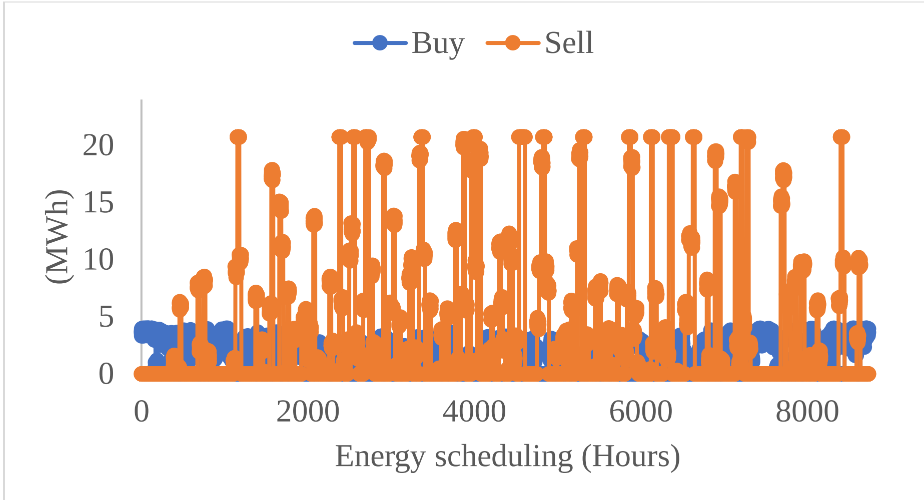

Figure 4.12: Energy purchased and sold for Case 3 in Salt Lake Store

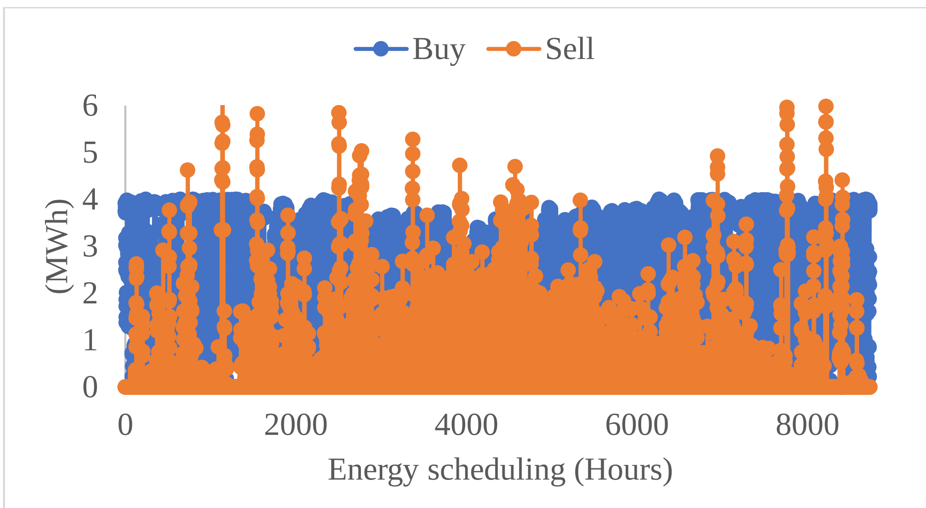

Figure 4.13: Energy purchased and sold for Case 3 in San Jose Store

Case 4

Table 4.7: Results summary of Case 4 in Network 1

Type	Factory		Warehouse	Store	
	Phoenix	**Reno**	**Las Vegas**	**Salt Lake**	**San Jose**
WT (MW)	0	0	7.02	0	13.07
PV (MW)	13.80	14.9	15.15	8.5	0
BSS (MWh)	0	0	0	0	0

In case 4, we implement TOU rate to test the model. In TOU the utility companies charge their customers based on the time of the day the energy is used. TOU is high during peak hours, and low in off-peak hours. The total system cost in this case is \$85,342,594. The model chooses to install WT and PV based on the climate profiles in each city. The hourly energy trading is given in Figures 4.14 to 4.18.

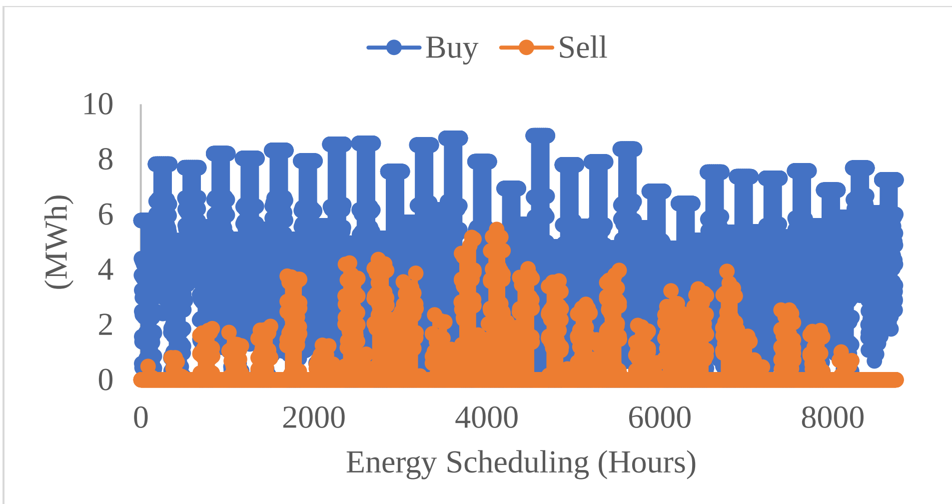

Figure 4.14: Energy purchased and sold for Case 4 in Phoenix Factory

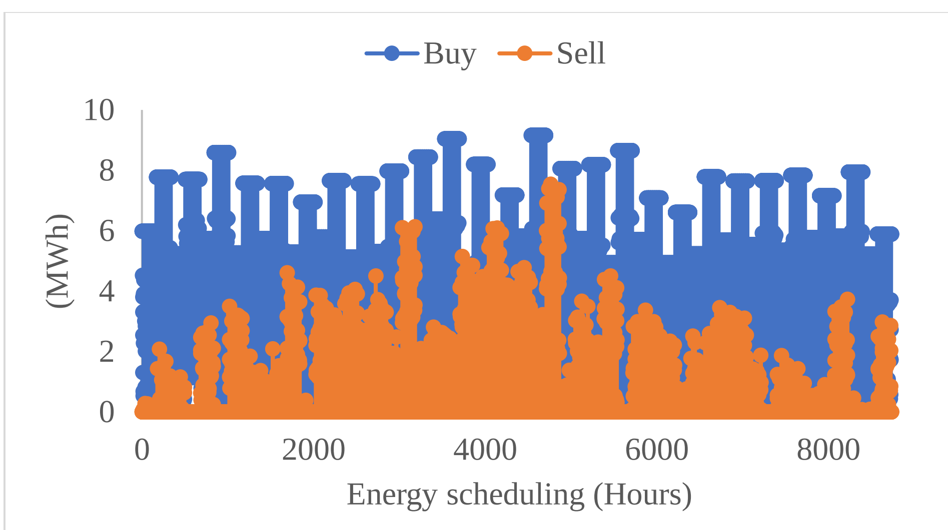

Figure 4.15: Energy purchased and sold for Case 4 in Reno Factory

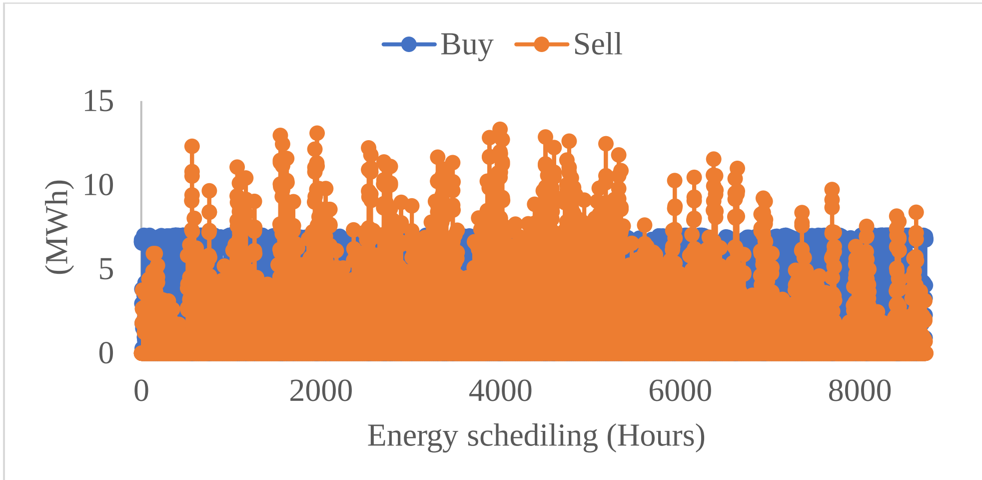

Figure 4.16: Energy purchased and sold for Case 4 in Las Vegas Warehouse

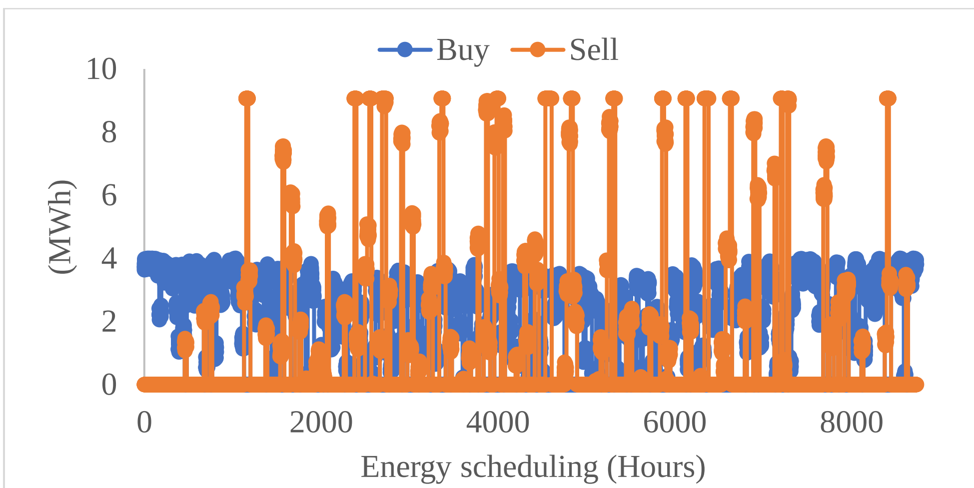

Figure 4.17: Energy purchased and sold for Case 5 in Salt Lake Store

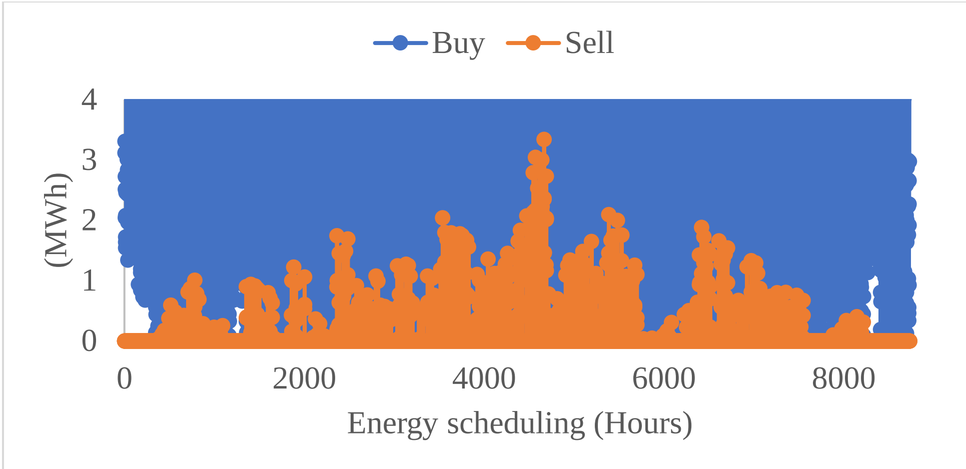

Figure 4.18: Energy purchased and sold for Case 4 in San Jose Store

Case 5

Table 4.8: Results summary of Case 5 in Network 1

Type	Factory		Warehouse	Store	
	Phoenix	Reno	Las Vegas	Salt Lake	San Jose
WT (MW)	0	0	1.64	4.27	0
PV (MW)	0	0	8.76	0	0
BSS (MWh)	0	0	0	0	0

In Case 5 we test the model by reducing the battery cost from \$0.4M/MWh to \$0.05M/MWh. The model still chooses to purchase from the grid in Phoenix, Reno and, San Jose. WT and PV are only installed in Las Vegas and Salt Lake. The results are like the benchmark case shown in Figures 4.2 to 4.6. The total system cost remains the same as the cost of Case 1 because there is no change in WT and PV installation per site.

Case 6

Table 4.9: Results summary of Case 6 in Network 1

Type	Factory		Warehouse	Store	
	Phoenix	Reno	Las Vegas	Salt Lake	San Jose
WT (MW)	0	0	1.5	4.27	0
PV (MW)	0	0	9.05	0	0
BSS (MWh)	0	0	0.55	0	0

We further reduce the cost of the battery cost to $0.02/MWh in Case 6. The results in Table 4.9 shows that the model chooses to install battery in Las Vegas facility. The decision on the other facilities remain the same as the benchmark. The total system cost for this case is $81,073,007. The intermediate results for Las Vegas facility are given in Figure 4.19.

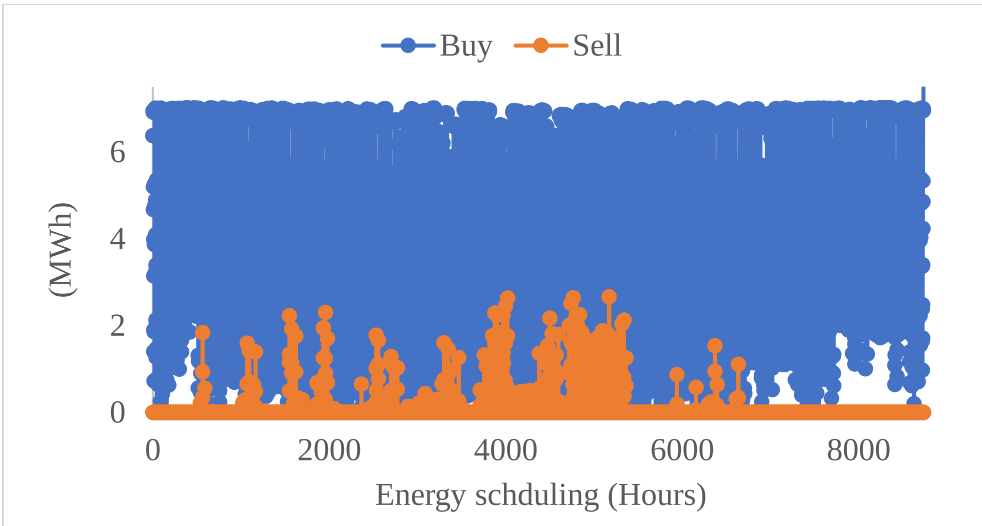

Figure 4.19: Energy purchased and sold for Case 6 in Las Vegas Warehouse

Case 7

Table 4.10: Results summary for Case 7 in Network 1

Type	Factory		Warehouse	Store	
	Phoenix	Reno	Las Vegas	Salt Lake	San Jose
WT (MW)	0	0	0.93	4.27	0
PV (MW)	0	0	12.35	0	0
BSS (MWh)	0	0	11.21	0	0

Further decrease of battery price sees to stimulate more installation of battery in Las Vegas facility. In Case 7, the battery cost is down to $0.01M/MWh. The decision on the rest of the facilities remains the same. The system cost is $81,070,090. The total system cost for Case 7 is further down compared with Case 6 because of lower battery cost. Figures 4.20 shows the hourly results.

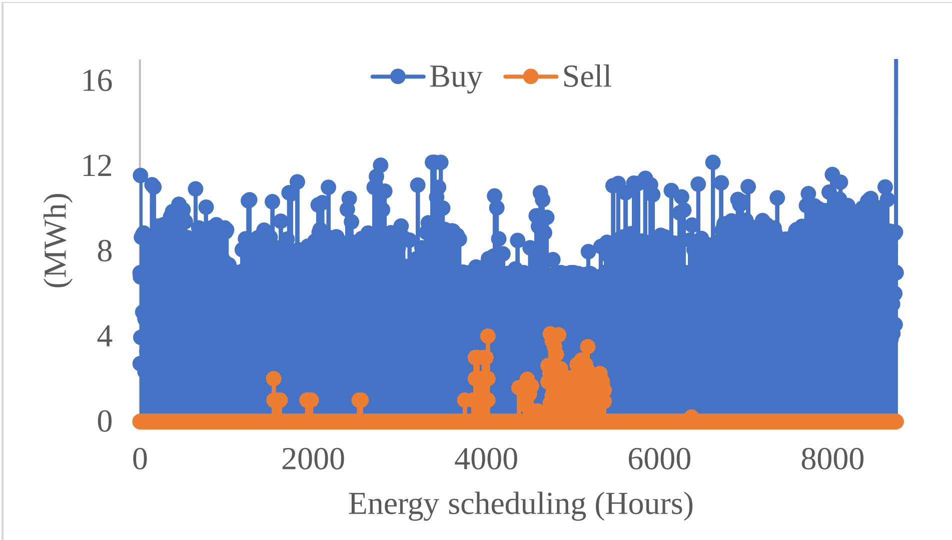

Figure 4.20: Energy purchased and sold for Case 7 in Las Vegas Warehouse

Case 8

Table 4.11: Results summary for Case 8

Type	**Factory**		**Warehouse**	**Store**	
	Phoenix	**Reno**	**Las Vegas**	**Salt Lake**	**San Jose**
WT (MW)	0	0	0	2.6	0
PV (MW)	14.87	15.12	15.06	4.9	9.27
BSS (MWh)	0	0	0	0	0

In Case 8 we test the model by reducing the PV cost from $2M/MW to $1M/MW and keeping the selling price as $0/MWh. By keeping zero selling price, it can truly test whether the PV is competitive to power the facility as opposed to the grid energy. Table 4.11 shows the results of the installation at all the facilities. Since the PV system cost is low, the model chooses to install more PV across all the facilities. The intermediate results are given in the following Figures 4.21 to 4.25.

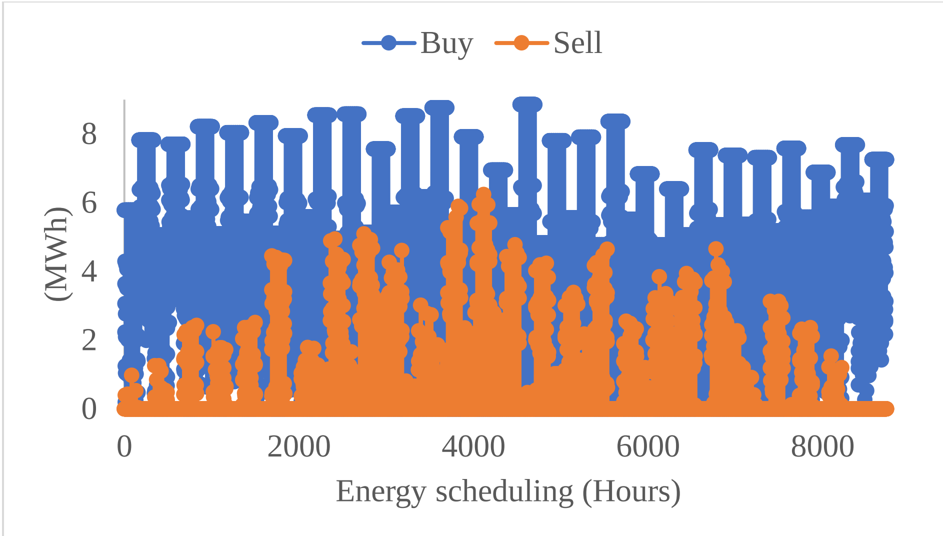

Figure 4.21: Energy purchased and sold for Case 8 in Phoenix Factory

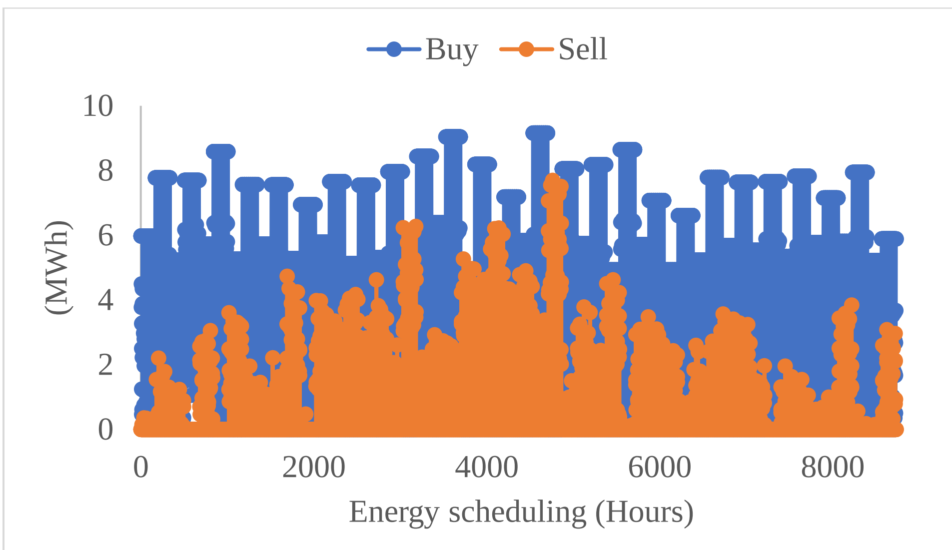

Figure 4.22: Energy purchased and sold for Case 8 in Reno Factory

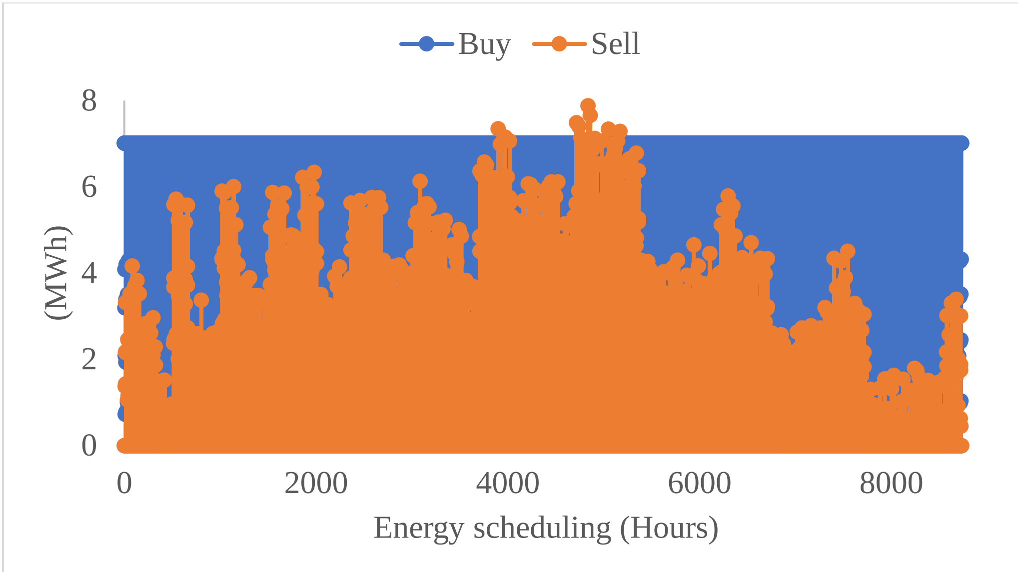

Figure 4.23: Energy purchased and sold for Case 8 in Las Vegas Warehouse

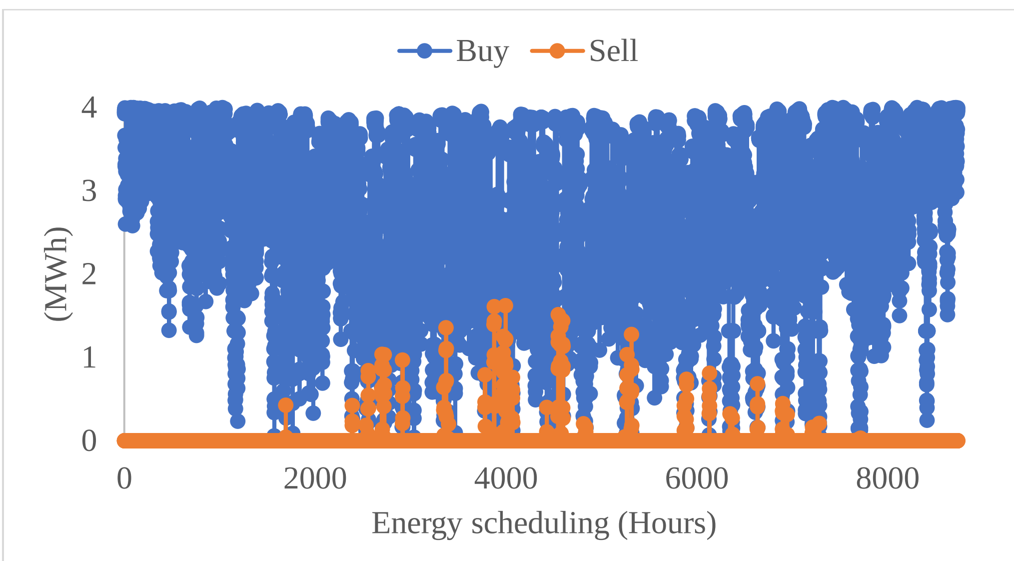

Figure 4.24: Energy purchased and sold for Case 8 in Salt Lake Store

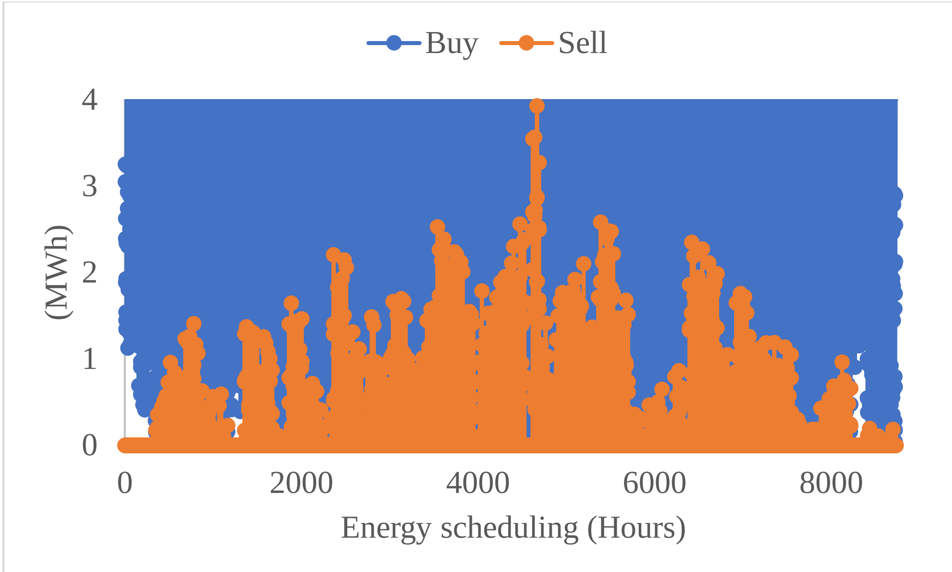

Figure 4.25: Energy purchased and sold for case 8 in San Jose Store

4.4 Four-Factory, Two-Warehouse, and Four-Store Network

Model 4.1 is further applied to an expanded supply chain network comprised of four factories, two warehouses and, four stores shown in Figure 3.12 of Chapter 3. The factories are located in Phoenix, Reno, Yuma and Tucson, respectively. Finished goods are shipped to two warehouses located at Las Vegas and Los Angeles from which they are distributed to the stores in Salt Lake, San Jose, Sacramento and San Francisco.

The production planning model is solved on a weekly basis and the microgrid sizing is solved hourly over a year. Figures 4.28 and 4.29 show the conversion of weekly production to hourly manufacturing rate. Products are shipped from Phoenix and Reno to the warehouse in Las Vegas as the distances are shorter. Products to the warehouse in Los Angeles are shipped from all the factories in order to meet the demand from the stores.

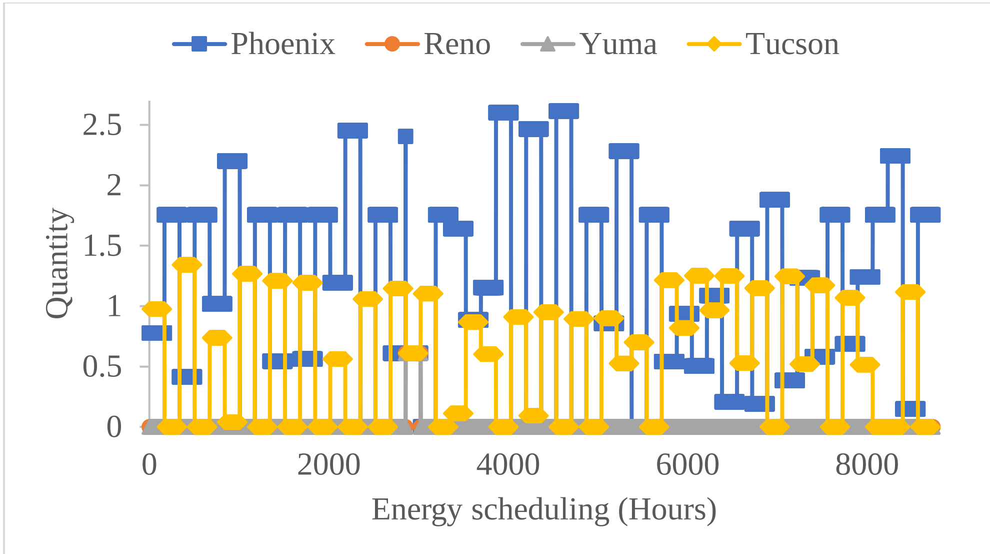

Figure 4.26: Product A shipped from the factories to Las Vegas Warehouse

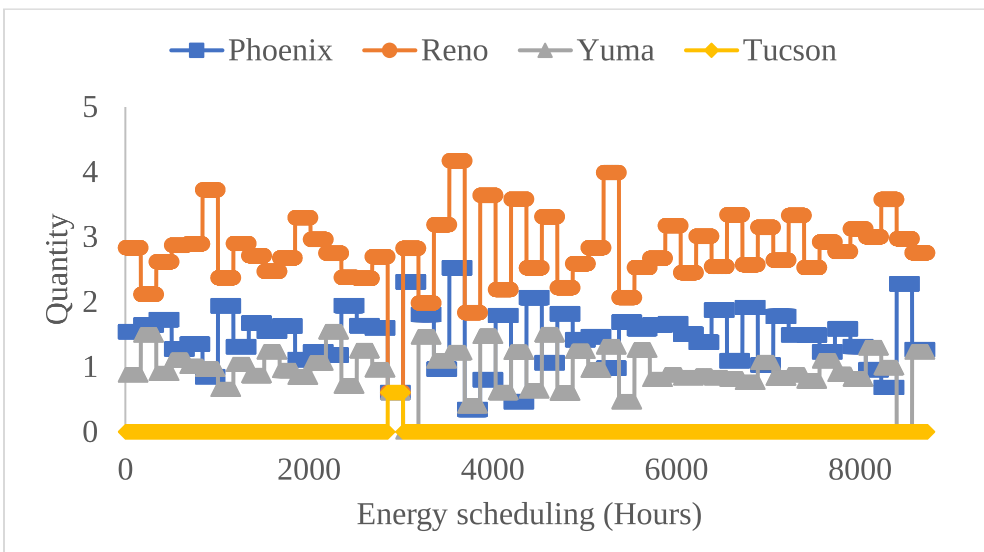

Figure 4.27: Product A shipped from the factories to Los Angeles Warehouse

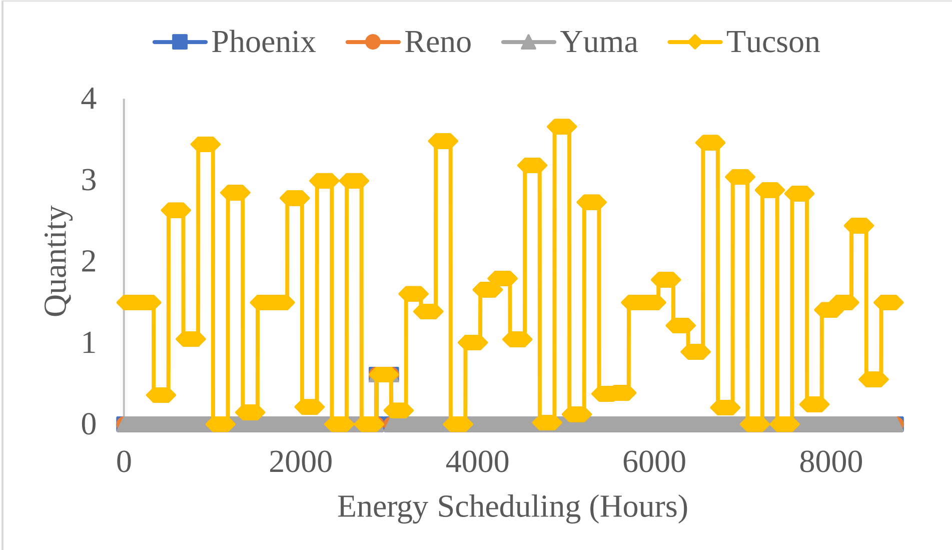

Figure 4.28: Product B shipped from the factories to Las Vegas Warehouse

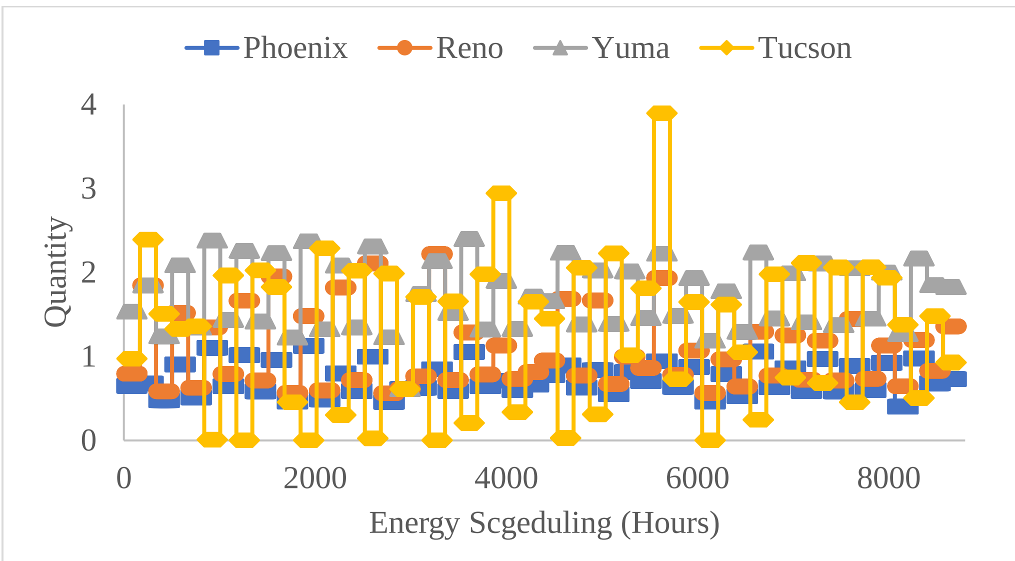

Figure 4.29: Product B shipped from the factories to Los Angeles Warehouse

4.4.1 Results analysis and discussion. The extended model for eight cases is given in Table 4.5. The results of the cases are discussed in detail below. Note that 1=Phoenix, 2 = Reno, 3 = Yuma, and 4 = Tucson for factories. 1 = Las Vegas, and 2 = Los Angeles for

Warehouse. 1 = Salt Lake City, 2 = San Jose, 3 = Sacramento, and 4 = San francisco for Store.

Table 4.12: Cost Comparisons with the Benchmark (Case 1) in Network 2

Case	Total Cost	Cost Difference	Cost Difference in %	Energy Cost	Cost Difference	Cost Difference in %
1	89,236,964	-	-	22,110,021	-	-
2	89,934,595	-697,632	0.78	22,807,653	-697,632	3.11
3	104,407,143	-15,170,179	15.67	37,280,201	-15,170,179	51.09
4	94,626,270	-5,389,307	5.86	27,499,328	-5,389,307	21.73
5	89,236,964	-	0.00	22,110,021	-	0.00
6	89,224,409	12,555	0.01	22,097,467	12,555	0.06
7	89,179,414	57,549	0.06	22,052,472	57,549	0.26
8	86,487,885	2,749,079	3.13	19,360,943	2,749,079	13.26

Case 1

Table 4.13: Case 1 results summary for Network 2

Type	**Factory**				**Warehouse**		**Store**			
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**
WT (MW)	0	0	0	0	1.6	7	4.2	0	0	20
PV (MW)	0	0	0	5.8	8.7	0	0	0	0	0
BSS (MWh)	0	0	0	0	0	0	0	0	0	0

Table 4.13 shows the results of microgrid installation at each facility. The model chooses to install WT and/or PV in Tucson, Las Vegas, Los Angeles, Salt Lake and San Francisco. It chooses to purchase electricity from the grid at all other cities as it is a less expensive option. The total system cost for this case is $89,236,954. The hourly purchasing and selling results are given in Figures 4.30 to 4.39.

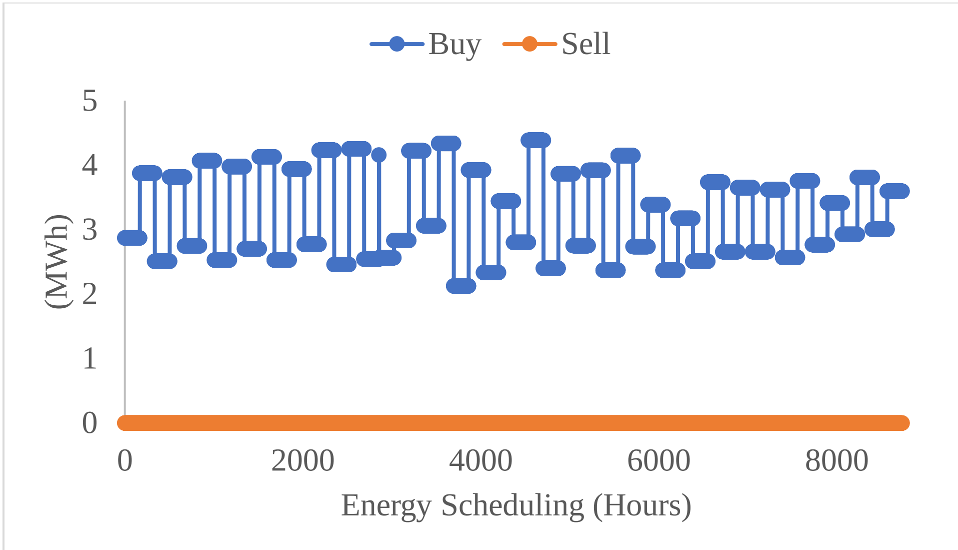

Figure 4.30: Energy purchased and sold for Case 1 in Phoenix Factory

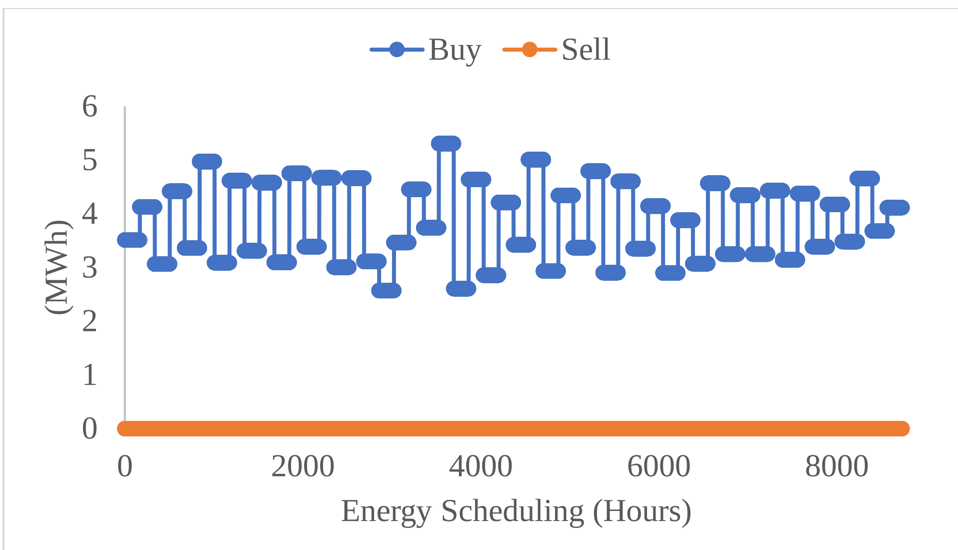

Figure 4.31: Energy purchased and sold for Case 1 in Reno Factory

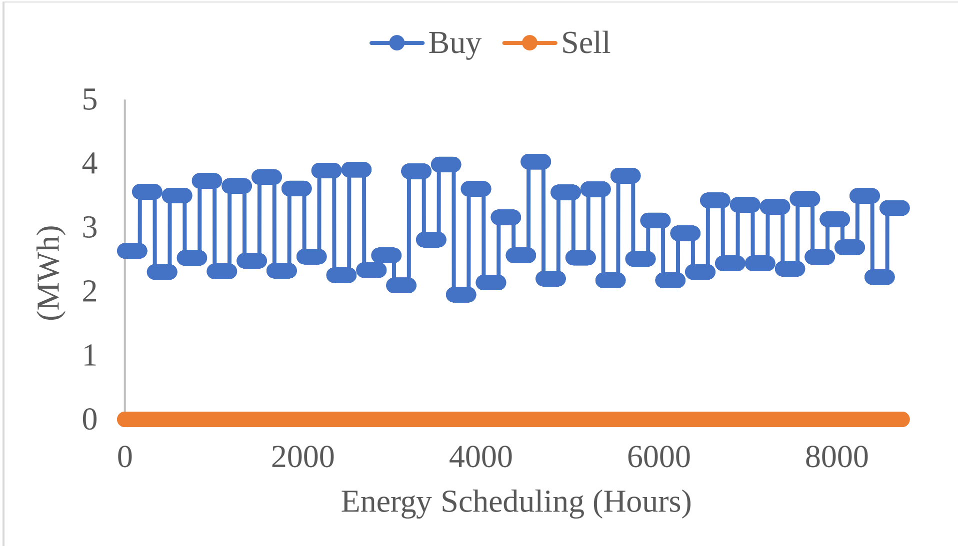

Figure 4.32: Energy purchased and sold for Case 1 in Yuma Factory

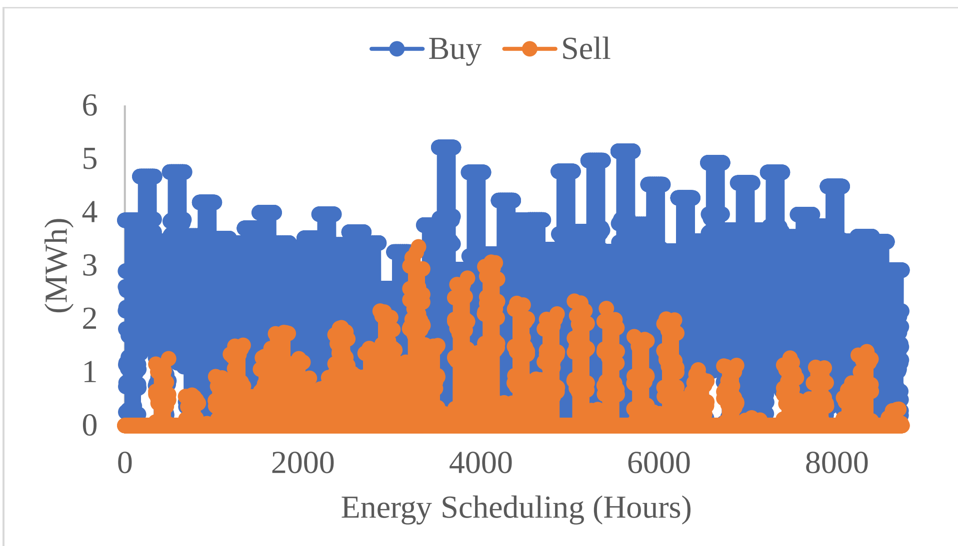

Figure 4.33: Energy purchased and sold for Case 1 in Tucson Factory

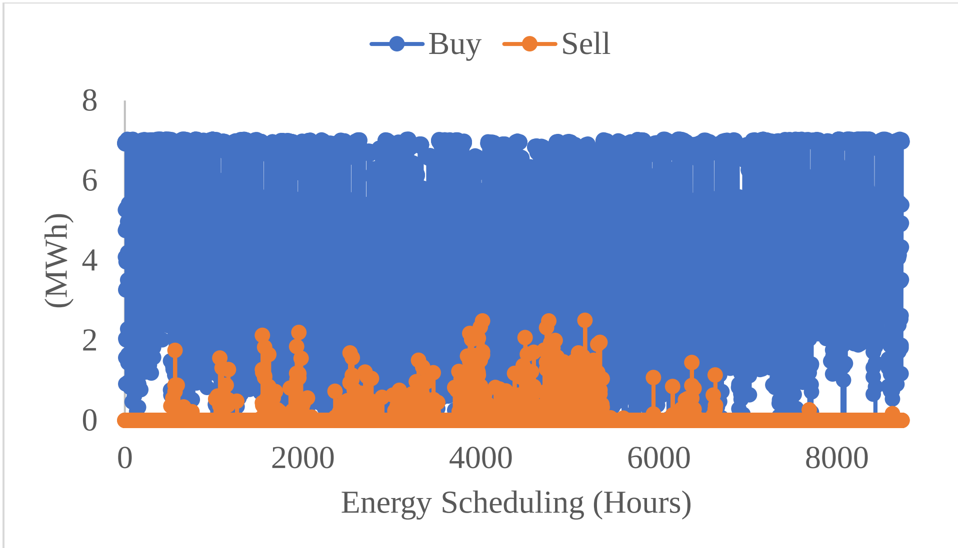

Figure 4.34: Energy purchased and sold for Case 1 in Las Vegas Warehouse

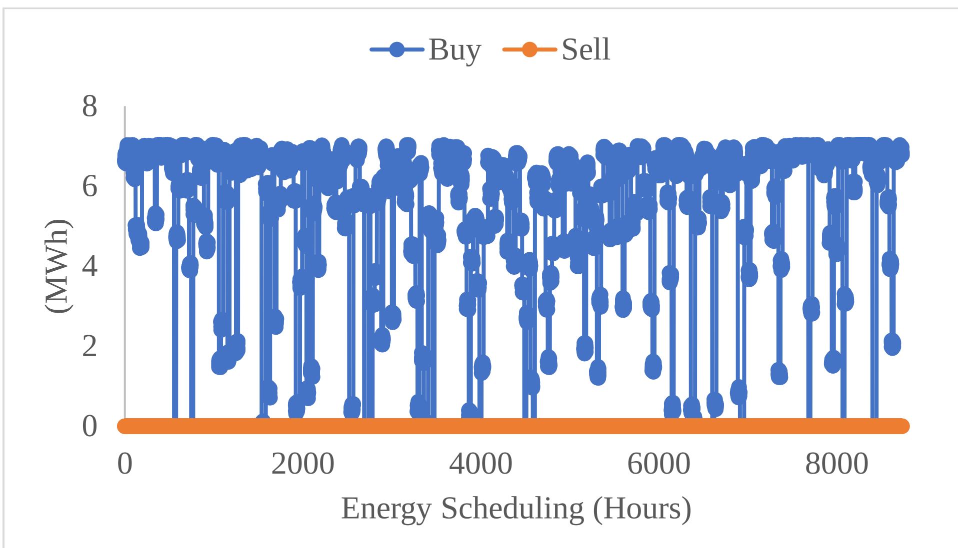

Figure 4.35: Energy purchased and sold for Case 1 in Los Angeles Warehouse

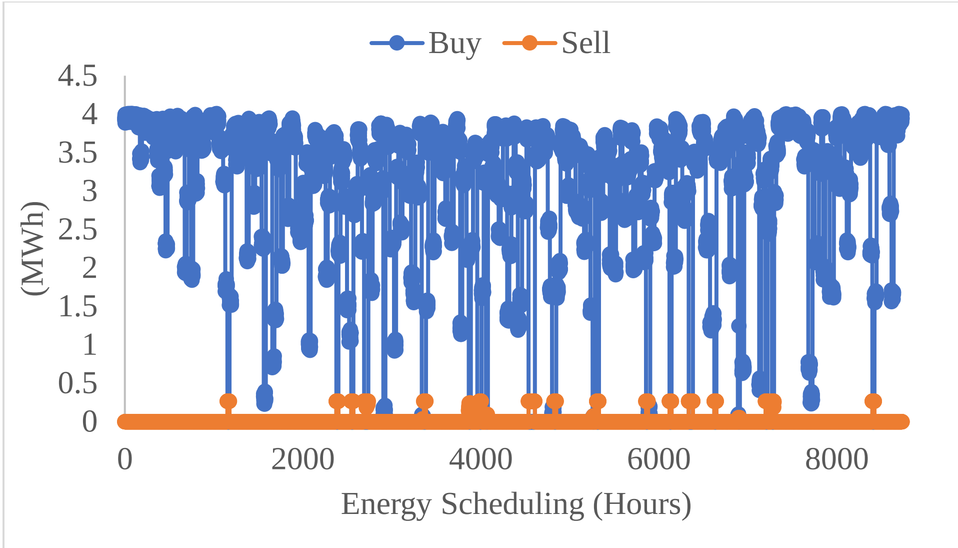

Figure 4.36: Energy purchased and sold for Case 1 in Salt Lake Store

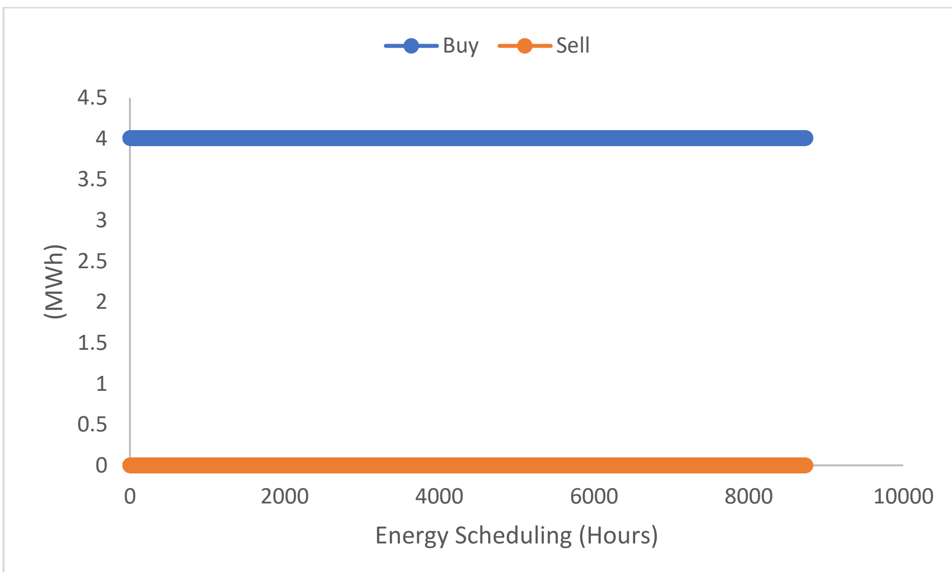

Figure 4.37: Energy purchased and sold for Case 1 in San Jose Store

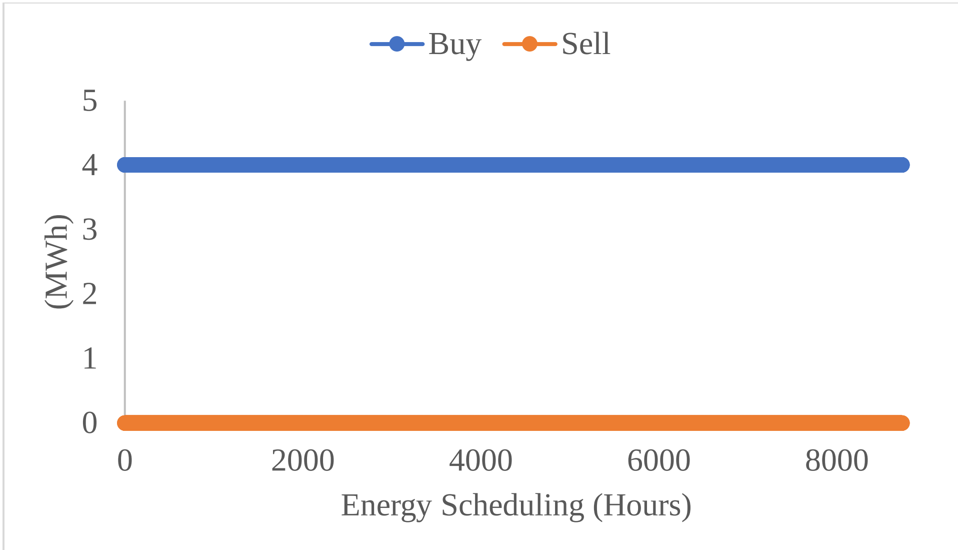

Figure 4.38: Energy purchased and sold for Case 1 in Sacramento Store

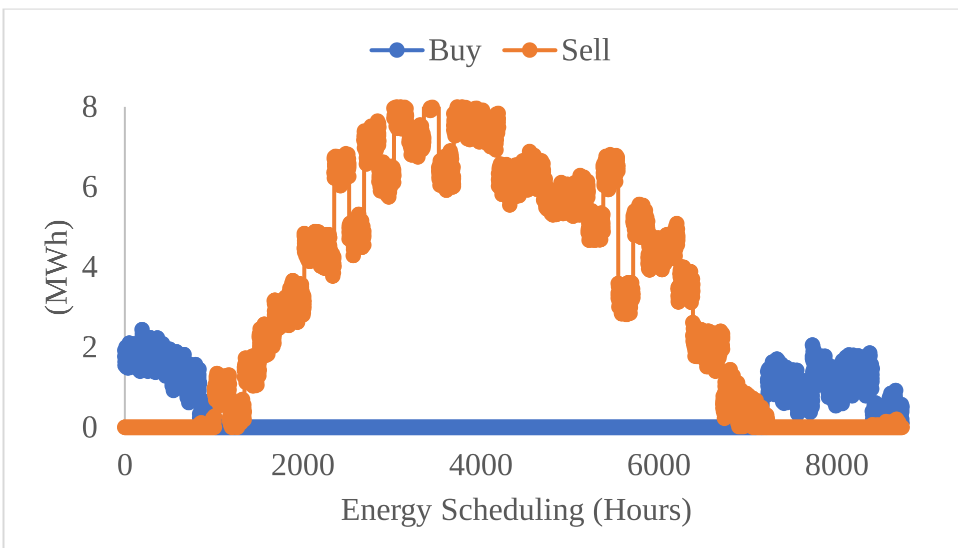

Figure 4.39: Energy purchased and sold for Case 1 in San Francisco Store

Case 2

Table 4.14: Case 2 results summary for Network 2

Type	Factory				Warehouse		Store			
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**
WT (MW)	0	0	0	0	1.6	7	4.2	0	0	7.1
PV (MW)	0	0	0	4.7	8.7	0	0	0	0	0
BSS (MWh)	0	0	0	0	0	0	0	0	0	0

Table 4.14 shows the Case 2 results for the expanded network. Installation decision for Tucson Factory and San Francisco Store are the observed changes from Case 1. The hourly energy trading results are discussed in Figure 4.40 and 4.41. All the other results remain the same as Case 1. The total system cost for this case is $89,934,595.

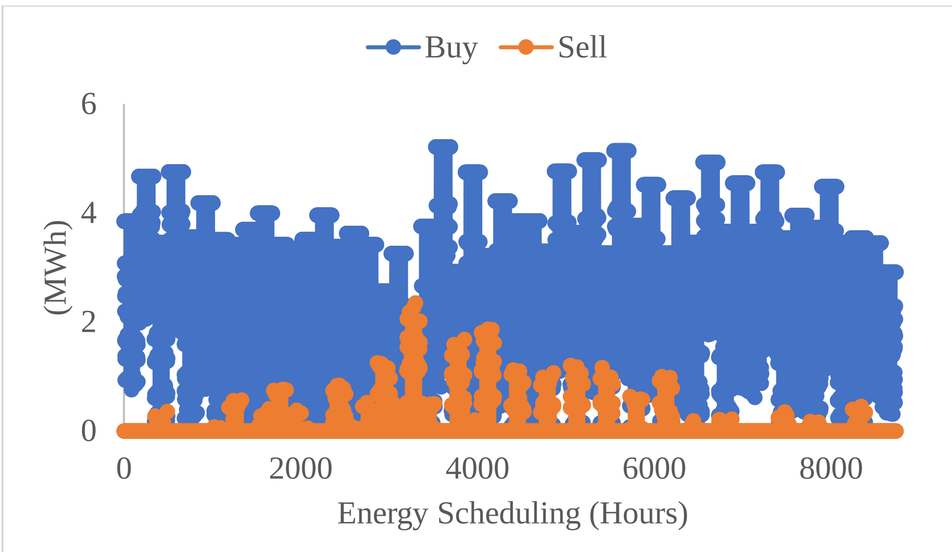

Figure 4.40: Energy purchased and sold for Case 2 in Tucson Factory

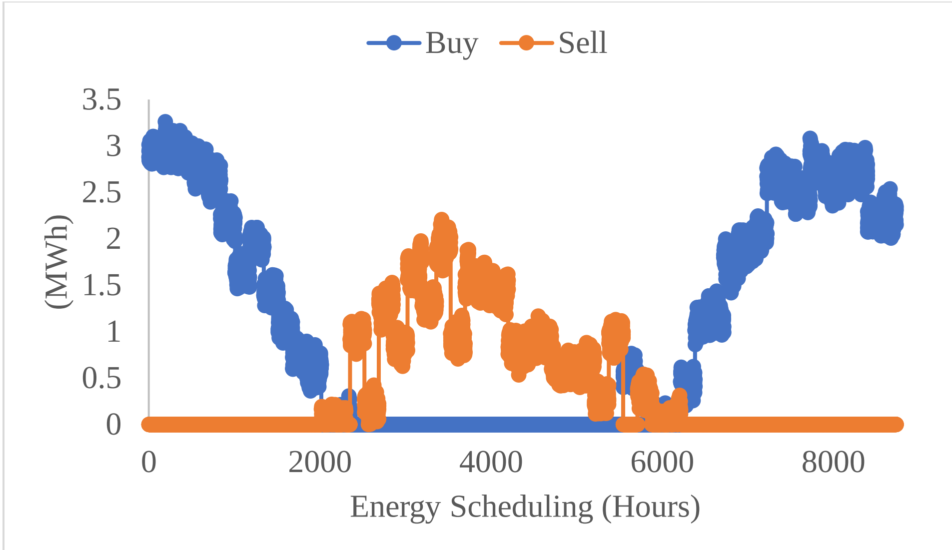

Figure 4.41: Energy purchased and sold for Case 2 in San Francisco Store

Case 3

Table 4.15: Case 3 results summary for network 2

Type	**Factory**				**Warehouse**		**Store**			
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**
WT (MW)	0	6.4	8	7.2	19.2	20	20	7.36	10.2	20
PV (MW)	8.8	8.4	5.8	10	15.7	9.47	0	8.46	8.7	0
BSS (MWh)	0	0	0	0	0	0	0	0	0	0

In Case 3 the model is tested by increasing the purchasing price to \$150/MWh. In this case it is observed that the system chooses to install more WT and/or PV systems across all facilities as it is determined that this is much feasible than purchasing electricity from the grid. The total system cost for this case is \$104,407,143. The intermediate results of each facility is shown in Figures 4.42 to 4.50.

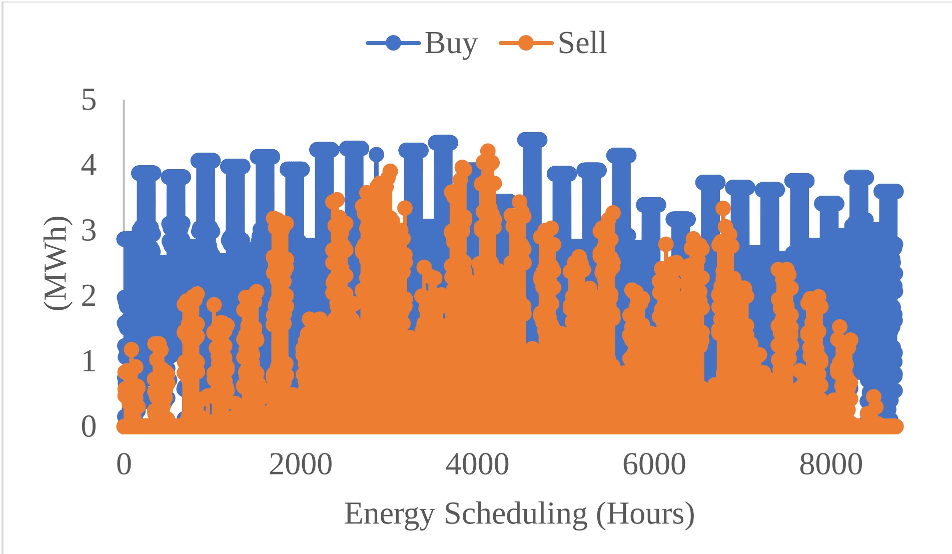

Figure 4.42: Energy purchased and sold for Case 3 in Phoenix Factory

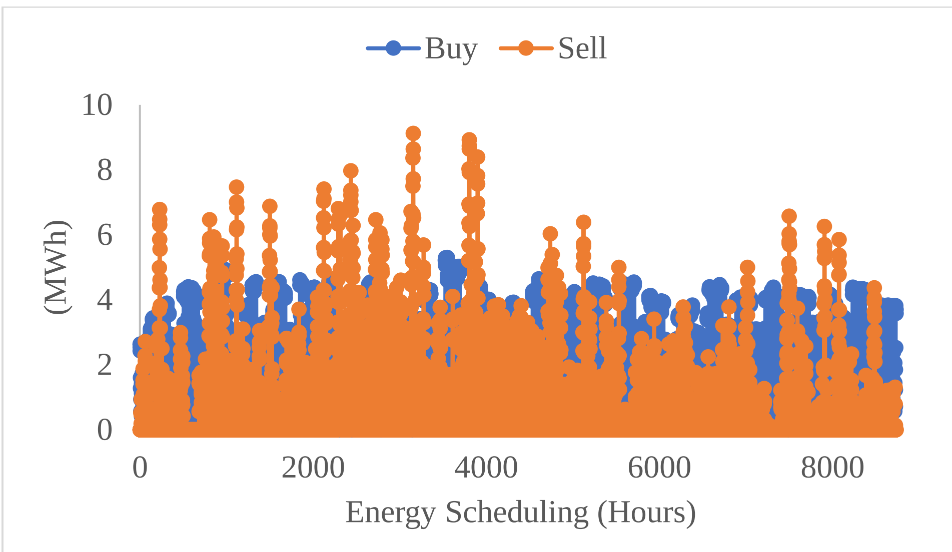

Figure 4.43: Energy purchased and sold for Case 3 in Reno Factory

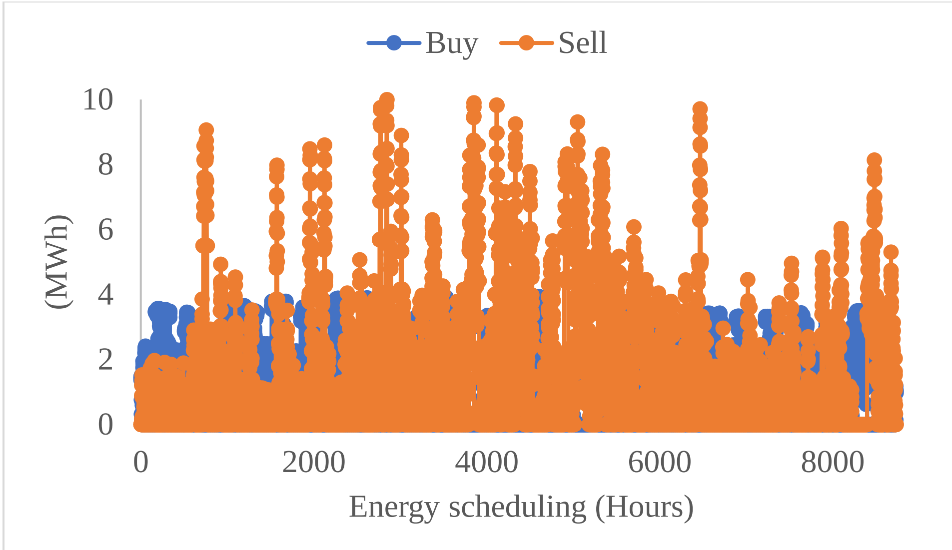

Figure 4.44: Energy purchased and sold for Case 3 in Yuma Factory

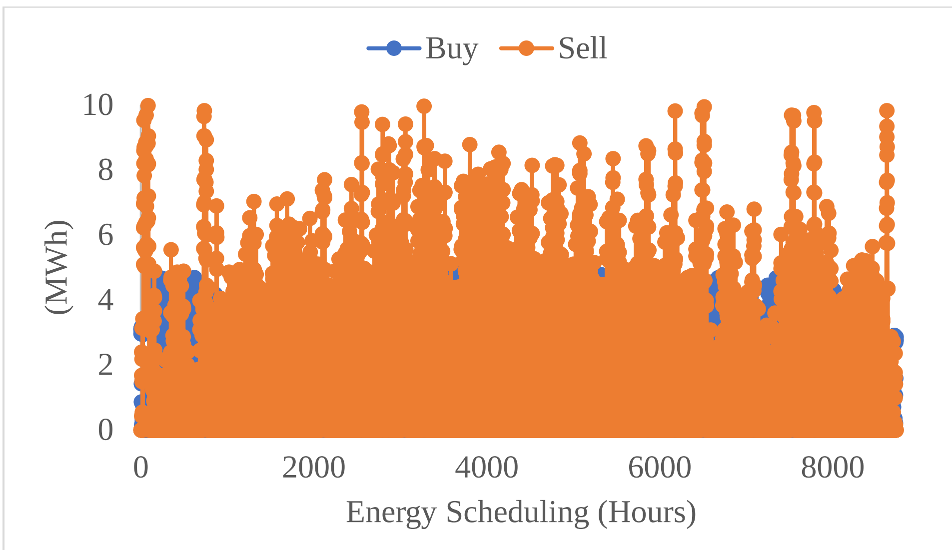

Figure 4.45: Energy purchased and sold for Case 3 in Tucson Factory

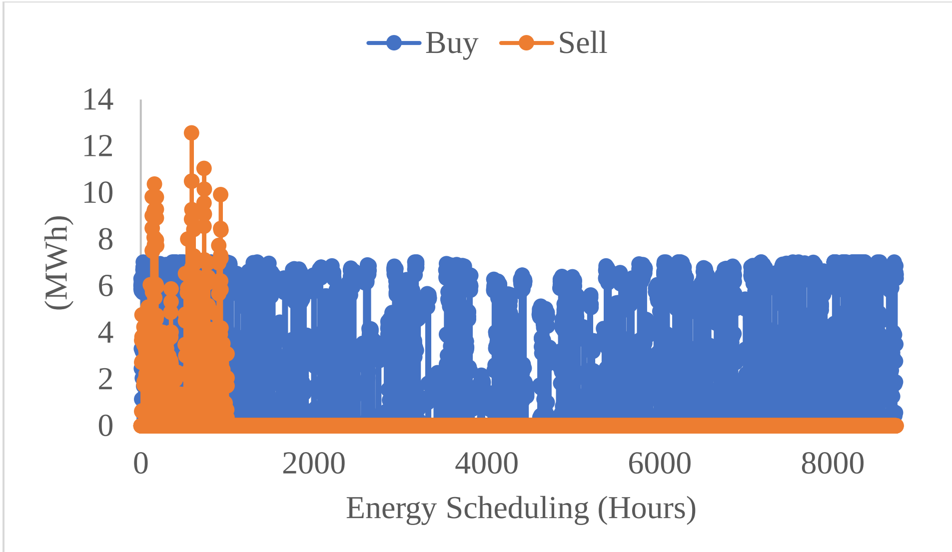

Figure 4.46: Energy purchased and sold for Case 3 in Las Vegas Warehouse

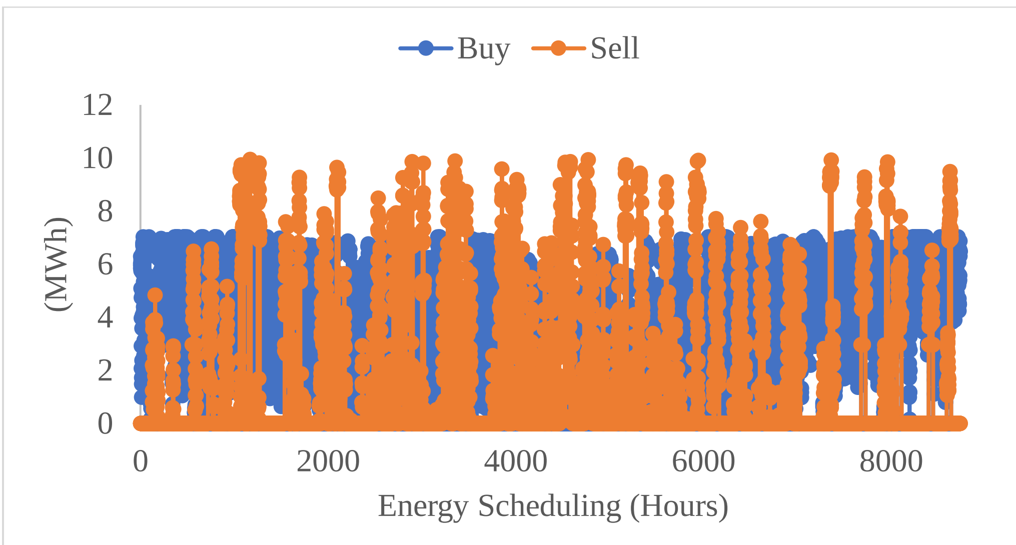

Figure 4.47: Energy purchased and sold for Case 3 in Los Angeles Warehouse

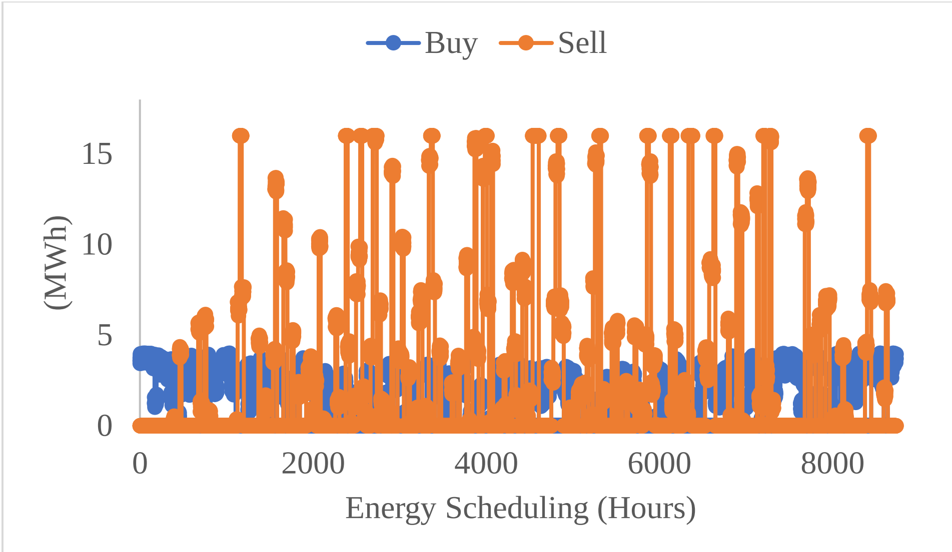

Figure 4.48: Energy purchased and sold for Case 3 in Salt Lake Store

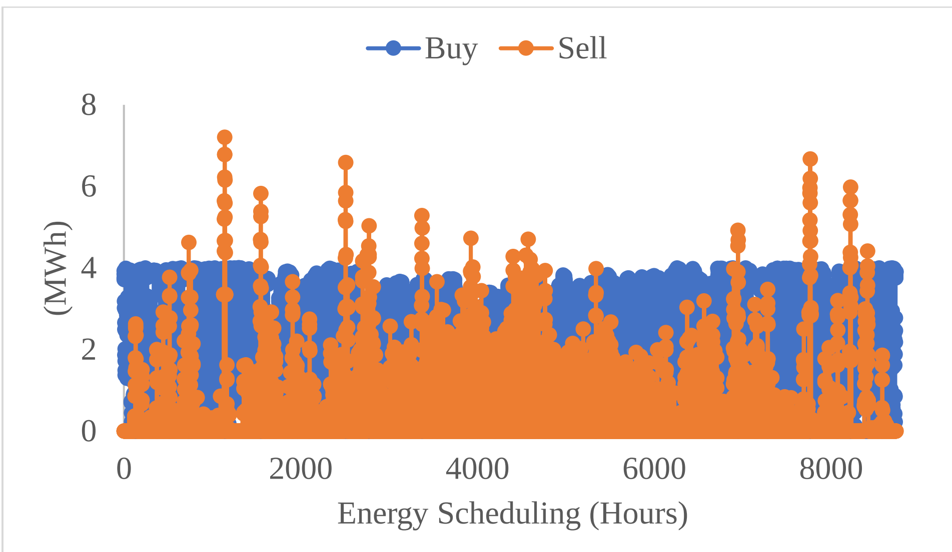

Figure 4.49: Energy purchased and sold for Case 3 in San Jose Store

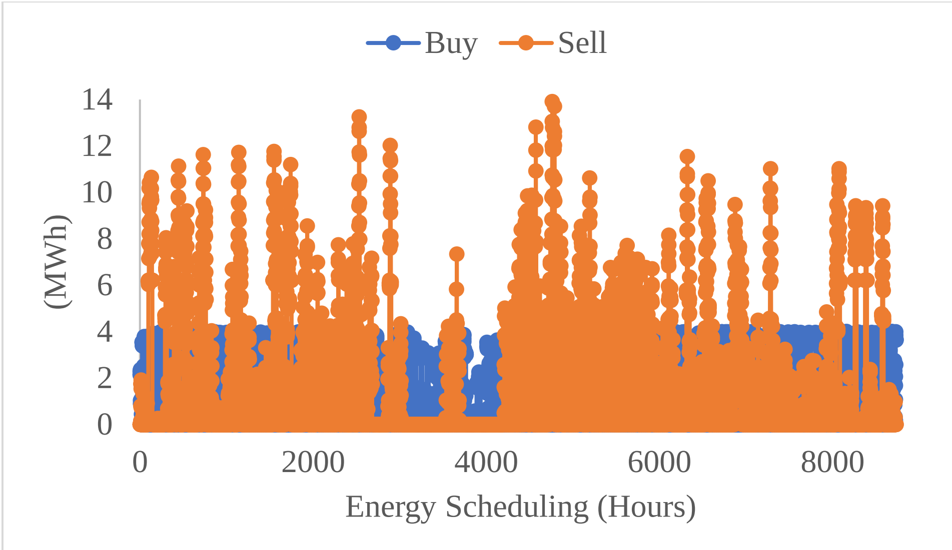

Figure 4.50: Energy purchased and sold for Case 3 in Sacramento Store

The amount of energy purchased and sold for Case 3 in San Francisco Store remains the same as Case 1 which is given in Figure 4.39.

Case 4

Table 4.16: Case 4 results summary for network 2

Type	**Factory**				**Warehouse**		**Store**			
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**
WT (MW)	0	0	2.5	0	7.02	0	13.08	0	2.5	20
PV (MW)	6.7	8.6	5.8	10.7	15.18	16.33	0	8.5	8.9	0
BSS (MWh)	0	0	0	0	0	0	0	0	0	0

Time of use (TOU) pricing policy is used in Case 4. The model chooses to install more WT and/or PV across all facilities. The total system cost is $94,626,270. The results of amount of energy purchased and sold are shown in Figures 4.51 to 4.60.

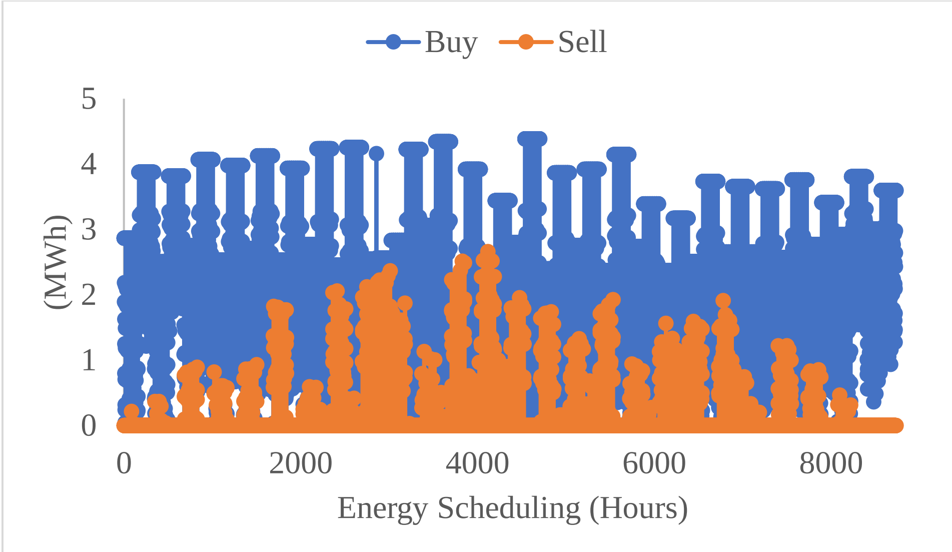

Figure 4.51: Energy purchased and sold for Case 4 for Phoenix Factory

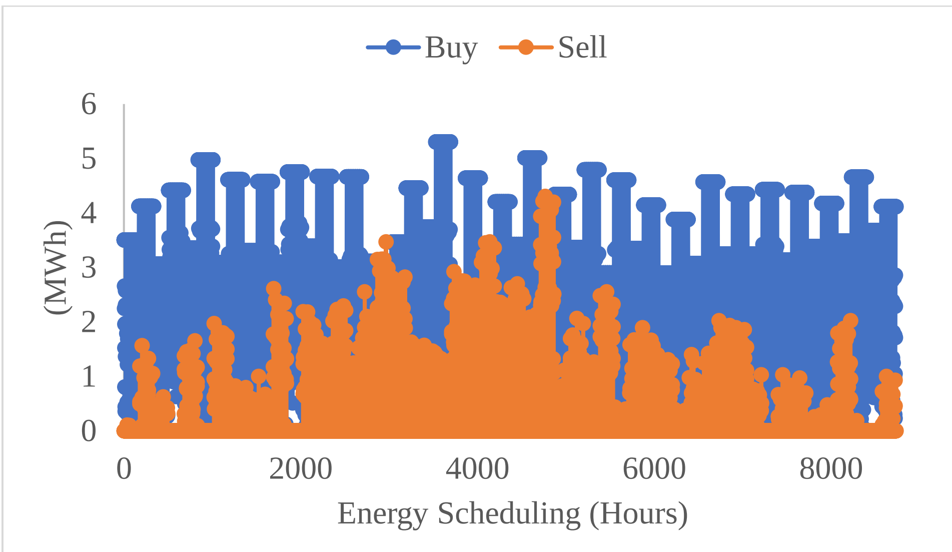

Figure 4.52: Energy purchased and sold for Case 4 for Reno Factory

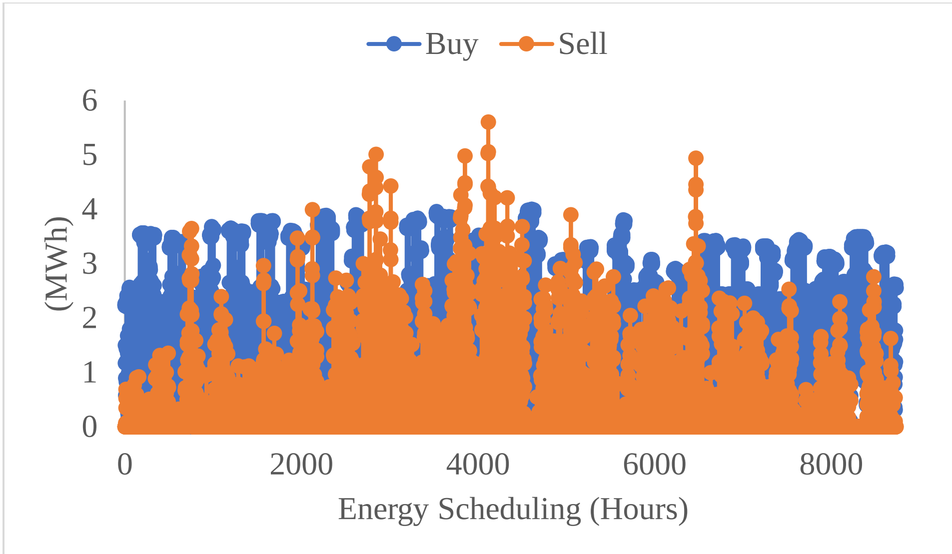

Figure 4.53: Energy purchased and sold for Case 4 for Yuma Factory

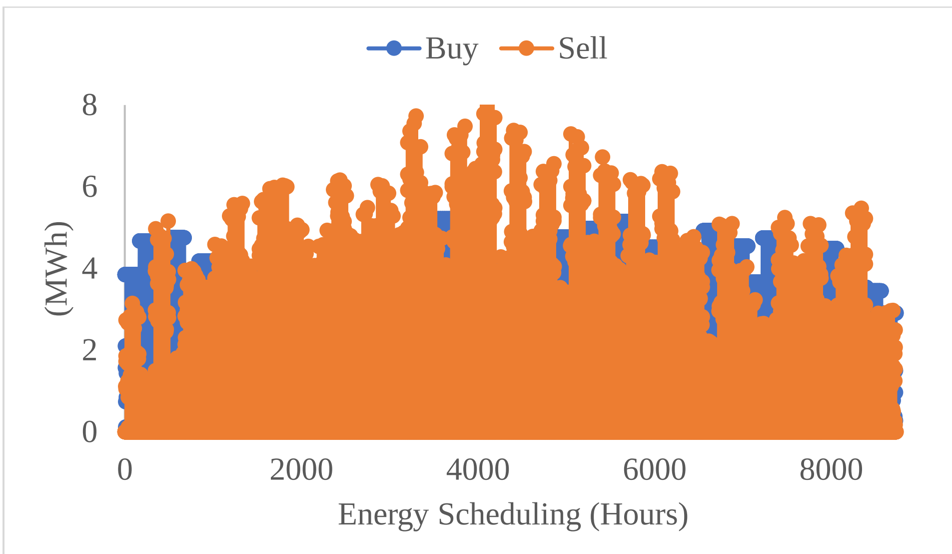

Figure 4.54: Energy purchased and sold for Case 4 for Tucson Factory

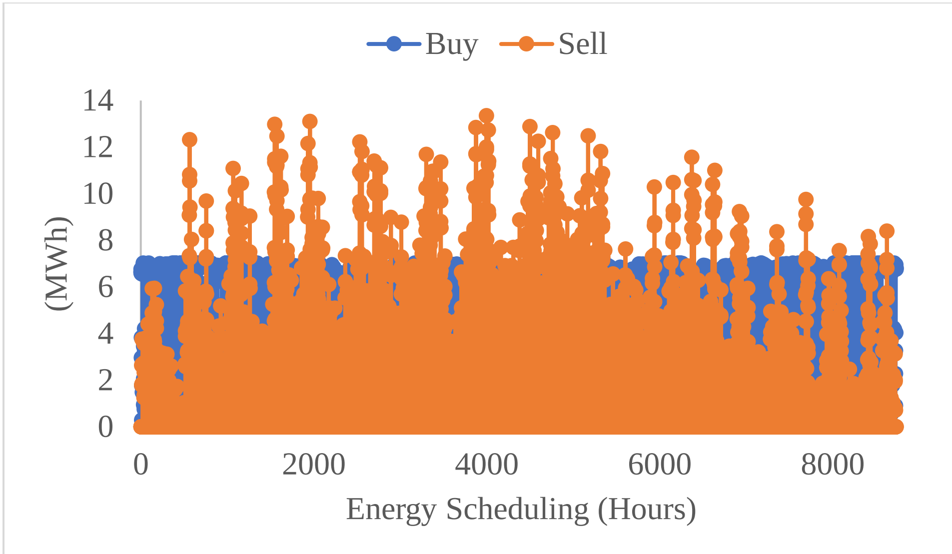

Figure 4.55: Energy purchased and sold for Case 4 for Las Vegas Warehouse

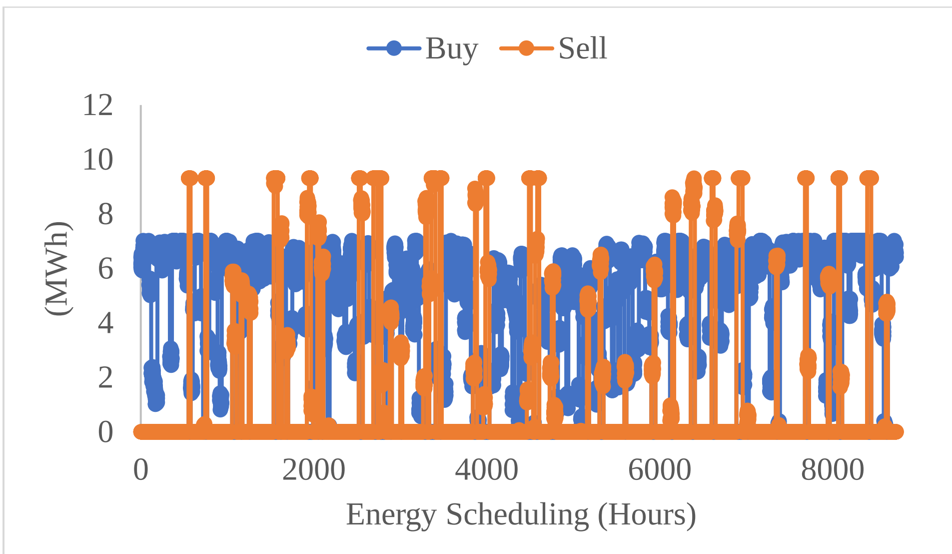

Figure 4.56: Energy purchased and sold for Case 4 for Los Angles Warehouse

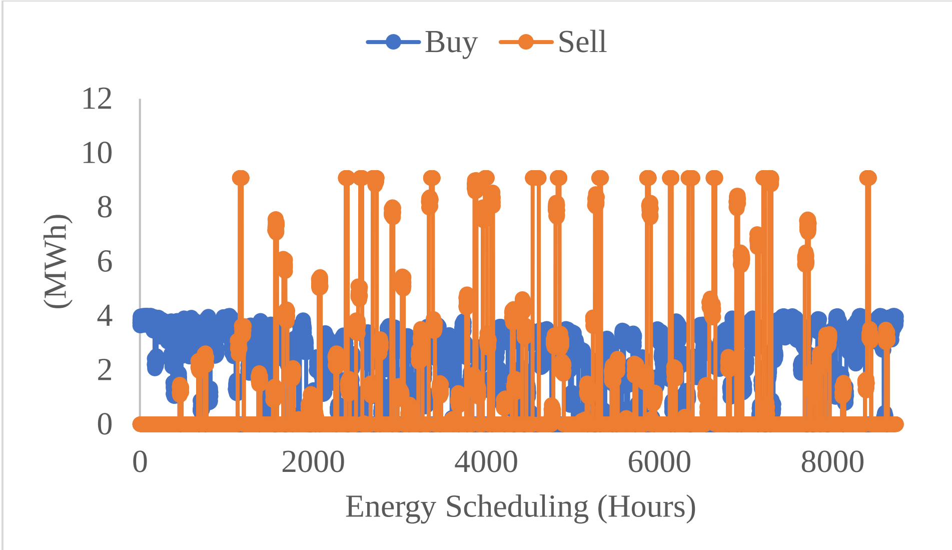

Figure 4.57: Energy purchased and sold for Case 4 for Salt Lake Store

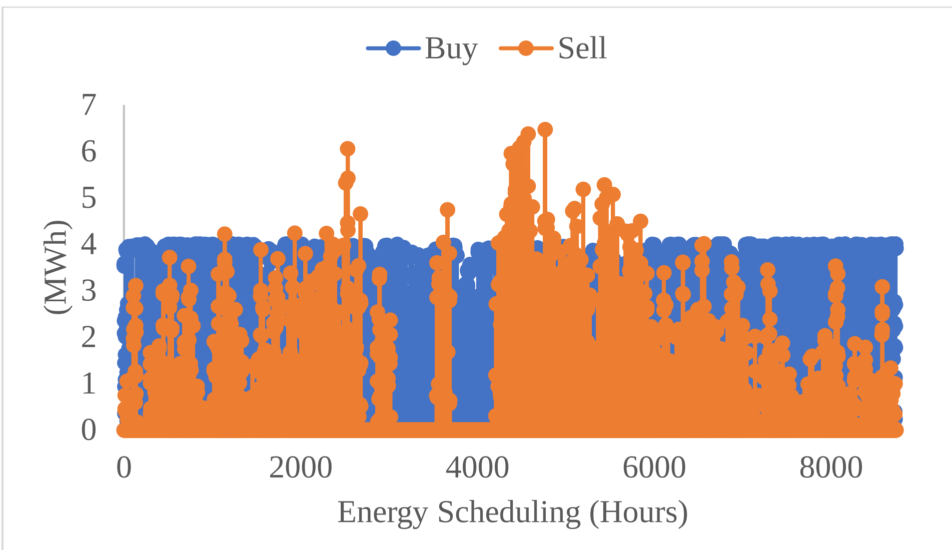

Figure 4.58: Energy purchased and sold for Case 4 for San Jose Store

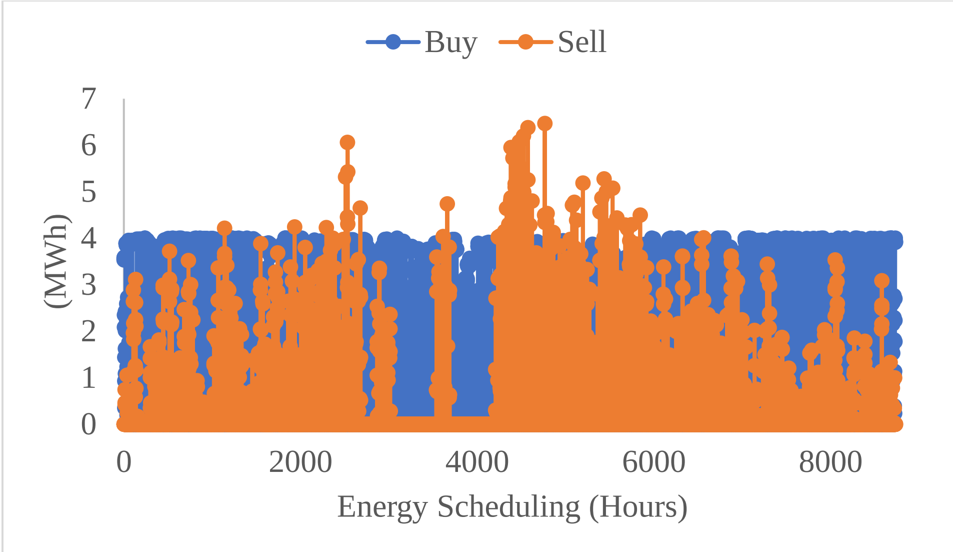

Figure 4.59: Energy purchased and sold for Case 4 for Sacramento Store

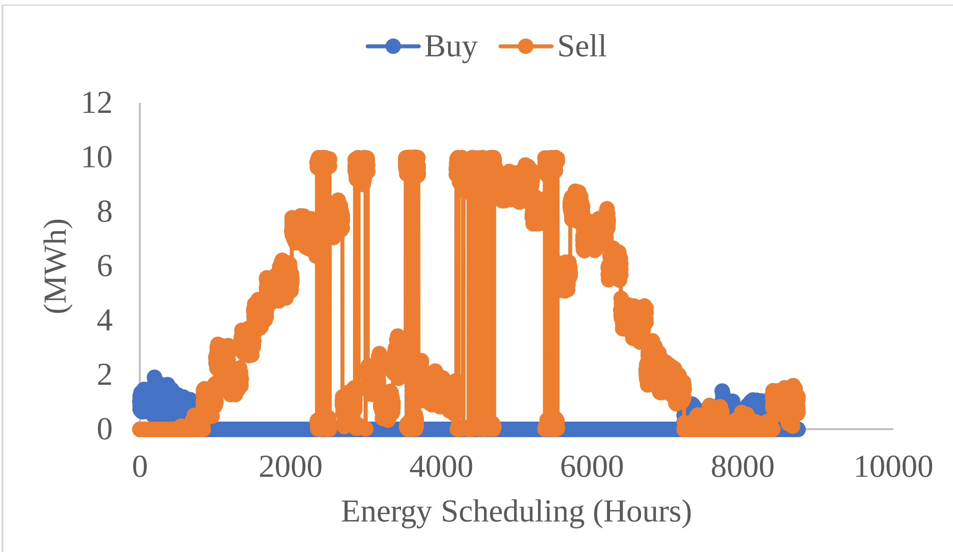

Figure 4.60: Energy purchased and sold for Case 4 for San Francisco Store

Case 5

Table 4.17: Case 5 results summary for network 2

Type	Factory				Warehouse		Store			
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**
WT (MW)	0	0	0	0	1.6	7	4.2	0	0	20
PV (MW)	0	0	0	5.8	8.7	0	0	0	0	0
BSS (MWh)	0	0	0	0	0	0	0	0	0	0

Battery cost is reduced and tested for Case 5. The decision on installation of WT and/or PV remains the same. The intermediate results are given in Figure 4.30 to Figure 4.39. The total system cost in this case is $89,236,963.

Case 6

Table 4.18: Case 6 results summary for network 2

Type	Factory				Warehouse		Store			
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**
WT (MW)	0	0	0	0	1.6	7	4.2	0	0	20
PV(MW)	0	0	0	10.3	9	0	0	0	0	0
BSS(MWh)	0	0	0	21.2	0.5	0	0	0	0	0.01

In Case 6 we further reduce the price of the battery. In this case we can see the model chooses to install battery in Tucson, Las Vegas and San Francisco facilities. The decision on all other facilities remain the same as the benchmark case. The total system cost for this case is $89,224,408. The intermediate results are shown in Figures 4.61 to 4.63.

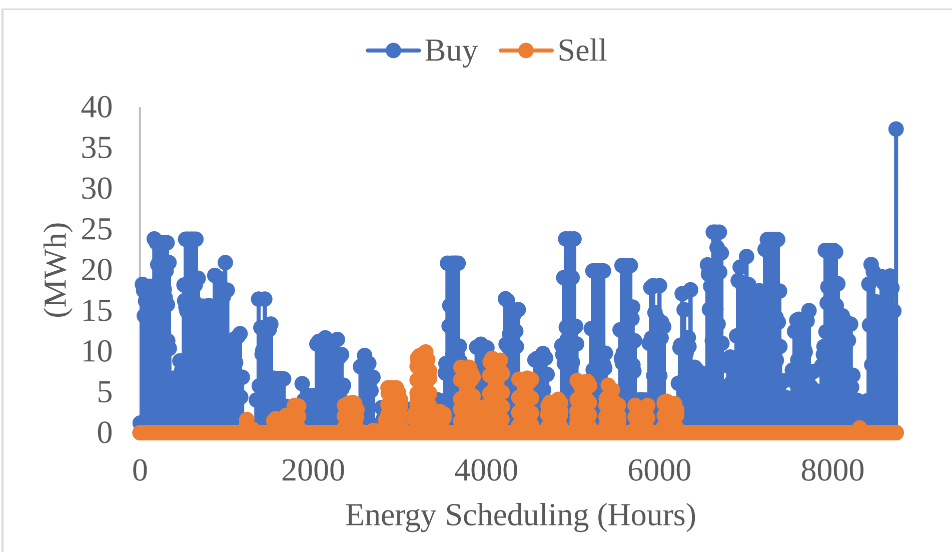

Figure 4.61: Energy purchased and sold for Case 6 in Tucson Factory

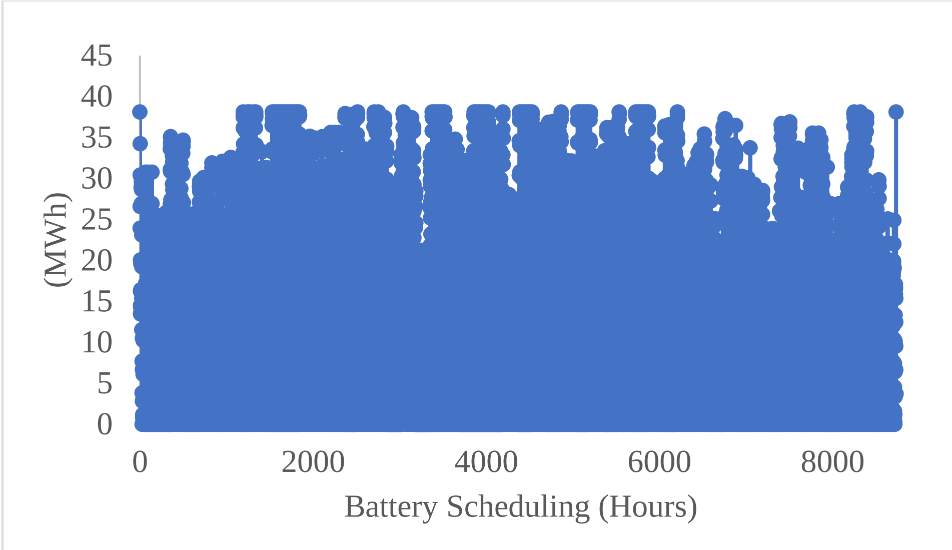

Figure 4.62: Energy Stored in battery for Case 6 in Tucson Factory

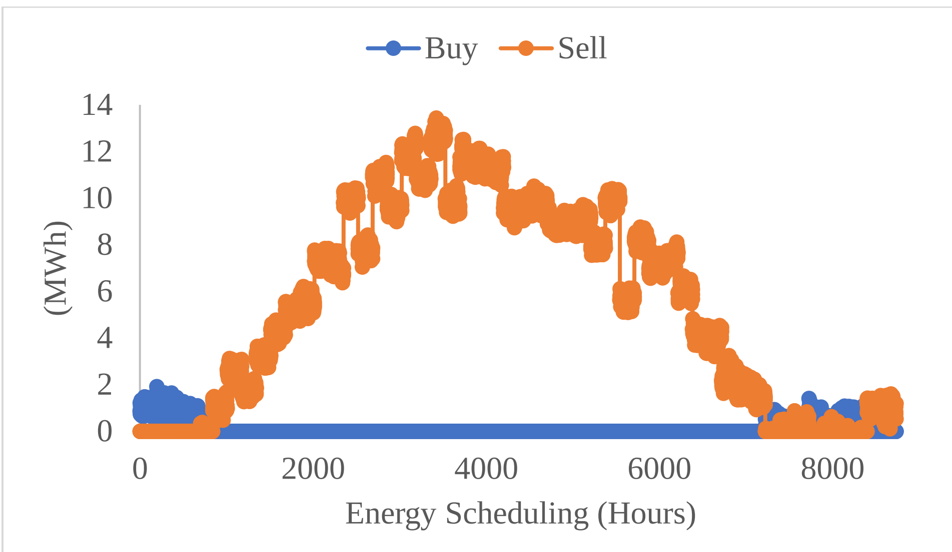

Figure 4.63: Energy purchased and sold for Case 6 in San Francisco Store

Case 7

Table 4.19: Case 7 results summary for network 2

Type	Factory				Warehouse		Store			
	1	2	3	4	1	2	1	2	3	4
WT (MW)	0	0	0	0	0.9	7	4.2	0	0	20
PV(MW)	0	0	0	13.2	12.3	0	0	0	0	0
BSS(MWh)	0	0	0	38.1	11.2	0	0	0	0	0.12

The model chooses to install more batteries as the price of the battery goes down. The total system cost for this case is $89,179,414. The results of Tucson Factory and Las Vegas warehouse are shown in Figures 4.64 and 4.65.

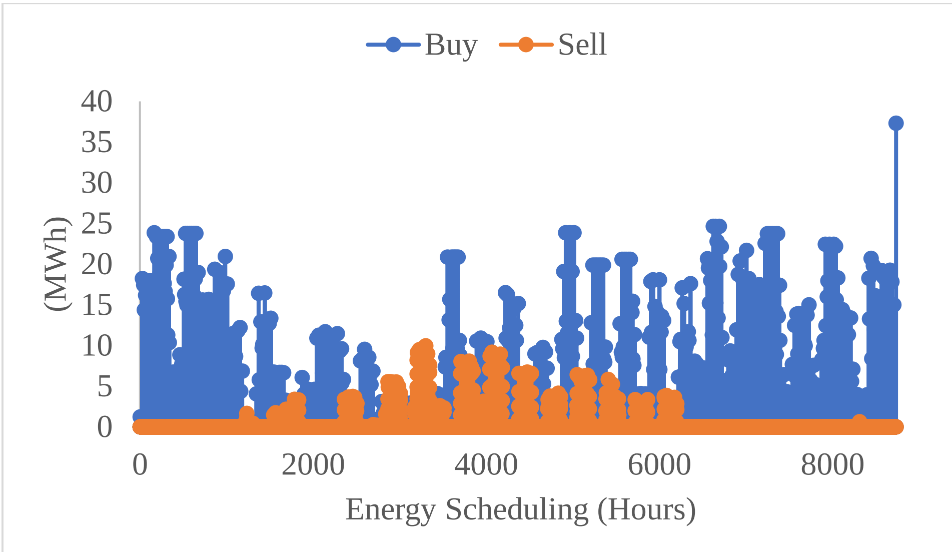

Figure 4.64: Energy purchased and sold for Case 7 in Tucson Factory

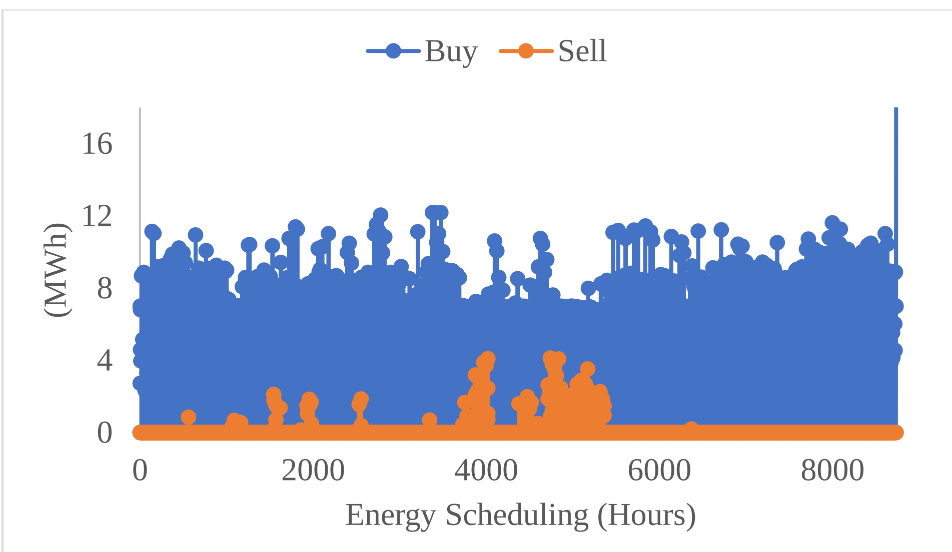

Figure 4.65: Energy purchased and Stored for Case 7 in Las Vegas Warehouse

Case 8

Table 4.20: Case 8 results summary for network 2

Type	Factory				Warehouse		Store			
	1	**2**	**3**	**4**	**1**	**2**	**1**	**2**	**3**	**4**
WT (MW)	0	0	0	0	0	0	2.6	0	0	5.9
PV(MW)	7.3	8.7	6.5	8.1	15	16.5	4.9	9.2	8.6	0
BSS(MWh)	0	0	0	0	0	0	0	0	0	0

In Case 8 we decrease the price of the PV system and make the selling price as $0/MWh. The model chooses to install more PV systems across all facilities. The total system cost for this case is $86,487,885. The results of each facility are shown in Figures 4.67 and 4.76.

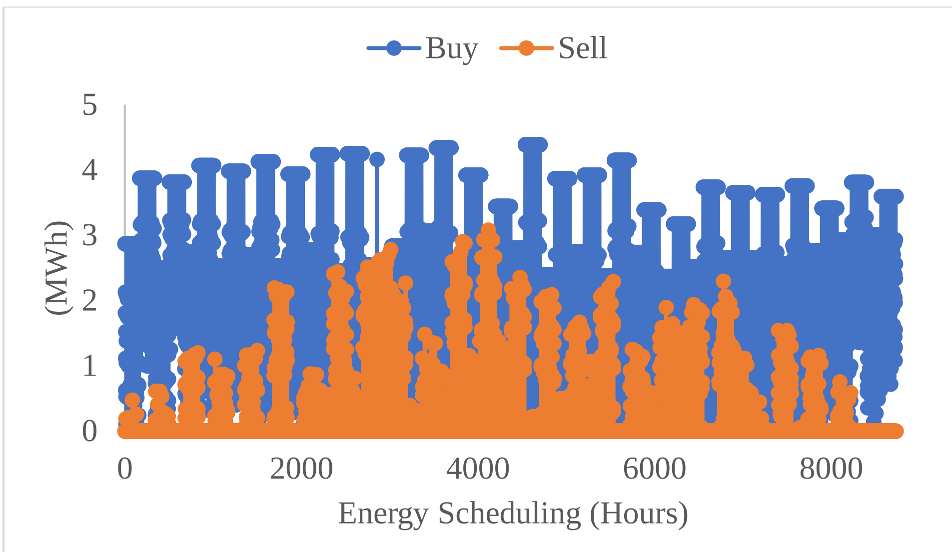

Figure 4.66: Energy purchased and sold for Case 8 in Phoenix Factory

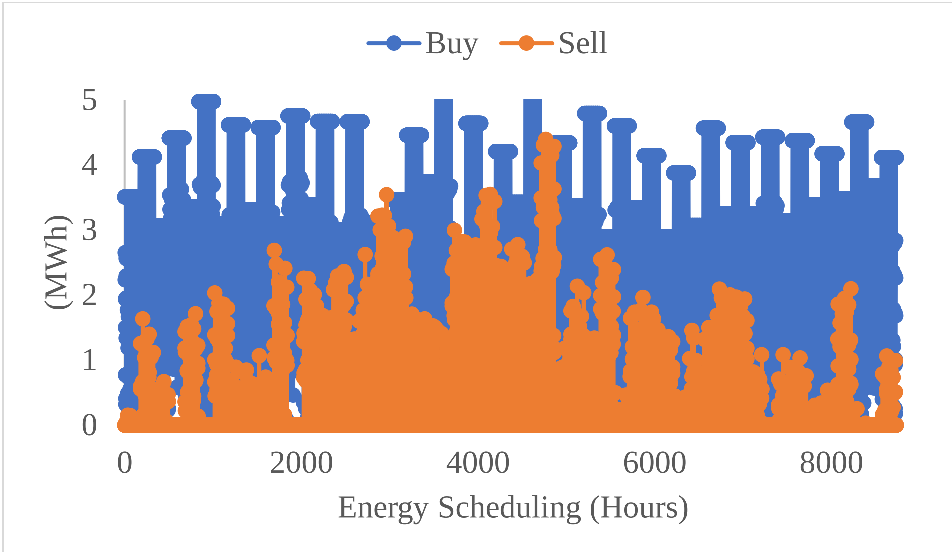

Figure 4.67: Energy purchased and sold for Case 8 in Reno Factory

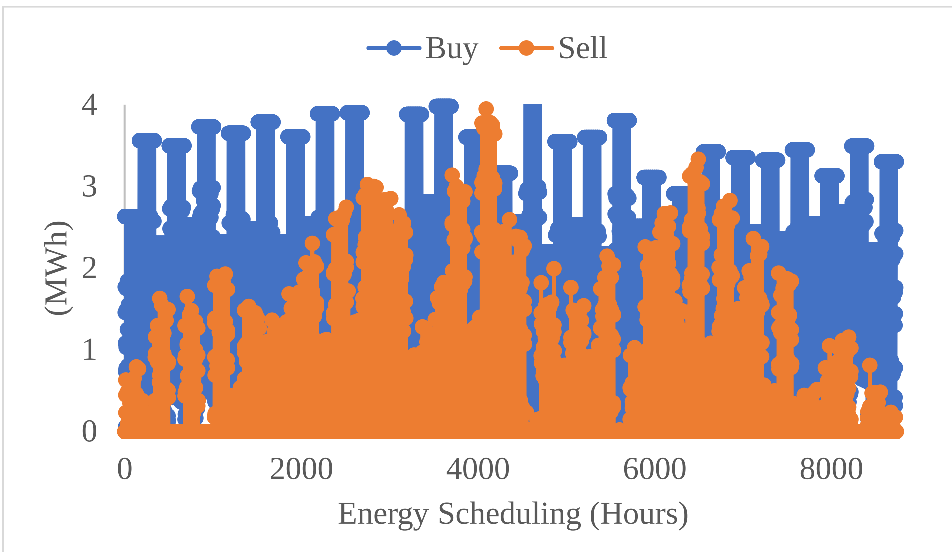

Figure 4.68: Energy purchased and sold for Case 8 in Yuma Factory

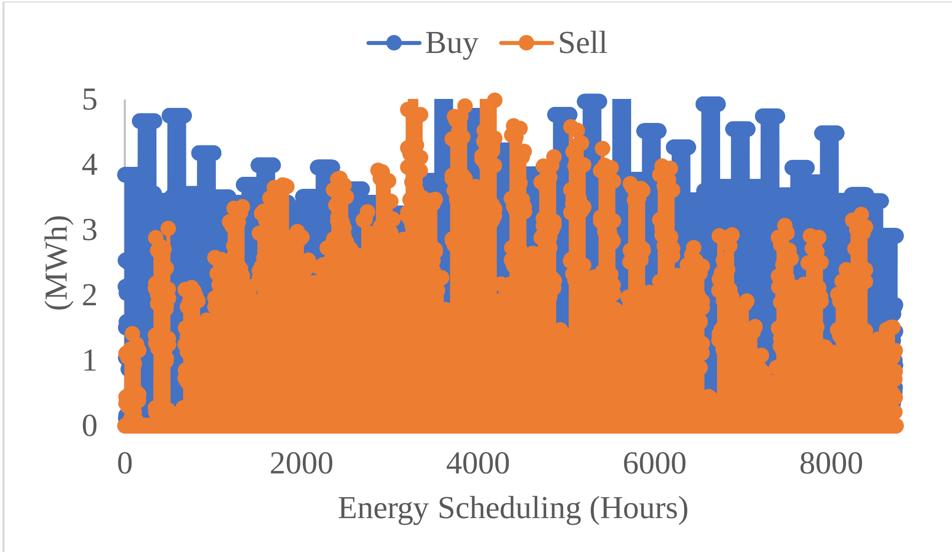

Figure 4.69: Energy purchased and sold for Case 8 in Tucson Factory

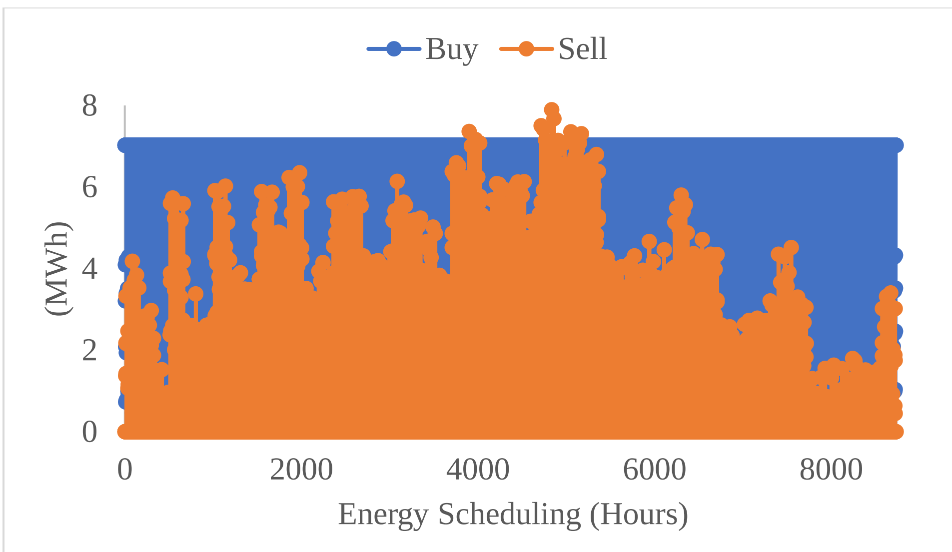

Figure 4.70: Energy purchased and sold for Case 8 in Las Vegas Warehouse

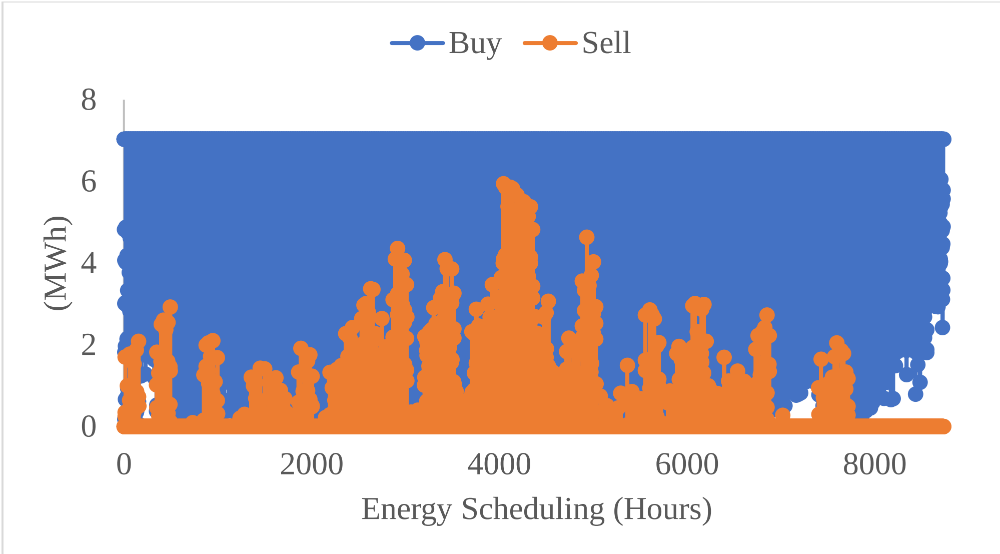

Figure 4.71: Energy purchased and sold for Case 8 in Los Angeles Warehouse

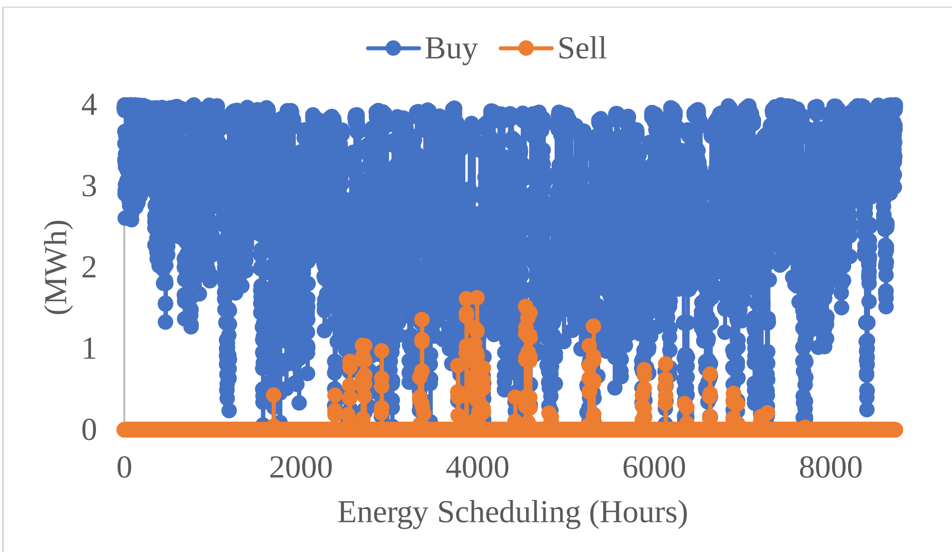

Figure 4.72: Energy purchased and sold for Case 8 in Salt Lake Store

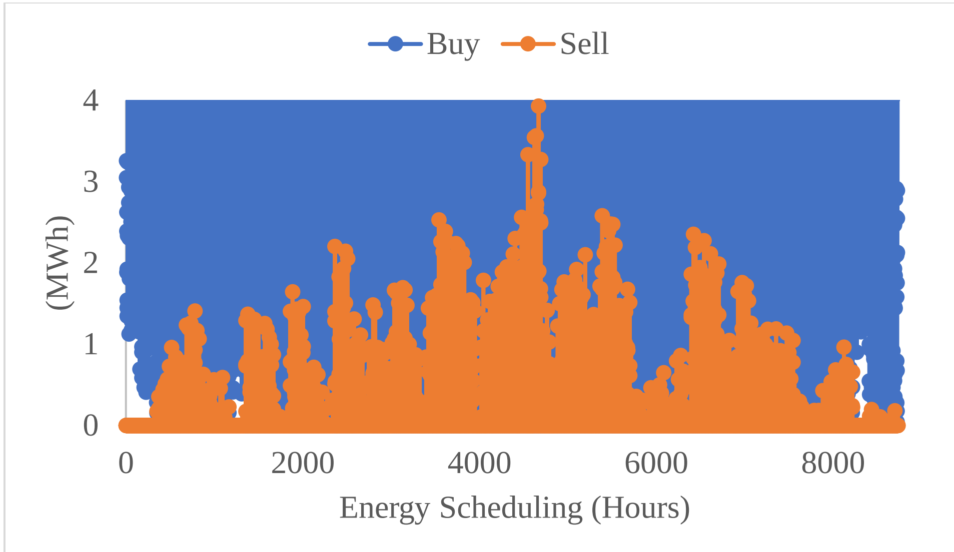

Figure 4.73: Energy purchased and sold for Case 8 in San Jose Store

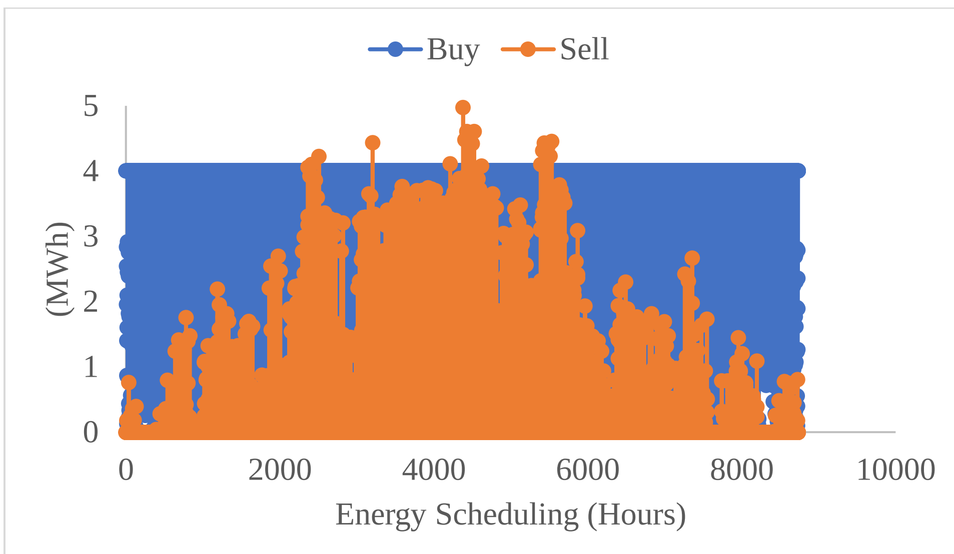

Figure 4.74: Energy purchased and sold for Case 8 in Sacramento Store

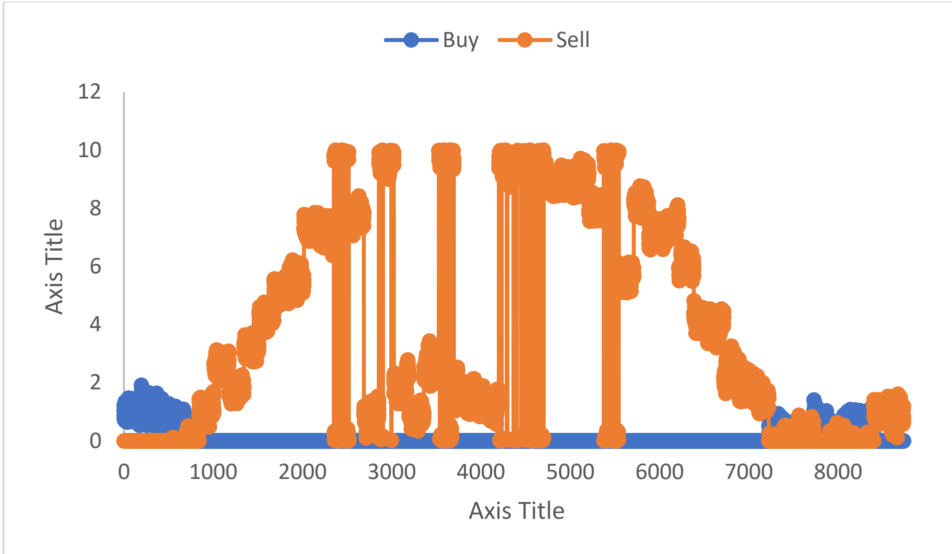

Figure 4.75: Energy purchased and sold for Case 8 in San Francisco Store

5. DESIGN OF VIRTUAL POWER PLANTS FOR MANUFACTURING SUPPLY CHAINS

5.1 Principle of Virtual Power Plants

A virtual power plant (VPP) is a power network formed by distributed energy resources (DER). Typical DER includes wind turbine (WT), solar photovoltaics (PV), combined heat and power (CHP) units as well as electrical and thermal storage systems. The objective of a VPP is to distribute the power generated by small DER units to meet the demand of a community during peak hours or in contingency. The VPP operates in such a way that the DER units can power the facility to which they are connected as well as to sell excess power generated to the utility company or any other facilities within the VPP network. The VPP participates in day-ahead energy market and commits the amount of power supply to maximize its own profit. The core principle behind the operation of a VPP is to link several DER units in such a way that the power generated by individual units can be scheduled or dispatched from a central control station. This control station is responsible for demand and production forecast and bid the energy to be sold in the day ahead market.

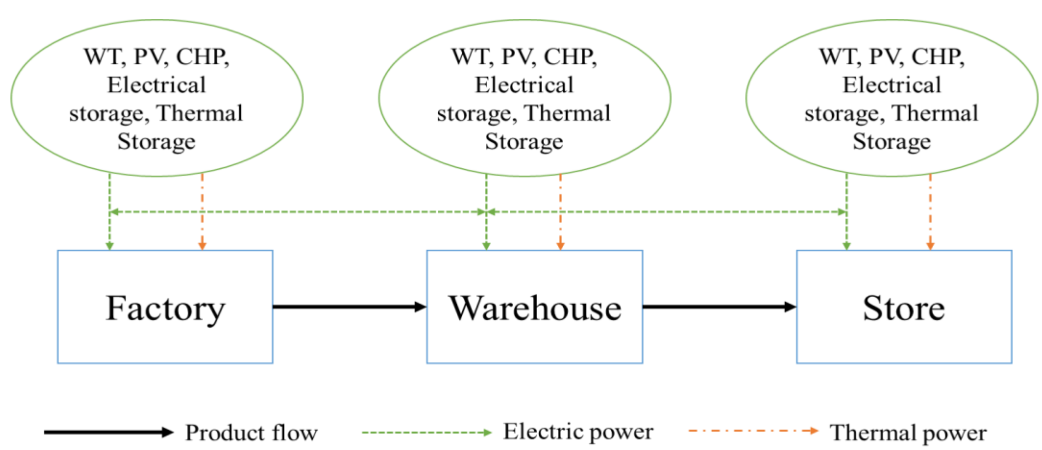

Figure 5.1:Electric and thermal power flow across different facilities

Figure 5.1 shows the layout of a VPP network. Usually the thermal energy is used locally within the facility and electrical energy can be transported between different facilities.

5.2 Modelling of Multi-tier Manufacturing Supply Chain with VPP

In this section, a VPP sizing model comprised of a factory, a warehouse, and a store is formulated. At each facility, WT, PV, CHP, electricity storage (ES) unit, and thermal storage (TS) units are the options to be installed. CHP differs from WT and PV in that it can produce electricity as well as thermal energy. The function of ES units is to store electric energy when surplus power is generated from WT, PV, or CHP. The function of TS is to store heat or thermal energy from CHP. Assuming CHP and TS units have been installed in these facilities, the goal is to determine the size of WT, PV, and ES units to minimize the aggregate energy cost of the VPP system during a year.

5.2.1 One factory, one warehouse, one store VPP setting. In this section, a mixed integer linear programming model to minimize the operational cost of the VPP system is presented. The notation used in formulating the model are as follows,

Sets	**Definition**
T	Number of energy scheduling period in a year.
G	Type of renewable energy generator.
Parameter	**Definition**
ϕ_g	capital recovery factor of renewable energy generator *g*.
a_g	capacity cost for renewable generator *g* (unit: $/MW).
ϕ_{ES}	capital recovery factor of ES system.
d_{ES}	capacity cost for ES system (unit: $/MWh).
o_{ES}	operating cost of ES system (unit: $/MWh/year).
b_g	operation and maintenance cost of renewable generator *g* (unit: $/MWh).
c_g	Carbon credits of renewable generator *g* in the facility (Unit: $/MWh).
λ_{gkt}	Capacity factor of renewable generator *g* in factory at time *t*.
λ_{gnt}	Capacity factor of renewable generator *g* in warehouse at time *t*.
λ_{gst}	Capacity factor of renewable generator *g* in store at time *t*.
τ_g	Operating time of renewable generator *g* in factory in a planning period.

$c_{\mathrm{CHP},k}$ Operating cost of CHP in factory. (unit: $/MWh).
$c_{\mathrm{CHP},n}$ Operating cost of CHP in warehouse. (unit: $/MWh).
$c_{\mathrm{CHP},s,}$ Operating cost of CHP in store. (unit: $/MWh).
$\rho_{DA,k,t}$ Price of day-ahead energy traded by factory at time t (unit: $/MWh).
$\rho_{DA,n,t}$ Price of day-ahead energy traded by warehouse at time t (unit: $/MWh).
$\rho_{DA,s,t}$ Price of day-ahead energy traded by store at time t (unit: $/MWh).
$L_{E,k,}$ Electric power load of factory. (unit: MW).
$L_{E,n,}$ Electric power load of warehouse. (unit: MW).
$L_{E,s,}$ Electric power load of store. (unit: MW).
$L_{TH,k}$ Thermal power load in factory (Unit: MW).
$L_{TH,n}$ Thermal power load in warehouse (Unit: MW).
$L_{TH,s}$ Thermal power load in store (Unit: MW).
$P_{E,CHP,k}^{\max}$ Maximum electric power of CHP in factory (Unit: MW).
$P_{E,CHP,k}^{\min}$ Minimum electric power of CHP in factory (Unit: MW).
$P_{E,CHP,n}^{\max}$ Maximum electric power of CHP in warehouse (Unit: MW).
$P_{E,CHP,n}^{\min}$ Minimum electric power of CHP in warehouse (Unit: MW).
$P_{E,CHP,s}^{\max}$ Maximum electric power of CHP in store (Unit: MW).
$P_{E,CHP,s}^{\min}$ Minimum electric power of CHP in store (Unit: MW).
$P_{TH,CHP,k}^{\max}$ Maximum thermal power of CHP in factory (Unit: MW).
$P_{TH,CHP,k}^{\min}$ Minimum thermal power of CHP in factory (Unit: MW).
$P_{TH,CHP,n}^{\max}$ Maximum thermal power of CHP in warehouse (Unit: MW).
$P_{TH,CHP,n}^{\min}$ Minimum thermal power of CHP in warehouse (Unit: MW).
$P_{TH,CHP,s}^{\max}$ Maximum thermal power of CHP in store (Unit: MW).
$P_{TH,CHP,s}^{\min}$ Minimum thermal power of CHP in store (Unit: MW).
$B_{ES,k}^{\min}$ Minimum capacity limit of ES in factory (Unit: MWh).
$B_{ES,n}^{\min}$ Minimum capacity limit of ES in warehouse (Unit: MWh).
$B_{ES,s}^{\min}$ Minimum capacity limit of ES in store (Unit: MWh).
$B_{TS,k}^{\max}$ Maximum capacity of thermal storage in factory (Unit: MWh).
$B_{TS,k}^{\min}$ Minimum capacity of thermal storage in factory (Unit: MWh).
$B_{TS,n}^{\max}$ Maximum capacity of thermal storage in warehouse (Unit: MWh).
$B_{TS,n}^{\min}$ Minimum capacity of thermal storage in warehouse (Unit: MWh).
$B_{TS,s}^{\max}$ Maximum capacity of thermal storage in store (Unit: MWh).
$B_{TS,s}^{\min}$ Minimum capacity of thermal storage in store (Unit: MWh).
η_{CHP} Electrical efficiency of CHP in the facilities (30-40%).
C_{NG} Natural gas price (unit: $/MWh).
γ_{CHP} Thermal to electric power ratio of CHP in the facilities (2 to 10).

Decision variables	**Definition**
$P^c{}_{gk}$	Power capacity of renewable generator *g* in factory (unit: MW)
$P^c{}_{gn}$	Power capacity of renewable generator *g* in warehouse (unit: MW)
$P^c{}_{gs}$	Power capacity of renewable generation *g* in store (unit: MW)
$B^c{}_{ES,k}$	Capacity of ES in factory (unit: MWh)
$B^c{}_{ES,n}$	Capacity of ES in warehouse (unit: MWh)
$B^c{}_{ES,s}$	Capacity of ES in store (unit: MWh)
$P_{E,CHP,k,t}$	Power output of electricity of CHP in factory at time *t* (unit: MW)
$P_{E,CHP,n,t}$	Power output of electricity of CHP in warehouse at time *t* (unit: MW)
$P_{E,CHP,s,t}$	Power output of electricity of CHP in store at time *t*, (unit: MW)
$B_{ES,k,t}$	Electricity stored in ES in factory at time *t* (unit: MWh)
$B_{ES,n,t}$	Electricity stored in ES in warehouse at time *t* (unit: MWh)
$B_{ES,s,t}$	Electricity stored in ES in store at time *t* (unit: MWh)
$P_{TH,CHP,k,t}$	Thermal power output of CHP in factory at time *t*. (Unit is MW)
$P_{TH,CHP,n,t}$	Thermal Power output of CHP in warehouse at time *t*. (Unit is MW)
$P_{TH,CHP,s,t}$	Thermal Power output of CHP in store at time *t*. (Unit is MW)
$B_{TS,k,t}$	Thermal energy stored in factory at time *t*. (Unit is MWh)
$B_{TS,n,t}$	Thermal energy stored in warehouse at time *t*. (Unit is MWh)
$B_{TS,s,t}$	Thermal energy stored in store at time *t*. (Unit is MWh)

Model 5.1

Minimize

$$\begin{aligned} & f(\mathbf{P}^c, \mathbf{B}^c, \mathbf{P_E}) \\ &= \sum_{g=1}^{G} \phi_g a_g P_{gk}^c + (\phi_{ES} d_{ES} + o_{ES}) B_{ES,k}^c + \sum_{g=1}^{G} \sum_{t=1}^{T} (b_g - c_g) \lambda_{gkt} P_{gk}^c \tau_g + \sum_{t=1}^{T} c_{CHP} P_{E,CHP,k,t} \tau - \sum_{t=1}^{T} \rho_{DA,k,t} P_{DA,k,t} \tau \\ &+ \sum_{g=1}^{G} \phi_g a_g P_{gn}^c + (\phi_{ES} d_{ES} + o_{ES}) B_{ES,n}^c + \sum_{g=1}^{G} \sum_{t=1}^{T} (b_g - c_g) \lambda_{gnt} P_{gn}^c \tau_g + \sum_{t=1}^{T} c_{CHP} P_{E,CHP,n,t} \tau - \sum_{t=1}^{T} \rho_{DA,n,t} P_{DA,n,t} \tau \\ &+ \sum_{g=1}^{G} \phi_g a_g P_{gs}^c + (\phi_{ES} d_{ES} + o_{ES}) B_{ES,s}^c + \sum_{g=1}^{G} \sum_{t=1}^{T} (b_g - c_g) \lambda_{gst} P_{gs}^c \tau_g + \sum_{t=1}^{T} c_{CHP} P_{E,CHP,s,t} \tau - \sum_{t=1}^{T} \rho_{DA,s,t} P_{DA,s,t} \tau \end{aligned} \tag{5.1}$$

Subject to:

$$\sum_{g=1}^{G} \lambda_{gkt} P_{gk}^c \tau - B_{ES,k,t} + B_{ES,k,t-1} + P_{E,CHP,k,t} \geq L_{E,k} + P_{DA,k,t} \text{, for } t=1, 2, \ldots, T \tag{5.2}$$

$$\sum_{g=1}^{G}\lambda_{gnt}P_{gn}^{c}\tau - B_{ES,n,t} + B_{ES,n,t-1} + P_{E,CHP,n,t} \geq L_{E,n} + P_{DA,n,t}\text{, for } t=1, 2, \ldots, T \tag{5.3}$$

$$\sum_{g=1}^{G}\lambda_{gst}P_{gs}^{c}\tau - B_{ES,s,t} + B_{ES,s,t-1} + P_{E,CHP,s,t} \geq L_{E,s} + P_{DA,s,t}\text{, for } t=1, 2, \ldots, T \tag{5.4}$$

$$P_{TH,CHP,k,t} - B_{TS,k,t} + B_{TS,k,t-1} \geq L_{TH,k}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.5}$$

$$P_{TH,CHP,n,t} - B_{TS,n,t} + B_{TS,n,t-1} \geq L_{TH,n}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.6}$$

$$P_{TH,CHP,s,t} - B_{TS,s,t} + B_{TS,s,t-1} \geq L_{TH,s}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.7}$$

$$P_{E,CHP,k}^{\min} \leq P_{E,CHP,k,t} \leq P_{E,CHP,k}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.8}$$

$$P_{E,CHP,n}^{\min} \leq P_{E,CHP,n,t} \leq P_{E,CHP,n}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.9}$$

$$P_{E,CHP,s}^{\min} \leq P_{E,CHP,s,t} \leq P_{E,CHP,s}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.10}$$

$$P_{TH,CHP,k}^{\min} \leq P_{TH,CHP,k,t} \leq P_{TH,CHP,k}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.11}$$

$$P_{TH,CHP,n}^{\min} \leq P_{TH,CHP,n,t} \leq P_{TH,CHP,n}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.12}$$

$$P_{TH,CHP,s}^{\min} \leq P_{TH,CHP,s,t} \leq P_{TH,CHP,s}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T. \tag{5.13}$$

$$B_{ES,k}^{\min} \leq B_{ES,k,t} \leq B_{ES,k}^{c}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.14}$$

$$B_{ES,n}^{\min} \leq B_{ES,n,t} \leq B_{ES,n}^{c}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.15}$$

$$B_{ES,s}^{\min} \leq B_{ES,s,t} \leq B_{ES,s}^{c}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.16}$$

$$B_{TS,k}^{\min} \leq B_{TS,k,t} \leq B_{TS,k}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.17}$$

$$B_{TS,n}^{\min} \leq B_{TS,n,t} \leq B_{TS,n}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T \tag{5.18}$$

$$B_{TS,s}^{\min} \leq B_{TS,s,t} \leq B_{TS,s}^{\max}\text{,} \quad \text{for } t=1, 2, \ldots, T. \tag{5.19}$$

$$c_{CHP,k,t} = \frac{c_{NG,k}}{\eta_{CHP,k,t}}, \qquad \text{for } t=1, 2, \ldots, T \tag{5.20}$$

$$c_{CHP,n,t} = \frac{c_{NG,n}}{\eta_{CHP,n,t}}, \qquad \text{for } t=1, 2, \ldots, T \tag{5.21}$$

$$c_{CHP,s,t} = \frac{c_{NG,s}}{\eta_{CHP,s,t}}, \qquad \text{for } t=1, 2, \ldots, T \tag{5.22}$$

$$P_{TH,CHP,k} = \gamma_{CHP,k} P_{E,CHP,k,t}, \qquad \text{for } t=1, 2, \ldots, T \tag{5.23}$$

$$P_{TH,CHP,n} = \gamma_{CHP,n} P_{E,CHP,n,t}, \qquad \text{for } t=1, 2, \ldots, T. \tag{5.24}$$

$$P_{TH,CHP,s} = \gamma_{CHP,s} P_{E,CHP,s,t}, \qquad \text{for } t=1, 2, \ldots, T \tag{5.25}$$

The objective function in equation (5.1) minimizes the total annualized cost of the VPP system, where the summation terms 1-5 indicate the cost associated with the factory, the summation terms 6-10 are the cost associated with the warehouse and the summation terms 11-15 depicts the cost associated with the store. The first term is the installation cost of the renewable generator *g*, the second term is the installation and operating cost of the BSS units. The third term indicates the annual operations and maintenance cost and the carbon credits of the renewable generator *g*. The fourth term is the operations cost of the CHP and the electrical power output of the CHP unit. The fifth term represents the total revenue obtained by selling electricity in the day-ahead energy market. The definition of each term is the same for the factory, warehouse, and store.

Constraints (5.2) to (5.4) represent the electrical power balance at the factory, warehouse, and store, respectively. The power from the renewables, CHP and ES units must meet the local electrical demand of the facility and the power traded to the energy market. Constraints (5.5) to (5.7) constitute the thermal power balance at the factory, warehouse, and store, respectively. The thermal power from the CHP and TS units must meet the local thermal demand of the facility. Constraints (5.8) to (5.10) are the electrical output limits of CHP units at the facilities. Constraints (5.11) to (5.13) are the thermal output limits of CHP units at the facilities. Constraints (5.14) to (5.16) are the electrical energy storage limit. Constraints (5.17) to (5.19) are the thermal storage limit. The output power falls in a specific range. Constraints (5.20) to (5.22) depict the electrical output efficiency of CHP unit. Constraints (5.23) to (5.25) indicate the connection between thermal power and electrical power of the CHP unit.

Table 5.1: Summary of Model 5.1 test cases

Case	Change in parameters
1	Power trading is 50% of facility load and variation is 5%
2	Power trading is 100% of facility load and variation is 5%
3	Power trading is100% of facility load and variation is 20%
4	PV capacity cost is $1M/MW
5	Battery Capacity Cost is $0.1M/MWh, O_{ES}=$0.0025M/MWh/year
6	Battery Capacity Cost is $0.05M/MWh, O_{ES}=$0.00125M/MWh/year
7	Using TOU rate for selling price to the grid
8	Natural gas price is $15/MWh

5.2.2 Numerical experiments. The model is tested on a supply chain with one factory, one warehouse, and one store. The factory is located in San Francisco, California, the warehouse is in Las Vegas, Nevada, and the store is in Phoenix, Arizona. All the facilities are powered by a microgrid of its own which is comprised of WT, PV, CHP, ES and TS units. All the facilities participate in VPP initiative in which the facilities bid on the day-ahead energy market. The facilities commit the amount of energy it can sell to the main grid 24 hours in advance for a selling price. We also assume that CHP and TS units are already installed in the facilities. Hence the decisions are the sizing of WT, PV and ES units.

Table 5.2: Experimental data for Model 5.1

Parameter	Value	Parameter	Value
T	8736 hours	ρ_{DA}	$70/MWh
G	2	$L_{E,k,t}$	5 MW
τ	1 hour	$L_{E,n,t}$	3 MW
τ_g	1 hour	$L_{E,s,t}$	2 MW
a_g	$1.5M/MW for WT, $2M/MW for PV	$L_{TH,chp,k,t}$	7 MW
d_{ES}	$0.3M/MWh	$L_{TH,n,t}$	6 MW
o_{ES}	0.0075M/MWh/year	$L_{TH,s,t}$	5 MW
b_g	$8/MWh for WT, $4/MWh for PV	η_{CHP}	0.35
c_g	$0/MWh for WT, $10/MWH for PV	c_{NG}	$7/MWh
ϕ_g	0.08024 for both WT and PV	γ_{CHP}	2
ϕ_{ES}	0.12	-	-

Case 1

Case 1 is treated as a benchmark case for solving the VPP Model. The parameters involved in solving the Model is given in Table 5.2. Model 5.1 is solved in AMPL using CPLEX solver.

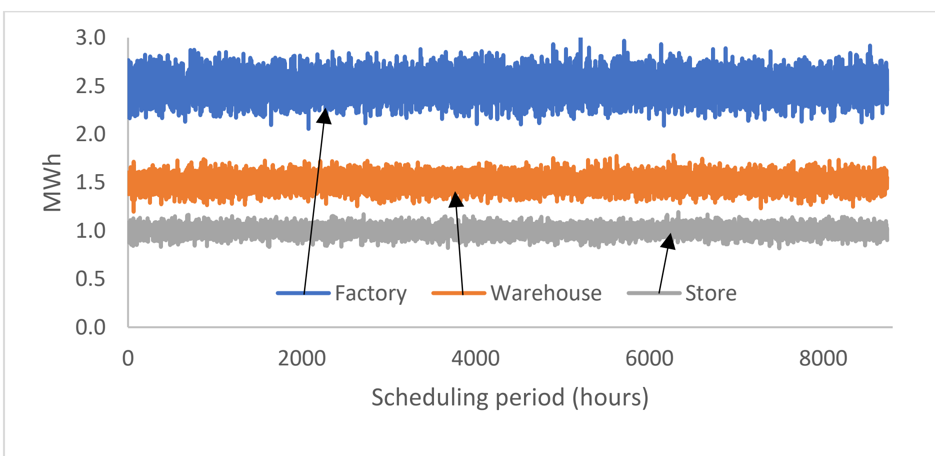

Figure 5.2: Day-ahead energy commitment for Case 1

Assume the maximum electrical power output from the CHP unit $P_{E,CHP}^{\max}$ at the factory, warehouse and store is 6 MW, 4 MW, and 3 MW, respectively. The minimum is 0 MW. The maximum thermal power output from the CHP unit $P_{TH,CHP}^{\max}$ are 12 MW, 8 MW, and 6 MW, respectively, at factory, warehouse and store. The minimum thermal output is 0 MW. The maximum capacity of the thermal storage across all facilities are 30 MWh. The day-ahead energy market commitment of each facility is given in Figure 5.2. Using these parameters, we compute the benchmark case for Model 5.1. The results of DER sizing are given in Table 5.3 and the intermediate results of electrical and thermal outputs of the CHP units are shown in Figures 5.3 and 5.4.

Table 5.3: Model 5.1 Case 1 results summary

Type	Factory	Warehouse	Store
WT (MW)	11	0	0.07
PV (MW)	0	3.09	0.08
BSS (MWh)	2.85	6.26	0.42
System cost ($)	1,427,973		

In this case, 11 MW of WT is installed at the factory in San Francisco which is usually considered to be a high wind location. The factory base load is 5 MW. The higher installation is because the system can bring income by selling the excess energy to the main grid. The system cost is inclusive of the money spent for installation of the units as well as the revenue generated from selling the money to the grid. ES units store energy from WT and PV as well as the electrical power output from CHP. In Las Vegas, PV installation dominates as the location has larger sunshine throughout the year. Load at the store is very small compared to other facilities, hence the PV installation is relatively small.

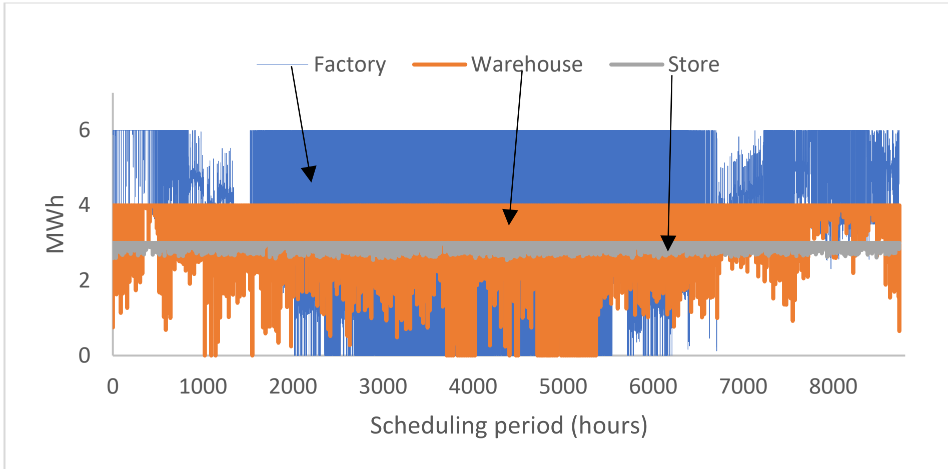

Figure 5.3: CHP electrical output for Case 1

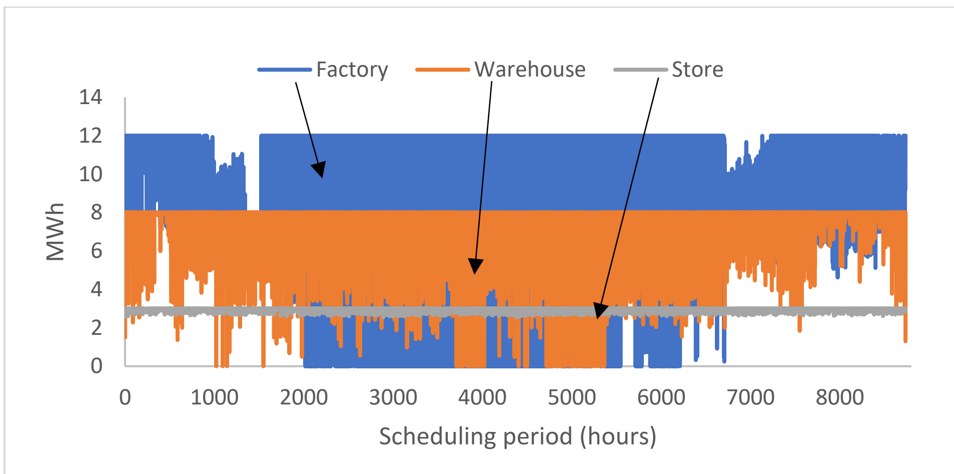

Figure 5.4: CHP thermal output for Case 1

Case 2

Table 5.4: Model 5.1 Case 2 results summary

Type	Factory	Warehouse	Store
WT (MW)	30	0	16.6
PV (MW)	0	12.8	2.7
BSS (MWh)	5.5	23.4	10.4
System cost ($)	6,272,066		

The energy which is the committed by the VPP to sell to the main grid in the day-ahead market is increased to 100% of the total electrical load at the facilities with 5%

variation and is shown in Figure 5.5. In this case, the VPP should sell more power to the grid. Hence the installation of DER and ES units are higher compared to Case 1. Higher energy bid to be sold in the market leads to higher DER installation. There is a 125% increase in the total system cost of the network. The electrical and thermal output of the CHP are given in Figures 5.6 and 5.7.

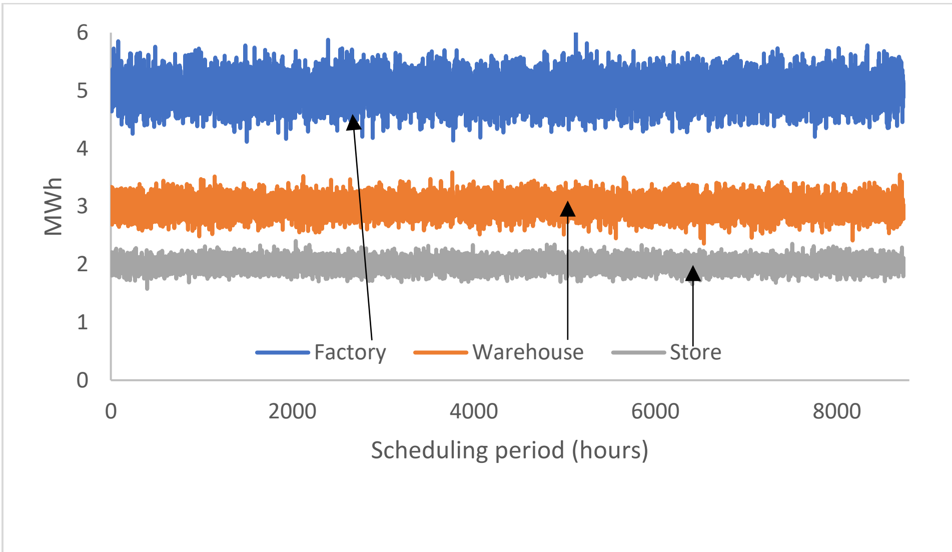

Figure 5.5: Day-ahead energy commitment for Case 2

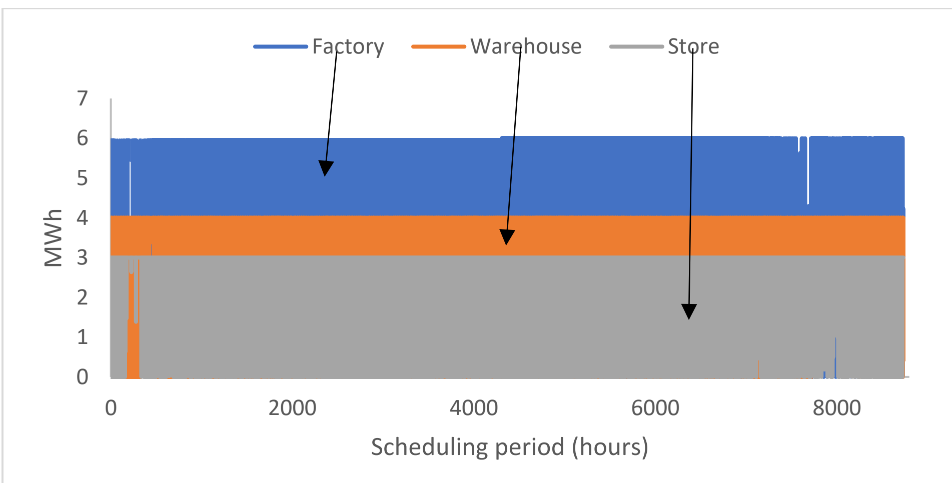

Figure 5.6: CHP electrical output for Case 2

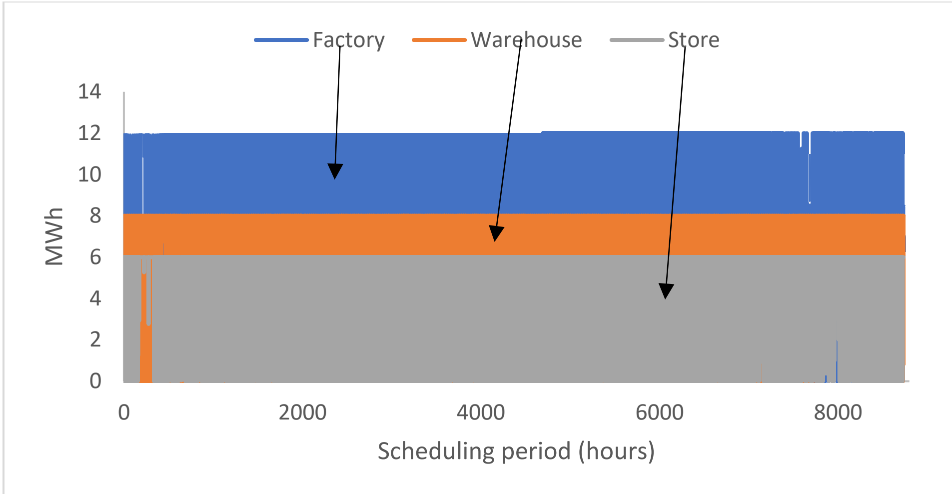

Figure 5.7: CHP thermal output for Case 2

Case 3

Table 5.5: Model Case 3 results summary

Type	Factory	Warehouse	Store
WT (MW)	31.5	0.1	18.2
PV (MW)	0	12.4	2.5
ES (MWh)	5.6	29	10.9
System cost ($)	6,887,916		

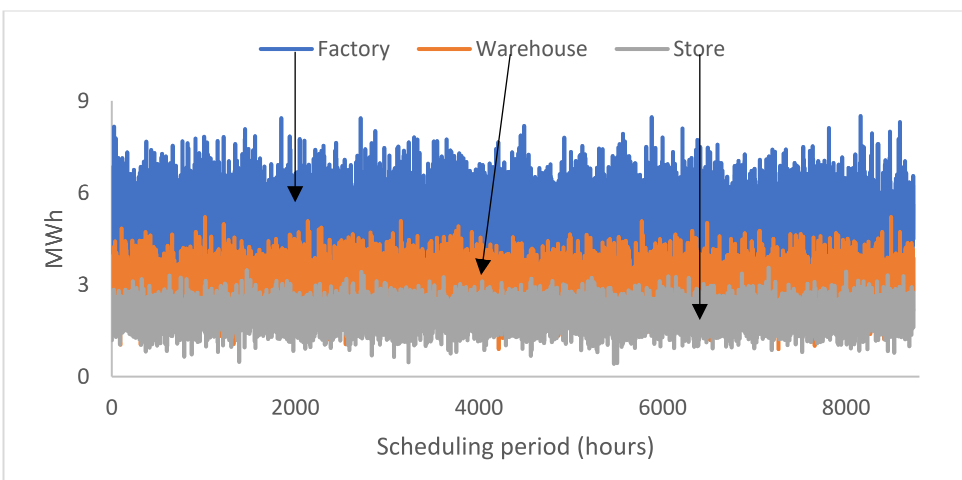

Figure 5.8: Day-ahead energy commitment for Case 3

The amount of energy to the traded to the main gird has 20% variation in Case 3. The decision on installation capacity is higher in Case 3 compared to benchmark Case 1. Factory installs 31.5MW WT, more PV installation is seen at the warehouse location, the system chooses to install 18.2MW WT and 2.5MW PV at the location of the store. The intermediate electrical and thermal output for Case 3 is discussed in Figures 5.9 and 5.10.

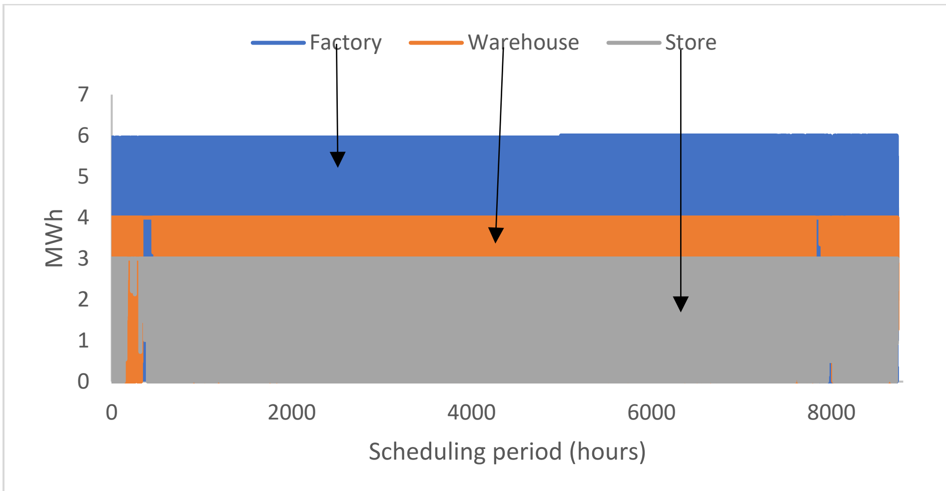

Figure 5.9: CHP electrical output for Case 3

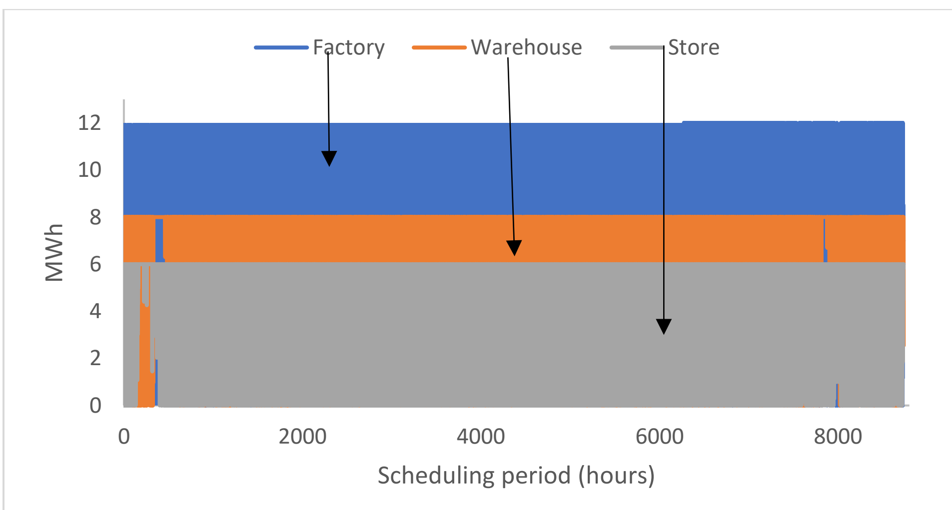

Figure 5.10: CHP thermal output for Case 3

Case 4

Table 5.6:Model 5.1 Case 4 results summary

Type	Factory	Warehouse	Store
WT (MW)	8.9	0	0.1
PV (MW)	3.3	3.1	0.1
ES (MWh)	3.9	6.3	0.4
System cost ($)	1,133,042		

Case 4 is solved by decreasing the PV capacity cost from $2M/MW in the benchmark Case to $1M/MW. The system installs more PV in San Francisco (Factory) compared to no PV installation in Case 1. Although, San Francisco is a windy city and the efficiency of WT operation is better due to low PV cost the model decides to install PV therefore reducing the total system cost as well. The intermediate electrical and thermal outputs for Warehouse and Store remains the same as Case 1. Figure shows the electrical and thermal output for Factory.

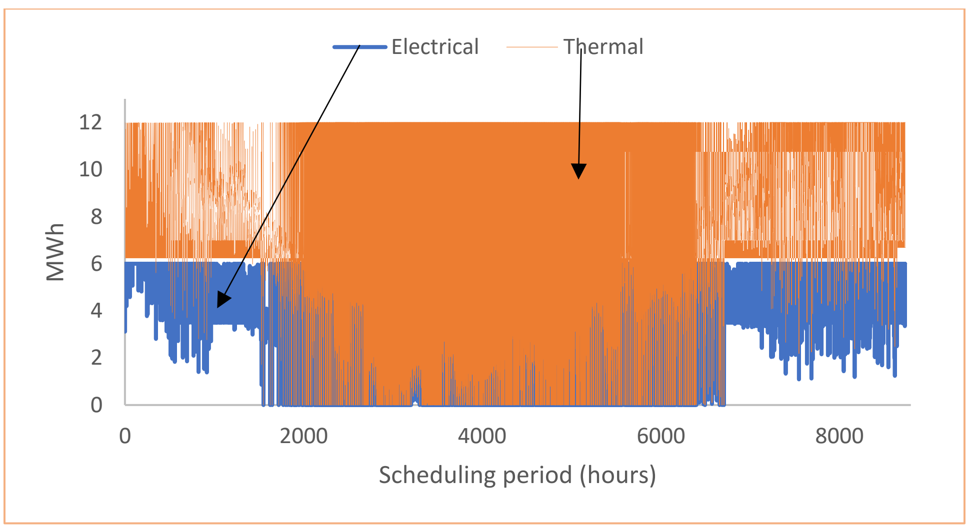

Figure 5.11: CHP outputs in Factory for Case 4

Case 5

Table 5.7:Model 5.1 Case 5 results summary

Type	Factory	Warehouse	Store
WT (MW)	10.3	0	0
PV (MW)	0	3	0.1
ES (MWh)	5.5	6.7	0.9
System cost ($)	1,071,036		

In Case 5, we solve the problem by reducing the battery installation and operations cost to $0.1M/MWh. More battery installation can be observed across all the facilities compared to Case 1. The total system cost of the VPP network is also reduced.

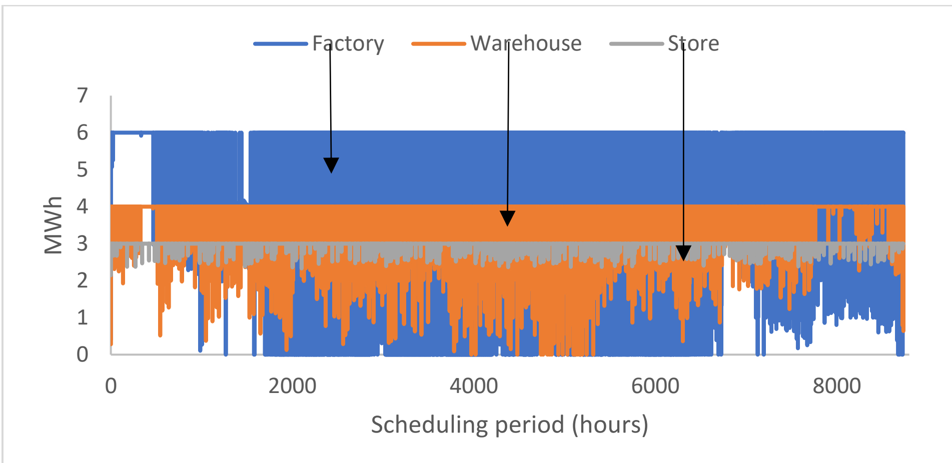

Figure 5.12: CHP electrical output for Case 5

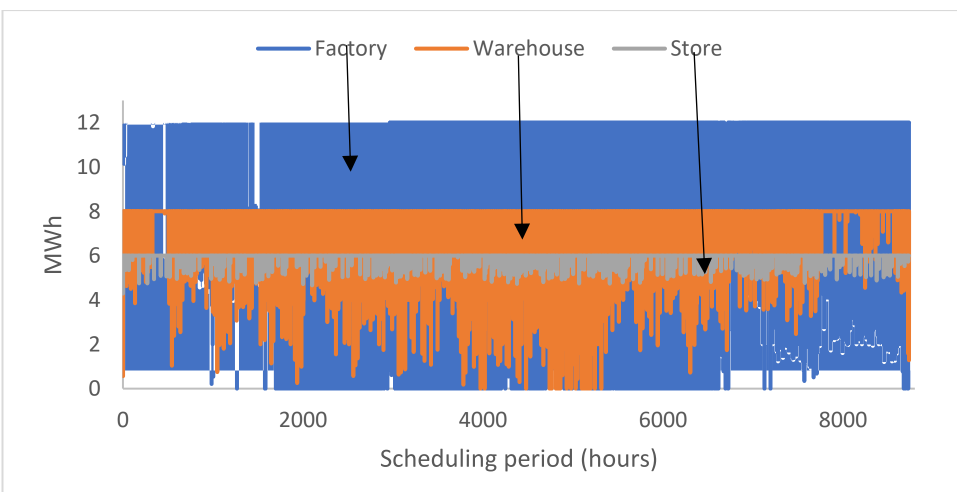

Figure 5.13: CHP thermal output for Case 5

Case 6

Table 5.8: Model 5.1 Case 6 results summary

Type	Factory	Warehouse	Store
WT (MW)	10.3	0	0
PV (MW)	0	3	0.1
ES (MWh)	5.5	6.7	0.9
System cost ($)	975,589		

In case 6, we further reduce the battery capacity cost to $0.05M/MWh to test the behavior of the model. In spite cheap cost of the battery there is no significant change on the decision made by the system when compared with Case 5. The total system cost reduces due to reduction in the battery cost.

Case 7

Table 5.9: Model 5.1 Case 7 results summary

Type	Factory	Warehouse	Store
WT (MW)	11	0	0.07
PV (MW)	0	3.09	0.08
ES (MWh)	2.85	6.26	0.42
System cost ($)	-99,660		

In Case 7, TOU policy is used for determining the selling price of energy in the day ahead market. The selling price is $140/MWh from 10am to 9pm and the price is $70/MWh from 10pm to 9am. In this Case we can observe that the system is making a profit, but the installation capacities remains same as Case 1. The installation capacity and the intermediate results remain the same as Case 1. In this case the system is making a profit of $99,660.

Case 8

Table 5.10: Case 8 results summary

Type	Factory	Warehouse	Store
WT (MW)	11.2	0	0.07
PV (MW)	0	3.09	0.08
ES (MWh)	2.4	6.26	0.42
System cost ($)	3,592,743		

In Case 8, we increase the natural gas price from $7/MWh to $15/MWh. There is a slight change in the installation capacities at the factory. The system cost increases by 86% in this Case. Other installations remain the same as the benchmark.

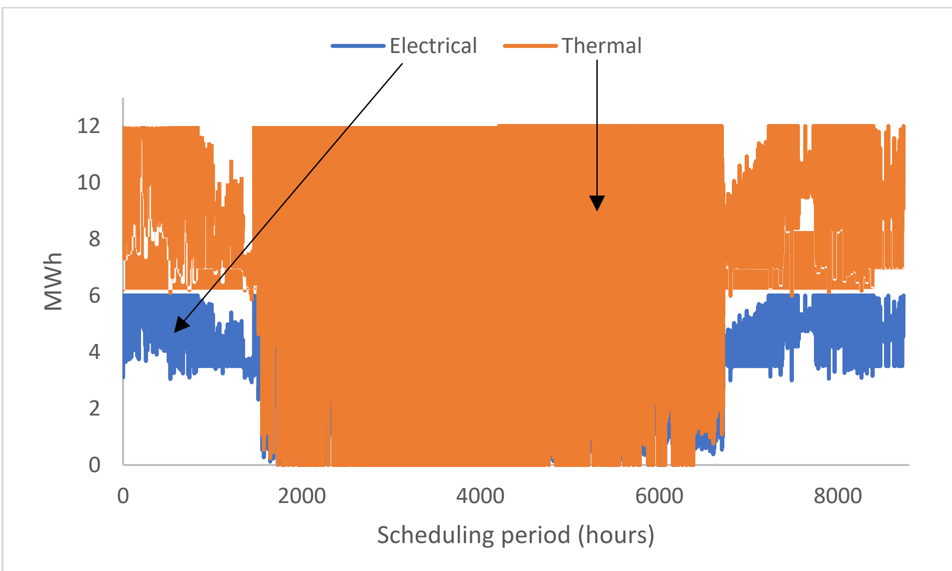

Figure 5.14: CHP thermal output for Case 8

Table 5.11: Model 5.1 system cost summary

Case	Cost ($)	Cost difference	Difference in %
1	1,427,973	-	0
2	6,272,066	-4,844,093	125.8
3	6,887,916	-5,459,943	131.3
4	1,133,042	294,931	23.0
5	789,272	638,701	57.6
6	975,588	452,385	37.6
7	3,592,743	-2,164,770	86.2

5.3 Profit Maximization Problem

In this section, a profit maximization problem for a manufacturing supply chain with one factory, one warehouse and one store operating as a VPP is introduced. This profit maximization problem includes revenue from selling excess electricity to the grid and selling excess thermal energy locally. It also includes the cost of installing the units at each facility. The profit is given by,

$$\text{Profit} = \text{VPP}_{\text{Revenue}} - \text{VPP}_{\text{Cost}} \tag{5.26}$$

Similar to the previous model each facility opts to install a microgrid comprised of heterogenous DG system such as WT, PV and CHP units, electricity storage and thermal storage units. The planning horizon is one year. The model notation is similar as in section 5.2.1. New parameters and decision variables are as follows,

Parameter	**Definition**
$\rho_{TH,k,t}$	Price of day-ahead thermal power traded by factory (unit: $/MWh).
$\rho_{TH,n,t}$	Price of day-ahead thermal power traded by warehouse (unit: $/MWh).
$\rho_{TH,s,t}$	Price of day-ahead thermal power traded by store at time t (unit: $/MWh).
ϕ_{CHP}	Capital recovery factor of CHP unit.
a_{CHP}	Capacity cost for CHP unit. (unit: $/MW).
ϕ_{TS}	Capital recovery factor of thermal storage unit.

d_{TS}	Capacity cost for thermal storage system (unit: \$/MWh).
o_{TS}	Operating cost of thermal storage system (unit: \$/MWh/year)

Decision variables	**Definition**
$P^c_{CHP,k}$	Capacity of CHP unit at factory (Unit: MW)
$P^c_{CHP,n}$	Capacity of CHP unit at warehouse (Unit: MW)
$P^c_{CHP,s}$	Capacity of CHP unit at store (Unit: MW)
$B^c_{TS,k}$	Capacity of thermal storage unit at factory (Unit: MWh)
$B^c_{TS,n}$	Capacity of thermal storage unit at warehouse (Unit: MWh)
$B^c_{TS,s}$	Capacity of thermal storage unit at store (Unit: MWh)

Model 5.2

Maximize

$$
\begin{aligned}
f_2(\mathbf{P}^c,\mathbf{B}^c) = &\sum_{t=1}^{T}\rho_{DA,k,t}P_{DA,k,t}\tau + \sum_{t=1}^{T}\rho_{TH,k,t}(P_{TH,CHP,k,t}-L_{TH,k,t})\tau + \sum_{t=1}^{T}\sum_{g=1}^{G}c_{gk}\lambda_{gkt}P^c_{gk}\tau_{gk} \\
&+\sum_{t=1}^{T}\rho_{DA,n,t}P_{DA,n,t}\tau + \sum_{t=1}^{T}\rho_{TH,n,t}(P_{TH,CHP,n,t}-L_{TH,k,t})\tau + \sum_{t=1}^{T}\sum_{g=1}^{G}c_{gk}\lambda_{gnt}P^c_{gn}\tau_{gk} \\
&+\sum_{t=1}^{T}\rho_{DA,s,t}P_{DA,s,t}\tau + \sum_{t=1}^{T}\rho_{TH,s,t}(P_{TH,CHP,s,t}-L_{TH,s,t})\tau + \sum_{t=1}^{T}\sum_{g=1}^{G}c_{gk}\lambda_{gst}P^c_{gs}\tau_{gk} \\
&-\sum_{g=1}^{G}\phi_g a_g P^c_{gk} - \sum_{t=1}^{T}\sum_{g=1}^{G}b_{gk}\lambda_{gkt}P^c_{gk}\tau_{gk} - \phi_{CHP}a_{CHP}P^c_{CHP,k} - \sum_{t=1}^{T}c_{CHP,k,t}P_{E,CHP,k,t}\tau \\
&-(\phi_{ES}d_{ES}+o_{ES})B^c_{ES,k} - (\phi_{TS}d_{TS}+o_{TS})B^c_{TS,k} \\
&-\sum_{g=1}^{G}\phi_g a_g P^c_{gn} - \sum_{t=1}^{T}\sum_{g=1}^{G}b_{gk}\lambda_{gnt}P^c_{gn}\tau_{gk} - \phi_{CHP}a_{CHP}P^c_{CHP,n} - \sum_{t=1}^{T}c_{CHP,n,t}P_{E,CHP,n,t}\tau \\
&-(\phi_{ES}d_{ES}+o_{ES})B^c_{ES,n} - (\phi_{TS}d_{TS}+o_{TS})B^c_{TS,n} \\
&-\sum_{g=1}^{G}\phi_g a_g P^c_{gs} - \sum_{t=1}^{T}\sum_{g=1}^{G}b_{gk}\lambda_{gst}P^c_{gs}\tau_{gk} - \phi_{CHP}a_{CHP}P^c_{CHP,s} - \sum_{t=1}^{T}c_{CHP,s,t}P_{E,CHP,s,t}\tau \\
&-(\phi_{ES}d_{ES}+o_{ES})B^c_{ES,s} - (\phi_{TS}d_{TS}+o_{TS})B^c_{TS,s}
\end{aligned}
\tag{5.27}
$$

Subject to

$$\sum_{g=1}^{G} \lambda_{gkt} P_{gk}^{c} \tau - B_{ES,k,t} + B_{ES,k,t-1} + P_{E,CHP,k,t} = L_{E,k} + P_{DA,k,t}, \text{ for } t=1, 2, \ldots, T \tag{5.28}$$

$$\sum_{g=1}^{G} \lambda_{gnt} P_{gn}^{c} \tau - B_{ES,n,t} + B_{ES,n,t-1} + P_{E,CHP,n,t} = L_{E,n} + P_{DA,n,t}, \text{ for } t=1, 2, \ldots, T \tag{5.29}$$

$$\sum_{g=1}^{G} \lambda_{gst} P_{gs}^{c} \tau - B_{ES,s,t} + B_{ES,s,t-1} + P_{E,CHP,s,t} = L_{E,s} + P_{DA,s,t}, \text{ for } t=1, 2, \ldots, T \tag{5.30}$$

$$P_{TH,CHP,k,t} - B_{TS,k,t} + B_{TS,k,t-1} \geq L_{TH,k}, \quad \text{for } t=1, 2, \ldots, T \tag{5.31}$$

$$P_{TH,CHP,n,t} - B_{TS,n,t} + B_{TS,n,t-1} \geq L_{TH,n}, \quad \text{for } t=1, 2, \ldots, T \tag{5.32}$$

$$P_{TH,CHP,s,t} - B_{TS,s,t} + B_{TS,s,t-1} \geq L_{TH,s}, \quad \text{for } t=1, 2, \ldots, T \tag{5.33}$$

$$P_{E,CHP,k}^{\min} \leq P_{E,CHP,k,t} \leq P_{CHP,k}^{c}, \quad \text{for } t=1, 2, \ldots, T \tag{5.34}$$

$$P_{E,CHP,n}^{\min} \leq P_{E,CHP,n,t} \leq P_{CHP,n}^{c}, \quad \text{for } t=1, 2, \ldots, T \tag{5.35}$$

$$P_{E,CHP,s}^{\min} \leq P_{E,CHP,s,t} \leq P_{CHP,s}^{c}, \quad \text{for } t=1, 2, \ldots, T \tag{5.36}$$

$$P_{TH,CHP,k}^{\min} \leq P_{TH,CHP,k,t} \leq \gamma_{CHP,k} P_{CHP,k}^{c}, \quad \text{for } t=1, 2, \ldots, T \tag{5.37}$$

$$P_{TH,CHP,n}^{\min} \leq P_{TH,CHP,n,t} \leq \gamma_{CHP,n} P_{CHP,n}^{c}, \quad \text{for } t=1, 2, \ldots, T \tag{5.38}$$

$$P_{TH,CHP,s}^{\min} \leq P_{TH,CHP,s,t} \leq \gamma_{CHP,s} P_{CHP,s}^{c}, \quad \text{for } t=1, 2, \ldots, T. \tag{5.39}$$

$$B_{TS,k}^{\min} \leq B_{TS,k,t} \leq B_{TS,k}^{c}, \quad \text{for } t=1, 2, \ldots, T \tag{5.40}$$

$$B_{TS,n}^{\min} \leq B_{TS,n,t} \leq B_{TS,n}^{c}, \quad \text{for } t=1, 2, \ldots, T \tag{5.41}$$

$$B_{TS,s}^{\min} \leq B_{TS,s,t} \leq B_{TS,s}^{c}, \quad \text{for } t=1, 2, \ldots, T. \tag{5.42}$$

The objective function in Equation (5.27) maximizes the profit of the VPP system. The profit is comprised of the revenue of the VPP system and the cost associated with system installing, operations and maintenance. This objective is subjected to following constraints. Equation (5.28) to (5.30) are the electricity load balance constraints at each facility respectively that guarantee the electricity load is balanced with the electrical output. Constraints (5.31) to (5.33) are the thermal load balance constraints that guarantee to satisfy the thermal load with thermal output at each facility. Constraints (5.34) to (5.36) are the maximum and minimum capacity of the electrical output from the CHP unit. Constraints (5.37) to (5.39) are the maximum and minimum capacity of the thermal output from the CHP unit. Note that the ratio of electrical to thermal output of the CHP unit considered is 2, which means for every MWh of electrical output the CHP generates 2 MWh of thermal energy. Constraints (5.40) to (5.42) are the maximum and minimum capacity of the thermal storage system at each facility. Equations (5.20) to (5.25) in section 5.2.1 are reused for the profit maximization problem.

Table 5.12: Summary of Cases for Model 5.2

Case	Change in parameters
1	Power trading is 50% of load and variation is 5%
2	Power trading is 100% of load and variation is 20%
3	PV capacity cost is \$1M/MW
4	BSS Capacity Cost is \$0.05M/MWh, O_{ES}=\$0.00125M/MWh/year
5	Using TOU rate for day ahead electricity selling price to the grid
6	Using TOU rate for day ahead thermal power selling price
7	Natural gas price is \$15/MWh

5.3.1 Numerical experiments. In this section, results of numerical experiments performed on Model 5.2 are discussed. The profit maximization model is tested under various cases by changing the key parameters. Similar to Model 5.1 the supply chain is comprised of a factory in San Francisco, a warehouse house in Las Vegas and a store in Phoenix. A summary of the cases is given in the Table 5.12.

Case 1

This is the baseline case which is used to test the model and its change in parameters. The energy committed in the day ahead energy market is simulated and given in Figure 5.2. Based on this simulation the installation capacities of WT, PV and CHP units as well as electricity storage (ES) and thermal storage (TS) are determined. Table 5.12 shows the results of the capacities.

Table 5.13: Case 1 results for Model 5.2

Type	Factory	Warehouse	Store
WT (MW)	0	0	0
PV (MW)	0	0.032	0
ES (MWh)	0.63	0.32	0.16
CHP (MW)	7.60	4.55	3.05
TS (MWh)	0	0	0

Table 5.13 represents the results of Model 5.1 solved under baseline condition. The model chooses to install 0.032 MW PV system at the warehouse and does not install WT or PV systems at any other facility. CHP units are installed across all facilities. ES units stores electrical energy from PV and CHP. To satisfy the local load as well as to sell excess electrical and thermal power, the model chooses to install 7.60 MW CHP in factory, 4.55 MW and 3.05 MW in warehouse and store, respectively. This trend is observed because CHP can produce cost-effective electrical and thermal power to satisfy the energy requirement. The excess power after fulfilling a facility’s thermal load is being

directly sold in day ahead thermal power market, thus there are no storage in the thermal storage units.

Case 2

Table 5.14: Case 2 results for Model 5.2

Type	Factory	Warehouse	Store
WT (MW)	0	0.10	0
PV (MW)	0	0	0
ES (MWh)	3.45	2.53	2.31
CHP (MW)	11.30	6.44	4.27
TS (MWh)	0	0	0

In Case 2, the electricity sold at the day ahead market is simulated as 100% the load with standard deviation of 20% as shown in Figure 5.8. This means that the commitment is higher than that in Case 1. Thus, the model chooses to install more capacities of all the units. As noticed from Table 5.14 in this case the model installs WT in the warehouse whereas it chose to install PV in the same site in Case 1. This is because of the higher commitment in Case 2 it is required to install higher capacity. Since WT cost is cheaper than PV, to maximize profit the model chooses to install WT in this case. CHP and ES capacity are higher as well because it has to satisfy the internal load as well as to sell the promised energy to the grid.

Case 3

Table 5.15: Case 3 results for Model 5.2

Type	Factory	Warehouse	Store
WT (MW)	0	0	0
PV (MW)	0	0.032	0.013
ES (MWh)	0.63	0.32	0.20
CHP (MW)	7.60	4.55	3.03
TS (MWh)	0	0	0

In Case 3, the model is tested by reducing the PV capacity cost to $1M/MWh as opposed to $2M/MWh in the benchmark. As mentioned in Table 5.15, PV system is installed at warehouse and store. Since this is a profit maximization problem by installing PV the total system cost is reduced, hence increasing the profit. There are no WT or PV installation at the factory as the CHP can satisfy the load.

Case 4

Table 5.16: Case 4 results for Model 5.2

Type	Factory	Warehouse	Store
WT (MW)	0	0.03	0
PV (MW)	0	0	0
ES (MWh)	1.13	1.12	0.52
CHP (MW)	7.55	4.50	3.03
TS (MWh)	0	0	0

Table 5.16 shows the results of Case 4 where the model is tested by reducing the ES capacity and operations cost. In Case 1 capacity cost is $0.4M/MWh and in Case 4 is reduced to $0.05M/MWh. This reduces the installation of generation units across the facilities and increases ES installation. The ES stores electrical energy from WT, PV or CHP unit. The excess electrical energy stored can be sold to the grid for incoming.

Case 5

Table 5.17: Case 5 results for Model 5.2

Type	Factory	Warehouse	Store
WT (MW)	0	0	0
PV (MW)	0	0.03	0
ES (MWh)	0.63	0.31	0.16
CHP (MW)	7.60	4.55	3.05
TS (MWh)	0	0	0

Table 5.17 shows the results of testing Model 5.2 in TOU pricing scheme. Current practices indicate that the selling price varies as per the time of the day. In this case, TOU

prices are used as $140/MWh from 10 am to 9 pm and $70/MWh from 10 pm to 9 am. The results indicate that the install capacity of all the units are similar to those in the benchmark case.

Case 6

Table 5.18: Case 6 results for Model 5.2

Type	Factory	Warehouse	Store
WT (MW)	0	0	0
PV (MW)	0	0.03	0
ES (MWh)	0.72	0.31	0.16
CHP (MW)	7.57	4.55	3.05
TS (MWh)	0	0	0

Case 6 represents TOU for selling price excess thermal energy stored. The model is tested using selling price as $15/MWh from 8 am to 6 pm and $30/MWh from 7 pm to 7 am. Table 5.18 shows the results of the installation capacity. There is a small increase in ES and CHP size at factory compared with the benchmark. This is observed because the system chooses to make more profit during the time the selling price is high. The excess thermal energy produced is sold directly, thus there is no need of TS unit.

Case 7

Table 5.19: Case 7 results for Model 5.2

Type	Factory	Warehouse	Store
WT (MW)	0	0	0
PV (MW)	0	0.03	0.013
ES (MWh)	0.63	0.31	0.207
CHP (MW)	7.60	4.55	3.03
TS (MWh)	0	0	0

CHP units operates by burning natural gas. Case 7 represents the sensitivity analysis on the natural gas price. Benchmark case is tackled with natural gas price $7/MWh. This analysis uses a higher natural gas price of $15/MWh (i.e., to create 1

MWh energy, it costs $15 by burning natural gas). Table 5.19 list the results of this analysis. As noted, there is a small change in the installation capacity in the store. This can be concluded that there is only a small impact on the microgrid capacity if natural gas price doubles.

Table 5.20: Model 5.2 system cost summary

Case	Profit ($)	Profit difference	Difference in %
1	3,254,969	-	0
2	7,555,507	4,300,538	79.56
3	3,258,338	3,369	0.10
4	3,310,321	55,352	1.69
5	4,782,603	1,527,633	38.01
6	1,833,137	-1,421,833	-55.89
7	262,754	-2,992,215	-170.12

Finally, Table 5.20 summarizes the profit in each of discussed cases. Case 1 is the baseline with total profit of $3,254,969. Case 2 has 79.56% increase in the profit as the case sells more electrical power to the grid making more profit than the baseline case. Case 3 has 0.10% increase in the profit as the cost of the system reduces due to decrease in PV system capital cost. Case 4 has 1.69% increase in the profit as the electrical storage capacity cost in reduced. Case 5 uses TOU selling price and sees an increase of 38.01% in profit. Both cases 6 and 7 have losses compared to the baseline system profit.

6. CONCLUSIONS

6.1 Research Summary

This research is focused on integrating onsite renewable microgrid to aid the power production of multi-tier manufacturing and supply chain operations. Four types of energy supply and service modes are discussed: grid-tied operation, island operation, prosumer microgrid, and virtual power plants. Under demand and supply uncertainty, several mathematical models are developed and tested on different supply chain layouts comprised of factories, warehouses, and retail stores. Five types of distributed energy resources (DER) are considered in this study: wind turbine (WT), solar photovoltaics (PV), combined heat and power (CHP), electrical storage and thermal storage units. Excess energy can be stored and discharged using energy storage system.

Chapter 2 consists of developing and testing a joint optimization model for production-inventory and microgrid capacity planning. First, a stochastic optimization model with an objective to minimize the total expected cost is formulated. Second, to counter the chance constraint in this model, the stochastic model is further broken down into a two-stage deterministic model with deterministic constraints to reduce the variability and the easily solve the problem. The first stage is to determine the production, inventory and backorder quantity and using these as the input to the second stage where the capacity of the microgrid is further allocated. This model is developed for grid-tied operations; hence battery storage is not considered. The wind and solar characteristics are simulated for five locations using combinations of high, medium, and low climate profiles (i.e., wind speed and weather condition). Electrical vehicles (EV) are used to transport materials between the facilities within the supply chain network. Numerical studies are implemented to test the mathematical model using simulation data on weekly and daily planning basis over a year, respectively. The results indicate that the weekly planning horizon is more cost beneficial.

Chapter 3 is formulated as a three-tier supply chain with island microgrid operations. An island microgrid is such that the microgrid consisting of DER units are disconnected from the main grid. The facility is entirely powered by the microgrid power. Such an island setup requires the use of battery storage units. A joint optimization model is developed for production planning and energy scheduling in island mode. This model is solved as a two-stage mixed integer linear optimization under product demand and energy supply uncertainty. First stage is the production planning and the second stage is energy scheduling. The island microgrid model is tested on three different supply chain layouts comprising of ten U.S cities. The hourly capacity factor of WT and PV is extrapolated based on 11-year meteorological dataset retrieved from web portal of Weather Underground. The model is designed such that at random points in time higher energy throughput or the excess microgrid energy can be stored using BSS. Sensitivity analysis is carried out for weekly, daily, and hourly (8736 hours) planning horizon. The model is tested, respectively, on two-factory, one-warehouse, and two-store network and on four-factory, two-warehouse, and four-store network.

Chapter 4 introduces the concept of prosumers into the previously developed production-inventory-logistics system. A prosumer is an entity who can be a power producer and a consumer. In this chapter an energy prosumer is considered with the ability to buy or sell electricity between the facility and the main grid. The prosumer model is developed for grid-tied operations. The first stage of production planning is continued from Chapter 3. The second stage model is developed for onsite generation and scheduling on hourly basis in realizing two-way power flow under demand response. The objective of such cases is to use the energy generated by the microgrid for facilitating the production and transportation operations and to make revenue by selling the excess electricity to the main grid. Since a prosumer can buy electricity from the grid if needed the initial investment cost for setting up the microgrid is minimum.

Chapter 5 incorporates a virtual power plant (VPP) concept in the design and operations of the manufacturing supply chain. A VPP is a system consisting of several heterogenous DER units with an ability to transfer energy within the system itself. The VPP considered in this chapter consists of WT, PV and CHP units. Unlike WT and PV, a CHP unit has the capability of producing both electrical and thermal outputs. In case of excess electrical or thermal energy output, it can be sold locally to make revenue. Two models are solved in this chapter, one is a cost minimization model and the other is a profit maximization model. In this thesis a VPP system can only sell energy in day ahead market while the prosumer system can sell or buy energy.

The key parameters for solving all the production planning models are close to the real-world data replicated from an energy-intensive semiconductor manufacturing supply chain. The WT and PV capacity factor are derived by extracting hourly wind speeds and weather conditions of ten U.S cities between 2004 and 2015.

6.2 Key Managerial Insights

The results computed in this research can be used to derive some key managerial insights and can be implemented for real-world applications. Some of the insights are the most beneficial planning horizon for production planning is weekly (i.e., 52 weeks over a year). It is economically feasible to integrate renewable energy technologies to assist the facilities in achieving low carbon emissions. This can help the companies to contribute to the global pledge on decreasing carbon levels in the atmosphere. WT and PV characteristics can be modeled by analyzing climate profiles of any location. If the average capacity factory is higher than 0.3 for WT and 0.4 for PV, the location is suitable for placing the generating systems.

Subsequent carbon credits are still provided by governments to encourage the use of renewable technologies. These credits can further reduce the operations and maintenance cost of the systems. Prosumer initiative can be incorporated into new or existing systems which can be beneficial for the company and the local community. Reduction in energy costs can be achieved. The study shows being a prosumer can cut down the operational costs by 30%.

A VPP network can help the company to bring revenue stream by selling energy locally in the energy market, thus bringing down the operational costs. The facility has the option of biding in the day-ahead market based on the prediction of their production and demand. Using historical data to model WT and PV capacity factor helps to obtain anaccurate prediction. This provides an edge over the business competitors in the competitive world. Sustainability based manufacturing practices can also gain an advantage in the business's marketing venture.

6.3 Future Research

As a future work this research can be extended in multiple dimensions. The two-stage linear programming model can be jointly solved as one problem. This might reduce the running times in solving the models discussed in this research. Non-linear modelling approaches can be utilized to cope up with the uncertainty of supply and demand. Probabilistic models can be used to estimate the power consumption at the facilities and the numbers can be used as real time data. This would make the models more robust. EV batteries could be connected to the grid through smart chargers and they could provide sufficient power. Potential usage of EV to self-supply infrastructures through Vehicle to Grid applications can be explored. Commercially consumption-based pricing models are becoming popular. Utility pricings such as real time pricing, critical peak pricing can be incorporated in the Prosumer model. Current power networks are undergoing a major shift in designing and managing electricity grids. Concepts such as bidirectional peer to peer energy transactions, Internet of Energy (IoE), smart grids and Industry 4.0 can be investigated and possible integration on to manufacturing supply chains can be researched.

APPENDIX SECTION

APPENDIX A

Sample AMPL code for Model 4.1

#Model File

```
set type; #g
set factory; #k
set period; #j
set perdwith0;
set store; #s
set products; #i

param fib >=0;
param db >=0;
param fi >= 0;
param a {g in type} >= 0;
param b {g in type} >= 0;
param c {g in type} >= 0;
param tou {g in type} >=0;
param lamdaF {t in period, g in type, k in factory} >=0;
param lamdaWH {t in period,g in type} >=0;
param lamdaS {t in period,g in type, s in store} >=0;
param e {i in products} >=0;
param qv >= 0;
param wv >= 0;;
param toum >=0;
param ln >=0;
param ntn >= 0;
param dn {k in factory}  >= 0;
param tous >=0;
param ls >=0;
param nts >= 0;
param ds {s in store} >= 0;
param m {i in products} >= 0;
param x {i in products, t in period, k in factory} >=0;
param re{i in products, t in period, s in store} >=0;
param pu >=0;
param pv >=0;

var PcK {g in type, k in factory} >=0;
var PcN {g in type} >=0;
var PcS {g in type, s in store} >=0;
var BcK {k in factory} >=0;
var BcN >=0;
var BcS {s in store} >=0;
var BtK {t in perdwith0, k in factory} >=0;
var BtN {t in perdwith0} >=0;
var BtS {t in perdwith0,s in store} >=0;
var EtK {t in period, k in factory} >=0;
var EtN {t in period} >=0;
var EtS {t in period, s in store} >=0;
var uf {t in period,k in factory} >=0 binary;
```

```
var vf {t in period,k in factory} >=0 binary;
var uw {t in period} >=0 binary;
var vw {t in period} >=0 binary;
var us {t in period,s in store} >=0 binary;
var vs {t in period, s in store} >=0 binary;

minimize cost:
(fi * (sum {g in type} sum{k in factory} (a[g]*PcK[g,k]))) + ( sum{t in
period} sum{g in type} sum{k in factory} (tou[g] * (b[g] - c[g]) *
lamdaF[t,g,k] * PcK[g,k])) +  sum{ k in factory} (fib * db) * BcK[k] + sum{t
in period, k in factory} (pu*uf[t,k] - pv*vf[t,k]) * EtK[t,k] +
(fi * (sum {g in type} (a[g]*PcN[g])))+ (sum{t in period} sum{g in type}
(tou[g] * (b[g] - c[g]) * lamdaWH[t,g] * PcN[g])) +  (fib * db) * BcN + sum{t
in period} (pu*uw[t] - pv*vw[t]) * EtN[t] +
(fi * (sum {g in type} sum{s in store} (a[g]*PcS[g,s]))) + ( sum{t in period}
sum{g in type} sum{s in store} (tou[g] * (b[g] - c[g]) * lamdaS[t,g,s] *
PcS[g,s])) + sum{ s in store} (fib * db) * BcS[s] + sum{t in period, s in
store} (pu*us[t,s] - pv*vs[t,s]) * EtS[t,s] + 63945111.35 ;

subject to c1{k in factory, t in period}: (sum{i in products} ( e[i] + (qv *
dn[k] * m[i])) * x[i,t,k]) +(qv * ntn * dn[k] * wv) + BtK[t,k] - BtK[t-1,k] +
(vf[t,k] - uf[t,k]) * EtK[t,k] = sum{g in type} (tou[g] * lamdaF[t,g,k] *
PcK[g,k]);
subject to c2{t in period}: (toum * ln) + (sum{k in factory} qv * ntn * dn[k]
* wv) + sum{i in products} sum{s in store} (qv * ds[s] * m[i]) * re[i,t,s] +
sum{s in store} (qv * nts * ds[s] * wv) + BtN[t] - BtN[t-1] + (vw[t] - uw[t])
* EtN[t] =  sum{g in type} (tou[g] * lamdaWH[t,g] *PcN[g]);
subject to c3{s in store, t in period}: (tous * ls) + (qv * nts * ds[s] * wv)
+ BtS[t,s] - BtS[t-1,s] + (vs[t,s] - us[t,s]) * EtS[t,s] = sum{g in type}
(tou[g] * lamdaS[t,g,s] * PcS[g,s]);
subject to c4{t in perdwith0,k in factory}: BtK[0,k] = BcK[k];
subject to c5{t in perdwith0,k in factory}: BtK[8736,k] = BcK[k];
subject to c6{t in perdwith0}: BtN[0] = BcN;
subject to c7{t in perdwith0}: BtN[8736] = BcN;
subject to c8{t in perdwith0, s in store}: BtS[0,s] = BcS[s];
subject to c9{t in perdwith0,s in store}:BtS[8736,s] = BcS[s];
subject to c10{ t in perdwith0, k in factory}: 0 <= BtK[t,k];
subject to c11{ t in perdwith0, k in factory}: BtK[t,k] <= BcK[k];
subject to c12{ t in perdwith0 }: 0 <= BtN[t];
subject to c13{ t in perdwith0}: BtN[t] <= BcN;
subject to c14{ t in perdwith0, s in store }: 0 <= BtS[t,s];
subject to c15{ t in perdwith0, s in store }: BtS[t,s] <= BcS[s];
subject to c16{ t in period, k in factory }: uf[t,k] + vf[t,k] <=1;
subject to c17{ t in period }: uw[t] + vw[t] <=1;
subject to c18{ t in period, s in store }: us[t,s] + vs[t,s] <=1;
```

APPENDIX B

Sample AMPL code for Model 5.1

#Model File

```
set type; #g
set period; #t
set perdwith0;

param fig >=0;
param ag{g in type}>=0;
param fies >=0;
param des >=0;
param oes >=0;
param bg {g in type} >=0;
param cg {g in type} >=0;
param lamdak {t in period,g in type} >=0;
param tou {g in type} >=0;
param tou2 >=0;
param cchpk >=0;
param phrok >=0;
param lamdan{t in period,g in type} >=0;
param cchpn >=0;
param phron >=0;
param lamdas{t in period,g in type} >=0;
param cchps >=0;
param phros >=0;
param pdak {t in period} >=0;
param pdan {t in period}>=0;
param pdas {t in period}>=0;
param loadk >=0;
param loadn >=0;
param loads >=0;
param loadthk >=0;
param loadthn >=0;
param loadths >=0;
param pemaxk >=0;
param pemaxn >=0;
param pemaxs >=0;
param pemink >=0;
param peminn >=0;
param pemins >=0;
param pthmaxk >=0;
param pthmaxn >=0;
param pthmaxs >=0;
param pthmink >=0;
param pthminn >=0;
param pthmins >=0;
param bemaxk >=0;
param bemaxn >=0;
param bemaxs >=0;
param bemink >=0;
```

```
param beminn >=0;
param bemins >=0;
param efchpk >=0;
param efchpn >=0;
param efchps >=0;
param cngk >=0;
param cngn >=0;
param cngs >=0;
param gammak >=0;
param gamman >=0;
param gammas >=0;

var pgk {g in type} >=0;
var pgn {g in type} >=0;
var pgs {g in type} >=0;
var bcesk >=0;
var bcesn >=0;
var bcess >=0;
var pechpk {t in perdwith0}>=0;
var pechpn {t in perdwith0}>=0;
var pechps {t in perdwith0}>=0;
var besk {t in perdwith0} >=0;
var besn {t in perdwith0} >=0;
var bess {t in perdwith0} >=0;
var btsk {t in perdwith0} >=0;
var btsn {t in perdwith0} >=0;
var btss {t in perdwith0} >=0;
var pthchpk {t in perdwith0}>=0;
var pthchpn {t in perdwith0}>=0;
var pthchps {t in perdwith0}>=0;


minimize total_cost:

sum{g in type} (fig*ag[g]*pgk[g]) + ((fies*des)+oes)*bcesk + sum{t in period}
sum{g in type} (bg[g] - cg[g]) * (lamdak[t,g])*pgk[g]*tou[g] + sum{t in
period} cchpk*pechpk[t]*tou2 - sum{t in period} phrok*pdak[t]*tou2 +
sum{g in type} (fig*ag[g]*pgn[g]) + ((fies*des)+oes)*bcesn + sum{t in period}
sum{g in type} (bg[g] - cg[g]) * (lamdan[t,g])*pgn[g]*tou[g] + sum{t in
period} cchpn*pechpn[t]*tou2 - sum{t in period} phron*pdan[t]*tou2 +
sum{g in type} (fig*ag[g]*pgs[g]) + ((fies*des)+oes)*bcess + sum{t in period}
sum{g in type} (bg[g] - cg[g]) * (lamdas[t,g])*pgs[g]*tou[g] + sum{t in
period} cchps*pechps[t]*tou2 - sum{t in period} phros*pdas[t]*tou2 ;

subject to c1 {t in period}: sum{g in type} (lamdak[t,g]*pgk[g]*tou2) -
besk[t] + besk[t-1] + pechpk[t] = loadk + pdak[t];
subject to c2 {t in period}: sum{g in type} (lamdan[t,g]*pgn[g]*tou2) -
besn[t] + besn[t-1] + pechpn[t] = loadn + pdan[t];
subject to c3 {t in period}: sum{g in type} (lamdas[t,g]*pgs[g]*tou2) -
bess[t] + bess[t-1] + pechps[t] = loads + pdas[t];
subject to c4 {t in period}: pthchpk[t] - btsk[t] + btsk[t-1] = loadthk;
subject to c5 {t in period}: pthchpn[t] - btsn[t] + btsn[t-1] = loadthn;
subject to c6 {t in period}: pthchps[t] - btss[t] + btss[t-1] = loadths;
subject to c7 {t in period}: pemink <= pechpk[t];
subject to c8 {t in period}: pechpk[t] <= pemaxk;
```

```
subject to c9 {t in period}: peminn <= pechpn[t];
subject to c10 {t in period}: pechpn[t] <= pemaxn;
subject to c11 {t in period}: pemins <= pechps[t];
subject to c12 {t in period}: pechps[t] <= pemaxs;
subject to c13 {t in period}: pthmink <= pthchpk[t];
subject to c14 {t in period}: pthchpk[t] <= pthmaxk;
subject to c15 {t in period}: pthminn <= pthchpn[t];
subject to c16 {t in period}: pthchpn[t] <= pthmaxn;
subject to c17 {t in period}: pthmins <= pthchps[t];
subject to c18 {t in period}: pthchps[t] <= pthmaxs;
subject to c19 {t in period}: bemink <= besk[t];
subject to c20 {t in period}: besk[t] <= bemaxk;
subject to c21 {t in period}: beminn <= besn[t];
subject to c22 {t in period}: besn[t] <= bemaxn;
subject to c23 {t in period}: bemins <= bess[t];
subject to c24 {t in period}: bess[t] <= bemaxs;
subject to c31: cchpk = cngk/efchpk;
subject to c32: cchpn = cngn/efchpn;
subject to c33: cchps = cngs/efchps;
subject to c34 {t in period} : pthchpk[t] = gammak*pechpk[t];
subject to c35 {t in period} : pthchpn[t] = gammak*pechpn[t];
subject to c36 {t in period} : pthchps[t] = gammak*pechps[t];
subject to c37 {t in perdwith0}: besk[0] = bcesk;
subject to c38 {t in perdwith0}: besn[0] = bcesn;
subject to c39 {t in perdwith0}: bess[0] = bcess;
```

APPENDIX C

Weekly Labor and Machine Hours for 2F-1W-2S Network

Table B1: Resource Data for 2F-1W-2S Network (Note: F1=Factory 1, F2=Factory 2)

	Labor (hour)		Machine (hour)			Labor (hour)		Machine (hour)	
Week	F1	F2	F1	F2	Week	F1	F2	F1	F2
1	17871	19412	122693	150577	27	17567	19081	122998	150953
2	23963	26028	161238	197883	28	27251	29599	185471	227623
3	15531	16870	105179	129084	29	15008	16302	104506	128257
4	23810	25862	164141	201447	30	24055	26129	164533	201928
5	17020	18487	115050	141198	31	17082	18554	116094	142480
6	25516	27715	178157	218648	32	24361	26462	166074	203818
7	15806	17167	109757	134701	33	14922	16208	105226	129142
8	24907	27054	172894	212188	34	25848	28076	177572	217930
9	16817	18266	115034	141178	35	17068	18539	117494	144198
10	25744	27963	177118	217372	36	21218	23047	147419	180923
11	15654	17004	105661	129674	37	14681	15946	99626	122268
12	24750	26883	173807	213307	38	19834	21544	137372	168593
13	17130	18607	115341	141554	39	15590	16934	106354	130525
14	26236	28498	177504	217847	40	23474	25497	164676	202102
15	15336	16657	105793	129836	41	16581	18011	114349	140338
16	26527	28814	182681	224199	42	22794	24759	157022	192708
17	15736	17093	106150	130276	43	16545	17971	113408	139182
18	23364	25378	160770	197309	44	22714	24673	158422	194427
19	17637	15964	120826	148288	45	15986	17364	109791	134743
20	26231	28492	178312	218837	46	23443	25465	161554	198270
21	18956	20590	128436	157626	47	17212	18696	117720	144474
22	27107	29443	187268	229829	48	21403	23247	149436	183400
23	13394	14549	94626	116132	49	17975	19524	119144	146222
24	24284	26377	163848	201087	50	23839	25895	165547	203171
25	14600	15859	101396	124441	51	18728	16952	128554	157771
26	21334	23173	144616	177482	52	22326	24251	151885	186404

APPENDIX D

Weekly Labor and Machine Hours for 4F-2W-4S Network

Table C1: Resource Data for 4F-2W-4S Network for Weeks 1-26

	Labor (hour)				Machine (hour)			
Week	F1	F2	F3	F4	F1	F2	F3	F4
1	8846	10812	8541	12812	60733	74229	66254	99381
2	11862	14497	11452	17178	79813	97549	87069	130603
3	7688	9396	7423	11134	52064	63633	56797	85195
4	11786	14405	11379	17069	81250	99305	88637	132955
5	8425	10297	8134	12202	56950	69605	62127	93191
6	12630	15437	12194	18292	88188	107785	96205	144308
7	7824	9562	7554	11330	54330	66403	59269	88903
8	12329	15069	11904	17856	85582	104601	93363	140044
9	8324	10174	8037	12056	56942	69596	62118	93177
10	12743	15575	12304	18456	87673	107156	95644	143465
11	7749	9471	7482	11223	52302	63925	57057	85585
12	12251	14974	11829	17743	86034	105153	93855	140783
13	8480	10364	8187	12281	57094	69781	62284	93426
14	12987	15873	12539	18808	87864	107390	95853	143779
15	7591	9278	7329	10994	52367	64005	57128	85692
16	13131	16049	12678	19018	90427	110522	98648	147971
17	7789	9520	7521	11281	52544	64221	57321	85982
18	11565	14135	11166	16750	79581	97266	86816	130224
19	8730	10670	7024	10536	59809	73100	65247	97870
20	12984	15870	12537	18805	88264	107879	96288	144432
21	9383	11468	9059	13589	63576	77704	69355	104033
22	13418	16400	12955	19432	92698	113297	101125	151687
23	6630	8104	6401	9602	46840	57249	51098	76647
24	12021	14692	11606	17409	81105	99128	88478	132717
25	7227	8833	6978	10467	50191	61345	54754	82131
26	10560	12907	10196	15294	71585	87492	78092	117138

Table C2: Resource Data for 4F-2W-4S Network for Weeks 27-52 (**Continued**)

	Labor (hour)				Machine (hour)			
Week	F1	F2	F3	F4	F1	F2	F3	F4
27	8696	10628	8396	12594	60884	74414	66419	99629
28	13489	16487	13024	19535	91808	112210	100154	150231
29	7429	9080	7173	10759	51731	63226	56433	84650
30	11907	14553	11497	17245	81444	99543	88848	133272
31	8455	10334	8164	12246	57467	70237	62691	94037
32	12059	14739	11643	17465	82207	100475	89680	134520
33	7386	9028	7132	10698	52087	63662	56822	85233
34	12795	15638	12354	18530	87898	107431	95889	143834
35	8449	10326	8157	12236	58160	71084	63447	95171
36	10503	12837	10141	15211	72972	89188	79606	119409
37	7267	8882	7016	10524	49315	60273	53798	80697
38	9818	11999	9479	14219	67999	83110	74181	111272
39	7717	9432	7451	11177	52645	64344	57431	86147
40	11620	14202	11219	16828	81515	99629	88925	133387
41	8207	10031	7925	11887	56603	69181	61749	92623
42	11283	13790	10894	16341	77726	94999	84792	127187
43	8190	10010	7907	11861	56137	68612	61240	91860
44	11243	13742	10856	16284	78419	95845	85548	128322
45	7913	9671	7640	11460	54347	66424	59287	88931
46	11604	14183	11204	16807	79969	97740	87239	130858
47	8520	10413	8226	12339	58271	71221	63569	95353
48	10595	12949	10229	15343	73971	90409	80696	121044
49	8898	10875	8591	12886	58976	72082	64338	96507
50	11800	14423	11394	17091	81946	100156	89395	134093
51	9270	11330	7459	11189	63634	77775	69419	104129
52	11051	13507	10671	16006	75183	91891	82018	123027

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