DESIGNING MULTI-PERIOD PRODUCTION AND FLOW SHOP MANUFACTURING SYSTEMS WITH ISLAND MICROGRID OPERATION

by

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DEDICATION

To my family and friends,

for their endless support and love

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LIST OF ABBREVIATIONS

Abbreviation **Description**

AMPL - A Mathematical Programming Language

ASOS - Automated Surface Observing Systems

BESS - Battery Energy Storage System

BSS - Battery Storage Systems

CAPEX - Capital Expenditure

CF - Capacity Factor

CPP - Critical Peak Pricing

DER - Distributed Energy Resources

DG - Distributed Generation

DNO - Distribution Network Operator

DOE - Department of Energy

DR - Demand Response

DRM - Demand Response Management

ESS - Energy Storage System

EV - Electric Vehicle

FESS - Flywheel Energy Storage System

FSP - Flow-shop Scheduling Problem

G2V - Grid to Vehicle

HOMER - Hybrid Optimization Model for Electric Renewables

Kg - Kilogram

Km - Kilometer

KWh - Kilowatt-hour

LCA - Life Cycle Analysis

LCOE - Levelized Cost of Energy

LPSP - Loss of Power Supply Probability

MC - Mostly Cloud

MLCOE - Marginal Levelized Cost of Energy

MW - Megawatt

MWh - Megawatt-hour

OPEX - Operational Expenditure

PC - Partially Cloud

PHEV - Plug-in-Hybrid Electric Vehicle

PV - Photovoltaic

RER - Renewable Energy Resources

RTP - Real Time Pricing

SC - Scattered Cloud

SLP - Stochastic Linear Programming

TOU - Time-of-Use

UC - Utility Company

V2G - Vehicle to Grid

VPP - Virtual Power Plant

WIP - Work-in-Process

WT - Wind Turbine

ABSTRACT

Manufacturing industries consume one third of the global electricity. Over 70 percent of the electric power is generated by burning fossil fuels, resulting in climate change and depletion of natural resources. This research aims to address two fundamental challenges pertaining to manufacturing sustainability. First, how to model, design and optimize a carbon-neutral production system with intermittent power? Secondly, is it technically feasible and economically variable to deploy a wind- and solar-based island microgrid to power a multi-stage flow shop system? A two-stage, mixed integer programming model is formulated to minimize levelized cost of energy. We jointly optimize renewable generation capacity and flow shop production schedule considering environmental and facility constraints. The proposed model is tested using 11-year wind and weather data with nearly one million meteorological records. The results show that carbon-neutral operation is feasible and affordable for large scale manufacturing facilities if the capacity factor of local wind and solar generation exceeds 0.3 and 0.4, respectively. Solar power and battery storage can compete with wind had their current installation cost is cut off by 50 percent. Compared with flat rate net metering, time-of-use tariff stimulates the adoption of solar and battery storage use.

1. INTRODUCTION AND LITERATURE REVIEW

1.1 Research Motivation/Background

The demand for electric power will continue to increase in the next 10-20 years. There are various reasons that leads to high power demand such as rise in population, deployment of hybrid electric vehicles, climate change and the expansion of industry and business in developing countries. During the growth of a nation's economy, utilization of energy increases because of the rise in energy consuming activities like manufacturing, and the expansion of services and transport. The climate change towards warmer condition during the summer affects the human activity because of the need for heavy usage of electrical appliances like refrigerators, air conditioning and the increased use of water.

Nowadays, industrial sector is consuming on average 50% of the world's total generated power. Due to the heavy combination of economic activity and advancement of technology, there is a high increment in the power consumption. Manufacturing industries uses electricity for various purposes like machining process, products assembly, heating, cooling, lighting and air conditioning for buildings.

Due to the growing electricity needs, new challenges are faced by the utility companies and the consumers. These challenges motivate the first problem we study in this thesis. Namely, how to design a carbon neutral production-inventory system with demand response (DR) program? DR requires the industrial consumers to curtail certain amounts of the load in contingency, often occurring during the peak periods. With this DR contract, manufacturing facilities help utility companies to overcome at least certain amounts of power shortage. In this thesis, we develop a carbon neutral production-inventory planning model at different curtailment of levels (5%, 10%, 15% and 20%) in various time-periods.

Thus, the optimization of this model is useful to manufacturing facilities that strive for minimizing its energy cost as well as making best practices of DR program.

To mitigate the volatility of wind and solar generation, manufacturing companies can purchase and install battery storage systems to balance the load and renewable generation. To reduce the total energy drawn from the main grid, manufacturing facilities can use different approaches like shutting down idle-machines or adopting onsite generation systems. These issues motivate us to study the second problem in this thesis. Such problem is to optimize the energy flow between the sources and users in a multi-process flow shop system. Particularly, we model and optimize the energy flow between different energy sources and parallel machines each having different power and processing time. The goal is to jointly allocate the machine scheduling, onsite generation capacity and battery size to minimize the annual energy cost. Using this model, facilities can store excess energy produced by the resources and to discharge the stored energy when the output of onsite generators is low.

In this chapter, we focused the literature review on three major parts. First, we study the previous literature on production planning with integrated onsite generation using two phase approach, because we use such methodology in the first model of this thesis. Secondly, due to the consideration of demand response criteria and the usage of microgrid system for production planning in Chapters 2 and 3, respectively, we do literature on DR program, microgrid system and its levelized cost of energy. Finally, we focus on energy conservation by flow shop scheduling considering net-metering and time of use tariffs as those are topics closely related to work presented in Chapters 4 and 5 in this thesis.

1.2 Production Planning with Onsite Generation using Two-Stage Optimization

1.2.1 Production-Inventory Planning

Kira et al. (1997) have developed an algorithm for solving hierarchical production planning with uncertain demand using Stochastic Linear Programming (SLP). They have added the surplus and shortage penalties due to the fluctuating demand into the objective function. According to Kira et al. (1997), the shape of the demand distribution can have considerable impact on the production planning and SLP has approximately 3% more cost saving compared to the Linear Programming approach.

Mula et al. (2006) have provided a detailed review on previous studies related to demand uncertainty in production planning, including various modelling techniques involved in production planning with demand uncertainty.

Nagar et al. (2008) have developed a multi-stage supply chain planning model using the stochastic programming approach. Their model specifically focuses on new product introduction as the demand uncertainty plays a vital role in new product market. The model aims to determine the optimal procurement quantity, production quantity, transportation routes and outsourcing cost due to shortage in supply. It is claimed that the proposed model can attain supply chain savings by 5.43%.

Abass (2012) has proposed a non-linear optimization model to meet the demand based on available resources for net revenue maximization. In the model, two types of uncertainty are investigated. These are the environment uncertainty due to demand and supply variability, and system uncertainty due to process time and resource variability. The concept of stability has been incorporated into the model to maximize net revenue. Fuzzy parameters are employed to describe the available resources and demand at each period.

Jin et al. (2015) have developed a multi-period production planning model that integrates renewable energy planning. This model aims to minimize the aggregate cost comprised of energy and non-energy components by optimizing production quantity, inventory level, back-order quantity and renewable energy use in a multi-facility setting. To solve the problem, the original SLP model is converted to a deterministic counterpart by minimizing the expected cost.

Ji et al. (2016) have developed a stochastic optimization model considering the capacity and demand uncertainties focused on final assembly production planning. Their model considered a manufacturing firm with two final assembly products where both the production level and inventory level are optimized in the presence of uncertain demand and random capacity.

Felfel et al. (2016) studied a multi-period, multi-facility, multi-echelon supply planning problem that is solved as a two-stage stochastic linear programming. The proposed multi-objective SLP model aims to minimize the total cost. This is attained by minimizing the lost customer demand and minimizing the downside risk. The model was developed by considering a textile manufacturing firm as a case study. The developed model was able to achieve a downside risk reduction by 44% with a negligible amount of increase in the total cost.

1.2.2 Onsite Generation and Integration

Onsite generation which is also known as distributed generation, produces electricity by locally installing distributed energy resources (DER). Typical DER include wind turbine, solar photovoltaics, diesel generator, biogas fuel cell, combined heat and power, and battery storage. Large manufacturers are focused on developing onsite renewable energy generation to produce their own power due to their long-term contract with utility companies. Onsite wind and solar generation reduce carbon emissions by providing partial or full power to a factory or warehouse for daily operation. Additionally, net metering scheme is used to bring extra revenue or profits to the factory and becomes a main source of income for the individual.

In the United States, a strong growth the wind power is experienced in 2017 as the state level policies, production tax credit, low priced wind energy for co-operate, utility and other power procurers. The most important parts of wind market industry are turbines that are originally designed for lower wind speed sites dominate installations, improved wind turbine performance, multiple turbine configurations and partial repowering of wing projects.

The capacity factor is a measure of how closely the plant is operating at maximum output. Amongst the projects built during 2014 to 2016, the capacity factor was 42%, which is significantly higher than the 31.5% observed in the projects built from 2004 to 2011. Developments in manufacturing and design engineering led to greater heights and larger propellers, which have blades and the hub. The increase in size of these mechanisms have led to the trend of higher capacity factors. Powerful and larger turbines with big blades are originally developed to be arranged in less windy regions, where other turbines like conventional turbines would be less cost-effective. These turbines have less specific power, which is a measure of name plate capacity in watts. These larger rotors have helped in declining the specific power.

When mainly the old turbines are replaced with advanced turbine technology the partial wind projects are repowering. In 2017, about 2.13MW of capacity was repowered by wind developers. There is a gradual increase in these trends as the willingness amongst the turbine suppliers to supply more turbine configurations is being observed which helps to increase in optimization of site.

Luo et al. (2015) proposed a new hybrid model which deals with thermal overload issues. This algorithm mainly deals with the constraint satisfaction, which helps to solve the network constraint problem. Mainly, in this approach distributed generation and DR are jointly controlled. In this model different management techniques are implemented which contribute to network reinforcement deferral, cost effective capital expenditure, etc. This technique can benefit Distribution Network Operator (DNO) planning. The desired objectives are successfully achieved and assessed in comparison analysis.

Pechmann et al. (2016) introduced a model to reduce the costs of energy in manufacturing companies. The approach is to determine if the investment in the power plants with partial self-supply is useful or not. Various conditions are created to test a wide range of energy supply options. These conditions are obtained from an external provider to the other extreme, known as Virtual Power Plant (VPP) for autarkic supply. All the scenarios are calculated with local climate data, energy demand for VPP. The results show that using a partial self- supply of renewable energy is better option in financials.

Nandkeolyar et al. (2018) have proposed a model for a low carbon city, in which the grid is integrated to the renewable energy sources, but the inertia of the system is compromised. In general, DR in combination with conventional Energy Storage Systems (ESS) results in effective frequency response. In the proposed model, if demand response of household refrigerators with flywheel energy storage system (FESS) is implemented, the usage of fossil fuels will be reduced, thus helping the reduction of carbon emissions. This was successfully implemented in Bhubaneswar-Cuttack city.

1.2.3 Two-Stage Optimization

Huang et al. (2015) proposed a two-stage optimization model to optimize secondary energy production and distribution at community level. Goal programming approach is used to optimize the objective function by changing the variables in a range. The optimization model is validated with a real-time case study.

Bravo et al. (2018) developed a two-stage multi-objective optimization model to evaluate the trade-off between financial and technical performance in the design and operation of an energy source. The optimization model helps to optimize the design and operations simultaneously of a hybrid solar powerplant. The model also helps to analyze the hourly power flow and power loss. The model was validated with a real-time case study of a hybrid solar powerplant. The results indicate that the proposed model was able to reduce the levelized cost of energy by 5.6% and reducing loss of power supply probability (LPSP) by 90%.

Kim et al. (2018) used a two-stage optimization model for solving the production planning problem for a single product type with multiple parallel lines. The model considers variable production rates at different manufacturing lines for the same product. The model is applicable to both homogenous and heterogenous machine pool for production planning and distribution optimization. The developed model helps the user to select the optimal mix of machines for effective production planning considering its homogenous and heterogenous nature.

Ekin (2018) proposed a two-stage nonlinear stochastic optimization model for production planning considering stochastic yield rate and random demand. An augmented probability simulation model-based approach is used to solve the stochastic optimization model. This model is one of a kind in the sense that it considers uncertain yield using a stochastically proportional model with endogenous mean. The optimization model allows for decisions such as outsourcing or salvaging.

1.3 Demand Response and Microgrid System including Levelized Cost of Energy

1.3.1 Demand Response Management

Demand Response (DR) or Demand Response Management (DRM) is the major characteristic of a smart grid. At present, DRM is classified into two categories: utility company (UC) oriented and end-user oriented. UC-based DRM is a common exercise for power production companies in which they force customers to decrease power consumption due to heavy demand, whereas the end-user's DRM is defined as the user's reaction process to deal with their utilization of power because of supply conditions (Maharjan et al, 2013).

The main aim of DRM is to decrease the power generation cost and the customers electricity bills. DRM or DR is described by Department of Energy (DOE) as: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (Maharjan et al, 2013).

Aghaei et al. (2013) have explored the Renewable Energy Resources (RERs) management using the latest DR definition and classification. They have discussed the measurement and evolution methods besides the effects of DR in power rates. They also analyzed the successful DR implementations.

Jin et al. (2013) have proposed a new demand response scheme that integrates wind and solar energy to meet the load reduction compliance. They used newsboy inventory model to find the optimal capacity of renewable resources to maximize the energy savings. Probabilistic modeling approach is used to distinguish the uncertain variables. Discrete probability theory is adopted to differentiate the variability of curtailment levels.

Siano (2014) presented a survey of DR potentials and benefits in smart grids. The author has defined and explained innovative enabling techniques and systems like smart meters, energy controllers, communication systems to incorporate the conjunction of efficiency and DR in smart grids that relates to the industrial practice (Siano, 2014). Industrial case studies have proved that advanced DR programs and innovative enabling technologies are essential to support the coordination of DR in the smart grids.

Santana-Viera et al. (2015) have implemented the DR programs in large manufacturing facilities that incorporate onsite renewable resources like wind and solar energy. The have modelled and implemented an interruptible/curtailable DR program involved by a firm that consume onsite renewable generation. To maximize the DR program savings, they had modified a stochastic programming model to optimzie the capacity of the wind turbine and solar panels. Central composite design methodology was used to obtain optimal solutions. If there is a gradual decrease in the solar PV installation cost, the proposed model shows that the large PV installation benefits the DR commitment.

1.3.2 Microgrid System

A microgrid system is a group of distributed energy resources (DER) and can maintain independently and supply constant power along with the main grid, but it can also be disconnected and operate in island mode. Microgrid can enhance grid resilience, reduce grid disturbances and serve as grid resource to increase system response and recovery in extreme weather events. Generally, the microgrid is divided into two types: connected to the main grid and island microgrid. Microgrid system is the best energy solution for areas where it is expensive to construct long distance transmission or distribution lines. The local electricity requirements are met by adopting one or multiple distributed energy resources (DER) by both onsite generation and microgrid systems. The major difference between microgrid and onsite generation is that the microgrid can maintain independent supply if required while onsite generation usually co-supply the power with the main grid.

Samad et al. (2012) proposed a model to improve the use of smart grid applications in industry. An outline of smart grids and electricity usage in the industries is included. Various industrial case studies such as Alcoa, Amy’s Kitchen, cement manufacturing industry and supply side microgrid optimization project are provided. The case study on microgrid optimization for a utility plant is provided to discuss a microgrid optimization system that has been developed for atrium utility system and operated for several years. The growing demand of electricity has increased the need for power generation, consumption and delivery which initialized the launch of smart grids. But as the smart grids are not been used completely due to the emerging technologies, this paper provides a scope of smart grids in the industries by further improving its applications. The future work discusses improvement in automated demand response, energy use optimization and the dynamic markets.

1.3.3 Levelized Cost of Energy

The Levelized Cost of Energy (LCOE) is the net present value of the electricity cost per MWh or kWh over the lifetime of the generating source. LCOE allows to run comparative analysis on different power sources like wind and solar which may have different lifespans, capital cost, project lead times, returns and risks. The formula to calculate the LCOE is defined as follows:

$$LCOE\ (\$/\mathrm{MWh}) = \frac{Total\ Cost\ (\$)}{Total\ Energy\ Demand\ (\mathrm{MWh})}$$

Nandasiri et al. (2017) states that though Distributed Generation (DG) technologies like wind and solar has economic and environment benefits, uncontrolled DG penetrations could deliver adverse effects on the feeders. Marginal Levelized Cost of Energy (MLCOE) is proposed to optimize the DG output for residential PV. MLCOE is a modified LCOE, which is used to generate the loss of solar PVs generation cost. The proposed model is multi-objective optimization model for power flow optimization and the model with MLCOE concept analyzes the optimal power flow of a distribution network with large-scale DG penetration. The model has been validated with a real time case study and the results show that the model is able to reduce power loss and control voltage deviations.

Myhr et al. (2014) performed a comparative analysis of LCOE for offshore wind turbines. Life Cycle Analysis (LCA) was performed as an input for the LCOE model. The LCOE results were generated based on discounted values of capital expenditure (CAPEX), and operational expenditure (OPEX). The model explains that the LCOE for floating wind turbine is equal to or smaller than bottom fixed turbine.

Ebenhoch et al. (2015) have done a comparative study on bottom fixed and floating wind turbines in various offshore sites. The idea of the comparative study is to reduce the cost of offshore wind turbines during the pre-design and pre-installation using LCOE calculation tool. Life Cycle Analysis (LCA) is conducted to analyze all possible cost incurred in the floating offshore wind turbine for the optimization. The LCOE calculation tool helped the renewable developers to make decisions during the predesign phase in terms of the most cost-effective structure.

Sunderland et al. (2016) performed a LCOE comparative study of urban micro-wind turbines versus solar PV. Design of experiments was further conducted to analyze the insights of parameters such as primary energy source, capital cost, in the decision-making process of micro wind turbine as opposed to PV systems. The study concludes that solar PV is a better cost-effective source compared to micro-wind turbine even in a wind favorable atmosphere.

1.4 Energy Conservation by Flow Shop Scheduling under net-metering and time of use rates

1.4.1 Energy Conservation

Fang et al. (2011) have formulated a multi-objective mixed integer linear programming model for flow shop operation scheduling that involves energy consumption and machine productivity. Their formulation explicitly assumes that energy consumption is affected by variable operation speed. They have also differentiated the energy consumption based on the different machining operations (e.g., drilling). The model developed in the paper has reduced the carbon footprint by consuming the least energy.

Li et al. (2013) have developed an analytical model to minimize the energy consumption by considering multiple machines and buffers with different energy states. Markov Decision Process is used to model the relationship between energy control actions and developments in system environment. When compared to baseline model energy consumption, the proposed model can achieve a reduction of energy consumption by maintaining the system throughput in the power adjustment model.

Choi et al. (2013) have developed a linear programming model for production planning with an aim to minimize the energy consumption along with inventory holding and backorder cost. They have considered various process plans in flexible manufacturing systems to minimize the total use of the energy consumptions. The flow of energy is estimated by considering different operations in the manufacturing systems. The proposed model had achieved the minimum energy consumption for production planning while meeting the customer demands.

Beier et al. (2017) have presented a method for real-time control of the manufacturing systems with several processes and intermediate buffers to minimize the energy consumption from the grid as well as to maximize the onsite variable renewable generation. To decrease the grid energy consumption, the proposed method does not compromise the system throughput rate by integrating distributed and variable renewable energy resources like wind and solar.

1.4.2 Flow Shop Scheduling

Flow-shop scheduling Problem (FSP) is a class of optimization problems with a workshop or group shops in which the flow control shall enable an appropriate sequencing for each job to be processed on a set of machines in compliance with given processing orders.

Fang et al. (2011) had presented a new mathematical programming model for the flow shop scheduling that consumes peak power load, energy consumption, and associated carbon footprint along with cycle time. In their paper, the flow shop has two machines to produce different parts. To reduce the peak load energy consumption, the proposed scheduling model consumes an operation speed as an input parameter. Optimal schedules are obtained by developing specialized algorithms for the proposed new scheduling poblem and verifying the manageble approaches.

In the work by Zhang et al. (2014), the flow shop scheduling problem is defined to minimize the cost of power for a grid connected factory with onsite PV generation and battery storage systems. The proposed model is very useful for the facilities to clearly measure the amount of energy provided by on-site distributed power system. Maintenance and buffers were also involved in the integrated scheduling problem. Nowadays, factories are utilizing modern efficient devices instead of older inefficient devices. They have mentioned that “Recently, many energy suppliers have begun to implement a so-called time-of-use (TOU) tariff, that is, retail electricity pricing varies hourly to reflect changes in the wholesale electricity market” (Zhang et al, 2014).

More recently, Zhang et al. (2017) proposed an optimization framework which can be applied to discrete event machining production system. In their model, large amount of energy is stored to decrease the cost in addition to the better achievement of scheduling goals. Recently, in both residential and industrial sectors, battery storage systems coupled with renewable generation technologies are becoming an appealing energy solution.

Cheng et al. (2018) have proposed a modified job shop scheduling problem optimization algorithm using a differential evolution algorithm model that speeds up the mathematical model solution. They have considered the shortest processing time as the evaluation index that has better application value when compared to the other algorithms.

1.4.3 Net-metering and Time of Use (TOU) rates

Net-metering Scheme:

Net-Metering is a billing mechanism which allows customers to offset some or all their electricity use with self-produced electricity from roof-top PV or other onsite DG units. It records the energy flow in both directions using a net meter. The meter spins forward when power is utilized from the grid and backward when the unused electricity is fed back to the grid. However, the customer is billed only for the electricity consumed. Various countries have adopted different net-metering laws and it provides substantial economic benefits in terms of jobs, income and investment.

Chaitusaney (2017) investigated an appropriate battery capacity and operation schedule of Battery Energy Storage System for rooftop with Net-Metering scheme. The methodology used Genetic Algorithm to compare the investment cost and O&M cost of Battery Energy Storage System (BESS) to maximize the electricity charge reduction. They make a comparison between self-consumption and net-metering scheme. The results show that net-metering scheme reduces customers electric charge due to reverse power flow, a significant saving in electricity charge.

Alhamad (2018) under Abu Dhabi Net-Metering Scheme, measured the feasibility of utilizing PV panels on the rooftop. The grid connected PV system was designed and simulated using a HOMER software. As a result, the PV system provided a high percentage of the building daily demand and fed the surplus electricity into the city grid to help in times of shortage.

Time-of-Use (TOU) Scheme:

A time-of-use is a scheme where the electricity usage is billed according to the time of usage by a customer. Basically, the electricity is billed high on peak hours compared to off-peak hours. The consumption of electricity can be managed from time-of-use scheme which will allow the consumer to save on high electricity usage and bills.

Dubey et al. (2015) evaluated various aspects of EV charging under a TOU schedule. They aim to determine the best practical time to begin the off-peak rates in a TOU schedule considering EV charging's voltage quality. An analytical approach is then taken to determine the factors affecting the EV load-shape profile using Monte Carlo simulation. In conclusion, the TOU schedule maximizes both grid power and customer satisfaction and suggests the best time to begin off-peak rates.

Erol-Kantarci et al. (2010) studied the consumption of energy and proposed management application for reducing the consumer bills. The paper aims to show the impact of this application on the peak load. The proposed application uses wireless communication and the sensor network. An algorithm is developed to determine the residential energy management. Finally, wireless sensor networks and smart grid energy management applications are integrated to reduce the consumer contribution for significant savings.

Shao et al. (2010) analyzed the impact of electricity rates of time-of-use on residential community. A DR model for residential customers is developed with PHEV penetration. The methodology concludes that the model can be also used to analyze other real-time pricing schemes. In conclusion, the DR model is also expected to benefit utilities and regulatory bodies to analyze the pricing schemes used in smart grid environment. The comparisons of major required topics that are involved in this research project are summarized in Table 1.1.

The remaining chapters in this thesis are organized as follows. In Chapter 2, we propose a mathematical model to attain zero carbon emissions for both single factory and multi-factory with onsite renewable generation under the Demand Response (DR) scheme. In Chapter 3, we propose a mathematical model to obtain zero carbon emissions for both single and multi-factory problems with interconnected microgrid system. In Chapter 4, we develop two mathematical models of a flow shop with interconnected microgrid system. The first one looks for the optimal machine-scheduling problem in a flow shop to attain power demand for each time-period. The second one, optimizes energy flow between the sources and the users. In Chapter 5, we use the same mathematical models that are developed in Chapter 4, for studying an island flow shop with microgrid system. In Chapter 6, we conclude the whole research and discuss the possible future work.

Table 1.1: Comparison of several key previous works and the proposed research

Topic	Existing Works			Our/Proposed Work
	Authors	Objective	Proposed Model	
Production planning integrated with onsite generation considering DR	Santana-Viera et al. (2015)	Maximize the DR program savings	Stochastic programming model to calculate the capacity of WT and PV systems	We proposed a stochastic linear programming model for carbon neutral production planning considering DR (Chapter 2)
	Jin et al. (2015)	Minimize the aggregate cost of energy and non-energy components	Stochastic Linear Programming model to optimize the production planning and renewable energy usage.	
Production planning integrated with microgrid system	Ji et al. (2016)	Achieve optimal solutions of production planning with demand uncertainties.	Two-dimensional stochastic optimization model for optimization of production planning	We incorporate battery systems for carbon neutral production planning to store excess energy (Chapter 3)
	Samad et al. (2012)	Improve the use of smart grid applications in industry	A case study on microgrid optimization for the development of atrium utility system	
Energy conservation using flow shop scheduling with onsite generation	Zhang et al. (2017)	Minimize the cost of energy required for flow shop scheduling	Mixed integer linear programming model for energy savings	We developed a mixed integer linear programming model to minimize total cost of the energy demand required for flow shop that process different throughputs. We solve model for both inter-connected and island microgrid systems (Chapters 4 and 5)
	Cheng et al. (2018)	Speed up the mathematical model solution to find the shortest processing time of job shop scheduling	Differential evolution algorithm model to speed up the mathematical solution.	

2. CARBON-NEUTRAL PRODUCTION-INVENTORY WITH DEMAND RESPONSE

2.1 A Single Factory and Single Warehouse System with Demand Response

2.1.1 System Setting

In this section, we consider a single manufacturing factory with a warehouse. We use electric vehicles (EVs) to transport the finished products from the factory to the warehouse. We incorporate two onsite renewable power systems: wind turbines (WT) and photovoltaic cells (PV) to generate energy for daily operations of the factory, the warehouse and the EV fleet. The main aim is to design a carbon-neutral production-inventory system.

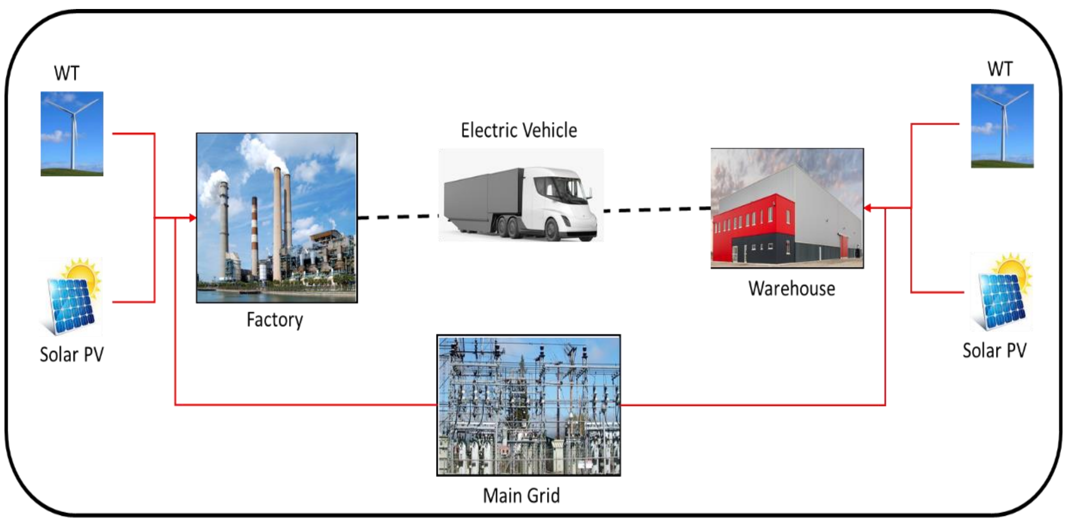

Figure 2.1:A single factory and single warehouse integrated with onsite generation

The goal of the optimization model is to determine the daily amount of energy produced through onsite WT and PV systems to meet the factory and warehouse power load. Due to the stochastic climate conditions, there is an uncertainty in the output of WT and PV, which leads to excess and scarcity of energy. At first, during the periods of energy shortage due to the low output of renewable energy resources, the factory needs to import the energy from the main grid to meet the required power demand. Secondly, if the onsite generation yields excess energy than the required, it is returned to the main grid. These two processes maintain the carbon-neutrality of the production-inventory system provided the sum of the imported and exported energy is zero. We consider two grid pricing policies, namely, net metering and feed-in-tariff rates. These policies are used for the energy exchange between the onsite energy generation and the main grid.

2.1.2 Production-Inventory Planning Model

In this section, we consider the production-inventory model for a single factory that produces multiple products over multiple periods. This model has been considered by Pham et al. (2018). The model is formulated and solved on weekly basis for 52 weeks (i.e. one year). In this research, the time-period is refined to a daily basis while the planning horizon spans also a whole year. In this model, we estimate the production cost, inventory cost and backorder cost for each product at each time-period produced by the factory. The mathematical model is formulated and explained in the following section.

I. Mathematical Model

The multi-period, multi-product, production-inventory model is denoted as Problem 2.1 and the following notation is used to formulate the model.

Notation

Set	**Definition**
I	Total number of products, i=1, 2, ..., I
J	Total number of production periods, j=1, 2, ..., J
K	Total number of facilities, k=0, 1, 2, ..., K, where k=0 for warehouse
R	Total number of resources required in production, for r=1, 2, ..., R

Parameter	**Definition**
p_{ijk}	Cost of making one unit of product *i* in period *j* in facility k ($/unit)
h_{ij}	Unit holding cost of product *i* in period *j* ($/period)
b_{ij}	Unit backorder cost of product *i* in period *j* ($/unit)
π_{ik}	Cost of shipping one unit of product *i* from facility *k* to the warehouse ($/unit)
v_{ikr}	Amount of resource *r* consumed for making one unit of product *i* in facility *k*
w_{jkr}	Available amount of resource *r* in period *j* in facility *k*
D_{ij}	Demand for product *i* in period *j*
μ_{ij}	Mean demand for product *i* in period *j*
σ_{ij}	Standard deviation of demand for product *i* in period *j*
γ	Probability of meeting the product demand γ

Decision Variable	**Definition**
x_{ijk}	Quantity of product *i* produced in period *j* in facility *k*
y_{ij}	Inventory of product *i* in period *j* in the warehouse
z_{ij}	Backorder of product *i* in period *j*

The objective of Problem 2.1 is to minimize the total production cost by finding the optimal values for the production, inventory and backorders. We formulate as Problem 2.1 as follows (Pham et al, 2018):

Problem 2.1:

Minimize:

$$f_1(\mathbf{x},\mathbf{y},\mathbf{z}) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}(p_{ijk}+\pi_{ijk})x_{ijk} + \sum_{i=1}^{I}\sum_{j=1}^{J}h_{ij}y_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J}b_{ij}z_{ij} \qquad (2.1)$$

Subject to:

$$\sum_{k=1}^{K} x_{ijk} + y_{ij-1} - y_{\mathrm{ij}} + z_{ij} \geq \mu_{D_{ij}} + Z_{\gamma}\sigma_{D_{ij}}\,; \quad for\ j = 1, and\ \forall i \tag{2.2}$$

$$\sum_{k=1}^{K} x_{ijk} + y_{ij-1} - y_{ij} + z_{ij-1} + z_{ij} \geq \mu_{D_{ij}} + Z_{\gamma}\sigma_{D_{ij}}\,;\ for\ j \geq 2, and\ \forall i \tag{2.3}$$

$$\sum_{i=1}^{I} v_{ikr} x_{ijk} \leq w_{jkr}; \quad \forall j,\ \forall r, and\ k = 1, 2, \dots, K \tag{2.4}$$

$$y_{ij} = 0\,; \quad for\ j = 1, and\ \forall i \tag{2.5}$$

$$z_{ij} = 0\,; \quad for\ j = \ J, and\ \forall i \tag{2.6}$$

x_{ijk}, y_{jk}, z_{jk} are non-negative integers

Problem 2.1 represents a deterministic linear integer programming model. The objective function (2.1) aims to minimize the total cost that includes production, inventory and backorder costs. Constraint (2.2) shows that for the first period, total production is greater than or equal to the demand with initial backorder and previous inventory, and not considering the initial inventory. Constraint (2.3) reveals that for all products, total production level with previous backorder and inventory should be greater than or equal to the Z-gamma percentile of the demand in the current period. Constraint (2.4) states that the total amount of resource *s* used to produce the products should be less than or equal to its capacity in any period. Constraints (2.5) and (2.6) indicates that inventory level for any product must be zero in first period and backorder level must be balanced to zero in last period.

II. Numerical Experiments

1. Input Parameters

To test the model, we consider various parameters and conduct numerical experiments to solve Problem 2.1 for a single factory and warehouse system. In this section, we reuse the major input parameters from Pham et al. (2018). To test the model, the production data is taken from a power intensive manufacturing process like a semiconductor fab that operates 24 hours a day, 7 days a week (i.e., 364 days). We assume that the factory produces two different types of product each with different demands per period. The various input parameters required to produce two products A and B are shown in Table 2.1.

Table 2.1: Input parameters for products A and B from Pham et al. (2018)

Parameter	**Notation**	**Product A (*i*=1)**	**Product B (*i*=2)**	**Unit**
Production cost (without energy)	p_i	400	600	$/unit
Holding cost	h_i	80	120	$/period/unit
Backorder cost	b_i	150	250	$/unit
Shipping cost (no EV recharge)	π_i	10	15	$/unit
Shipping cost (with EV recharge)	π_i	14	19	$/unit
Labor hours/item	v_{i1}	16	24	hours/unit
Machine hours/item	v_{i2}	100	200	hours/unit
Weight (including package)	m_i	3	4	Kg/unit
Mean demand	μ_{Dij}	1000	600	units/period
Standard deviation	σ_{Dij}	120	50	units/period

In this model we consider two important resources i.e., labor and machine hours, which are required to produce products in the factory. We re-use the capacity data of resources from the work by Pham et al. (2018) with the exception that the weekly resource capacity is now broken into the daily availability of resources. We then solve Problem 2.1 by considering the time-period as 364 days in a year. The availability of the labor and machine resources required for the production at each time-period are depicted in Figure 2.2.

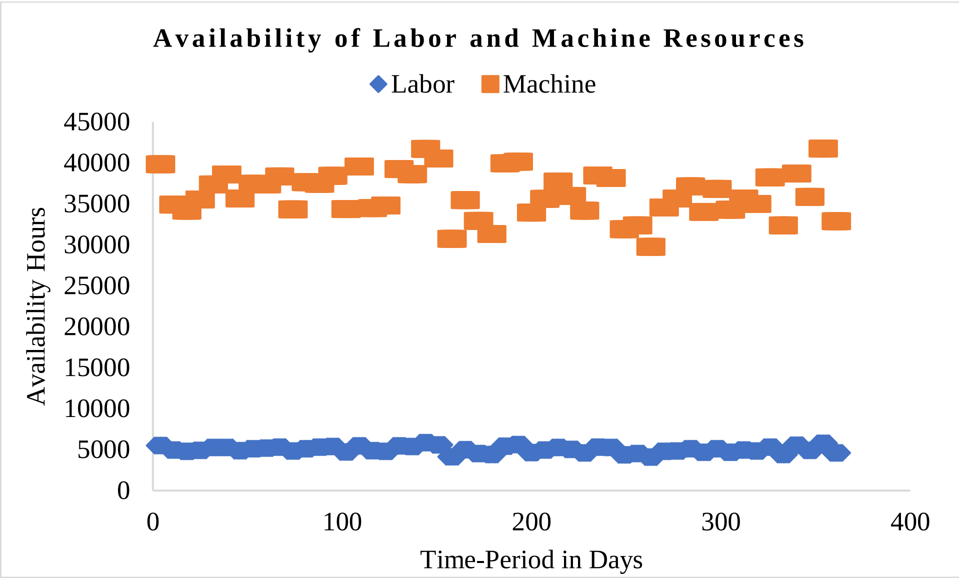

Figure 2.2: Daily available labor and machine capacity for the production.

2. Results and Analysis

We solved Problem 2.1 in AMPL software using CPLEX solver and the results of production, inventory and backorders of each product at each time-period for a factory are obtained. After solving Problem 2.1, we plot the amount produced of both products per period and the results are shown in Figures 2.3 and 2.4, respectively.

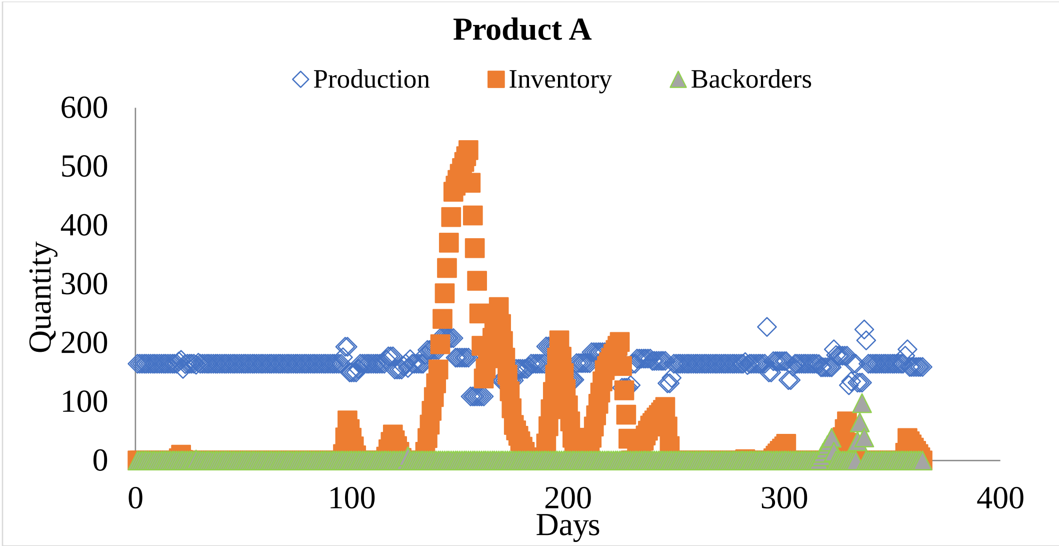

Figure 2.3: The production, inventory and backorders at each time-period for Product A.

In Figure 2.3, the quantity of production, inventory and backorders of Product A are drawn into graphs. The time-period of 364 days is represented in the horizontal axis, whereas the quantity of production, inventory and backorders are in the vertical axis.

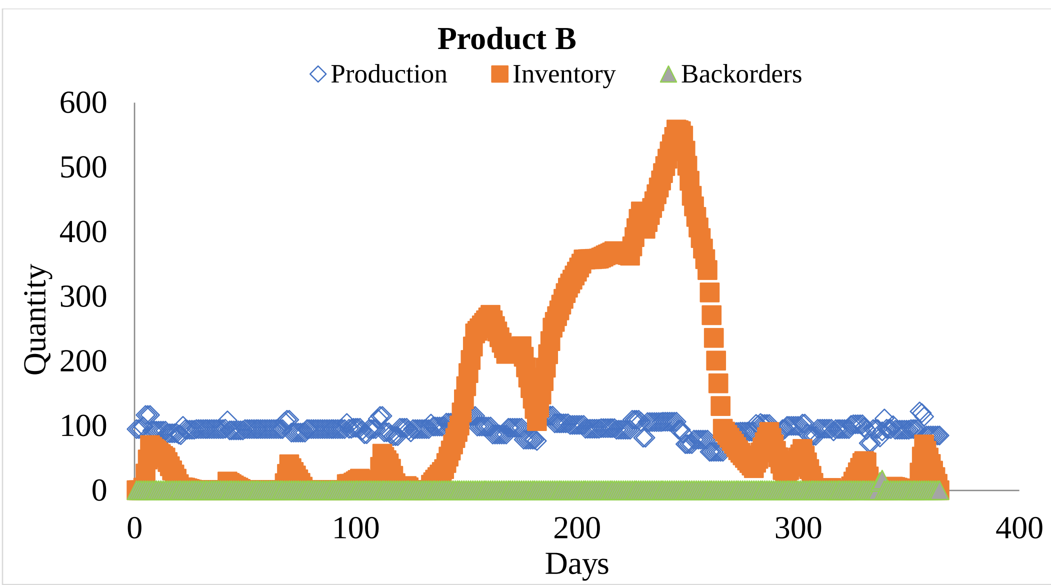

Figure 2.4: The production, inventory and backorders at each time-period for Product B.

Similarly, the optimal production, inventory and backorders for Product B in each time-period are represented in Figure 2.4. The model outputs, amount produced, inventory and backorders for Product B are represented in Y-axis.

2.1.3 Carbon-Neutral Production-Inventory with Demand Response

In this section, we develop and formulate a mathematical model for attaining carbon-neutral production-inventory operation with demand response. The model takes as input the production, inventory and backorder levels from the model represented in Section 2.1.2 and aims to minimize the onsite generation system cost model comprised of installation cost, operation and maintenance cost, and carbon credits. The model is also formulated to consider demand response (DR) events that occur between the factory and the utility company.

I. Mathematical Model

We label this model as Problem 2.2. The following notation is used to formulate the carbon-neutral production-inventory planning with DR model.

Notation

Parameter	**Definition**
q_v	Electric vehicle energy intensity rate (MWh/kg/km)
w_v	Vehicle self-weight (kg)
d_k	Distance between factory *k* and the warehouse (km)
m_i	Unit weight of product type *i* (kg/unit)
n_k	Number of yearly trips between factory *k* and the warehouse
τ_{gk}	Number of generation hours of technology *g* per period in facility *k*
t_w	Annual operating hours of the warehouse (hours)
a_g	Capacity cost for generation technology *g* ($/MW)
φ	Capital recovery factor of WT and PV system
b_g	Operation and maintenance cost for generation technology *g* ($/MWh)
c_g	Carbon credits for generation technology *g* ($/MWh)

e_{ik} Energy consumed for producing one unit of product *i* in facility *k* (MWh/unit)

L_0 Electricity demand (load) of the warehouse (MW)

$L_{jk}^{(DR)}$ Electricity load to be curtailed in facility *k* in period *j* (MW). It is random variable.

$T_{jk}^{(DR)}$ Duration of load curtailment in facility *k* in period *j* (hours). It is random variable.

ζ Random wind profile and weather conditions,

v_c, v_r, v_s Cut-in speed, rated speed and cut-off wind speed, respectively

x_{ijk} Quantity of product *i* produced in period *j* in facility *k*

$P_{gk}(\zeta)$ Random power output of generation technology *g* in location *k*

$\lambda_{gjk}(\zeta)$ Capacity factor of generation technology *g* in period *j* in facility *k*

E_ζ Expected value operator with respect to ζ

E_ψ Expected value operator with respect to DR event ψ

Decision Variable Definition

P_{gk}^c Capacity of generation technology *g* in facility *k*

P_{g0}^c Capacity of generation technology *g* in the warehouse

The Problem 2.2 is a mixed integer stochastic programming model that minimizes the renewable energy cost due to the installation of WT and PV in the factory and the warehouse. Problem 2.2 is formulated as follows.

Problem 2.2:

Minimize:

$$f_2(\mathbf{P^c}) = \varphi \sum_{g=1}^{G} \sum_{k=0}^{K} a_g P_{gk}^{c} + E_\zeta \sum_{g=1}^{G} \sum_{k=0}^{K} \sum_{j=1}^{J} \left(b_g \tau_{gk} \lambda_{gjk}(\zeta) P_{gk}^{c} - c_g \tau_{gk} \lambda_{gjk}(\zeta) P_{gk}^{c} \right) + f_1\,(x, y, z); \quad (2.7)$$

Subject to:

$$\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (e_{ik} + q_v d_k m_i) x_{ijk} + q_v n_k d_k w_v = E_\zeta \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{k=1}^{K} \tau_{gk} P_{gk}^{c} \lambda_{gjk}(\zeta) - E_\psi \sum_{j=1}^{J} \sum_{k=1}^{K} L_{jk}^{(DR)} T_{jk}^{(DR)};\ for\ k = 1,2, \dots, K \quad (2.8)$$

$$t_w L_0 + \sum_{k=1}^{K} q_v n_k d_k w_v = E_\zeta \sum_{j=1}^{J} \sum_{g=1}^{G} \tau_{g0} P_{g0}^{c} \lambda_{gj0}(\zeta) - E_\psi \sum_{j=1}^{J} \sum_{k=1}^{K} L_{j0}^{(DR)} T_{j0}^{(DR)};\ for\ k = 0 \quad (2.9)$$

$$P_{gk}^{c} \geq 0; \qquad \forall g\ and\ \forall k \quad (2.10)$$

In Problem 2.2, the objective function (2.7) minimizes the energy cost from the onsite microgrid. Constraint (2.8) is the energy balance equation that shows the annual power consumption by the factory *k* and e-vehicle must be counterbalanced with the energy produced by the onsite microgrid system plus the Demand response (DR) event that consist of curtailing events with length, $L_{jk}^{(DR)}$ and duration, $T_{jk}^{(DR)}$. Constraint (2.9) refers to the energy used at the warehouse and by the e-trucks. As in equation (2.9), this energy needs to be counteracted with the energy generated by the microgrid system. Constraint (2.10) describes the non-negativity of the P_{gk}^{c}.

To show the two-phase process for solving the stochastic optimization carbon neutral production-inventory planning model considering DR, a flowchart listing the different steps is provided in Figure 2.5.

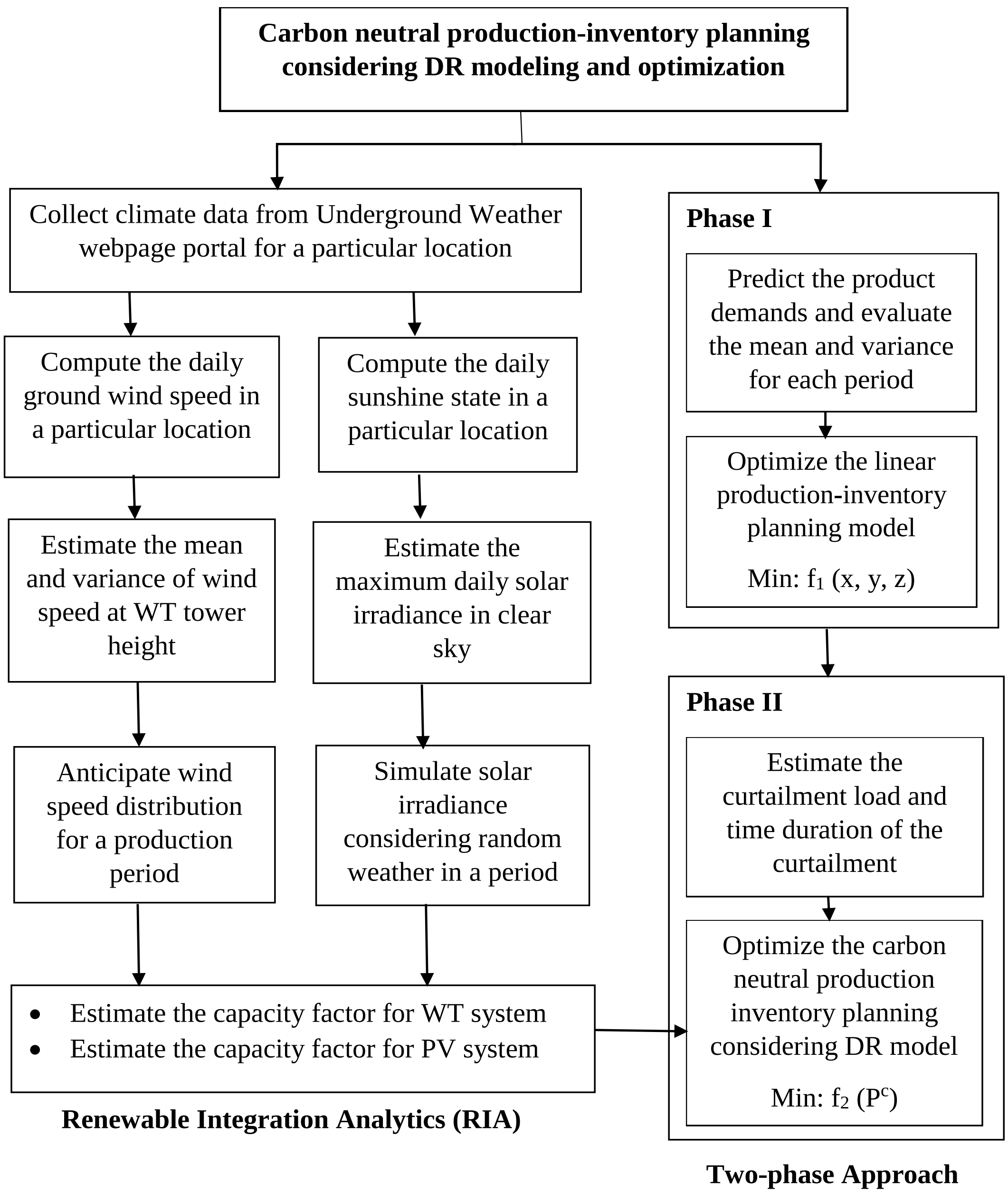

Figure 2.5:Flow chart for modeling and optimization of carbon neutral production-inventory planning considering DR.

II. Numerical Experiments

1. Input Parameters

To compare the results, we use the same input parameters as those in Pham et al. (2018). In this thesis, we use electric vehicle as transportation tool for goods being shipped from the factory to warehouse, which is mentioned in Section 2.1.1. We consider that the energy consumed, e_i, to produce Product A and Product B, is 0.27MWh/unit and 0.32MWh/unit, respectively. Let us assume that the self-weight and energy intensity rate of the vehicle are w_v = 5,000 kg and q_v = 1.19×10^{-7} MWh/kg/km, respectively. The factory operating period per year is t_w = 8,760 hours and a yearly power demand of the warehouse is L = 7 MW. We assume that, the maximum driving range for the electric vehicle considered in this model is d_{max} = 150 km and the vehicle will travel overall n_k = 186 trips/year between the factory and warehouse.

Problem 2.2 is a linear stochastic optimization model featuring two types of random variables:

1) Variable power generation $P_{gk}(\zeta)$ which is calculated by $P_{gk}(\zeta) = \lambda_{gk}(\zeta)\ P_{gk}^{c}$

2) Demand response (DR) event that consist of $L_{jk}^{(DR)}$ and $T_{jk}^{(DR)}$. A DR event typically involves three random variables: the probability of DR call in period j, and the curtailment level $L_{jk}^{(DR)}$(MW), and the duration of the curtailment $T_{jk}^{(DR)}$(hours).

The probability of DR call in period j can be modelled as Bernoulli random variable.

The curtailment level $L_{jk}^{(DR)}$ (MW) can be modelled as a discrete random variable as follows. We use the discrete probability to characterize the variability of curtailment levels. Let l_m for m=1, 2, ...q represents different levels to be curtailed under a DR call. Without loss of generality, it is assumed that $l_1<l_2<_{...}<l_q$. To make the model compact, we define l_1=0 to represent the case where no DR is called to facility k in period j. When a curtailment request is sent to the facility k in period j, the probability that the curtailment level is l_m can be expressed

$$Pr\left\{L_{jk}^{(DR)} = l_m\right\} = p_m, \text{for } m \in \{1,2 \ldots q\} \tag{2.9}$$

Obviously, the following condition is always satisfied

$$P_1+P_2+\ldots+P_q=1$$

We assume the manufacturer has no prior knowledge about the actual curtailment duration until he is notified 30-60 minutes in advance. However, the manufacturer should be aware of the maximum and the minimum durations of the DR event as they are usually written in the contract. Let $T_{jk}^{(DR)}$ be the duration of DR event in facility k in period j. Assume $T_{jk}^{(DR)}$ is in $[T_{min}, T_{max}]$ with an equal probability, where T_{min} and T_{max} be the minimum and the maximum curtailment durations, respectively. Then $T_{jk}^{(DR)}$ can be treated as a uniform random variable with the following probability density function.

$$f_{T_{jk}^{DR}}(x)=\begin{cases}\frac{1}{T_{max}-T_{min}}, & T_{min} \le x \le T_{max} \\ 0, & otherwise\end{cases}$$

By considering T_{max} = 8 hours and T_{min} = 4 hours, we generate random variables for 364 days, which gives time-duration of DR event for both factory and warehouse. The time duration of the DR event is shown in Figure 2.6.

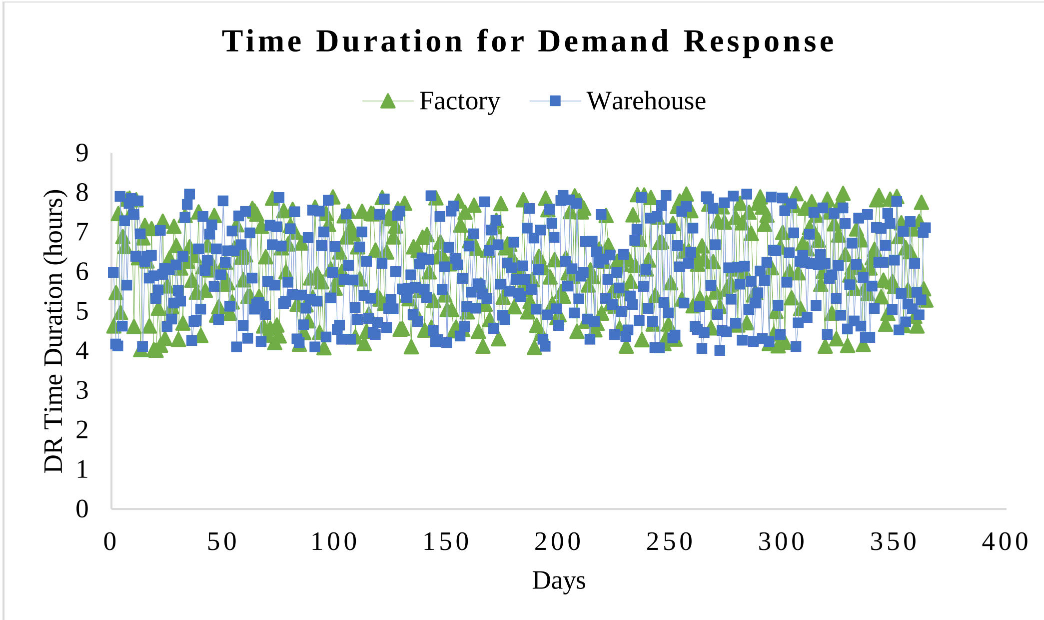

Figure 2.6: Time duration of the DR event in hours for both factory and warehouse.

We use the power demand data shown in Figure 2.7 for both factory and warehouse, which is required to calculate the load curtailment in DR.

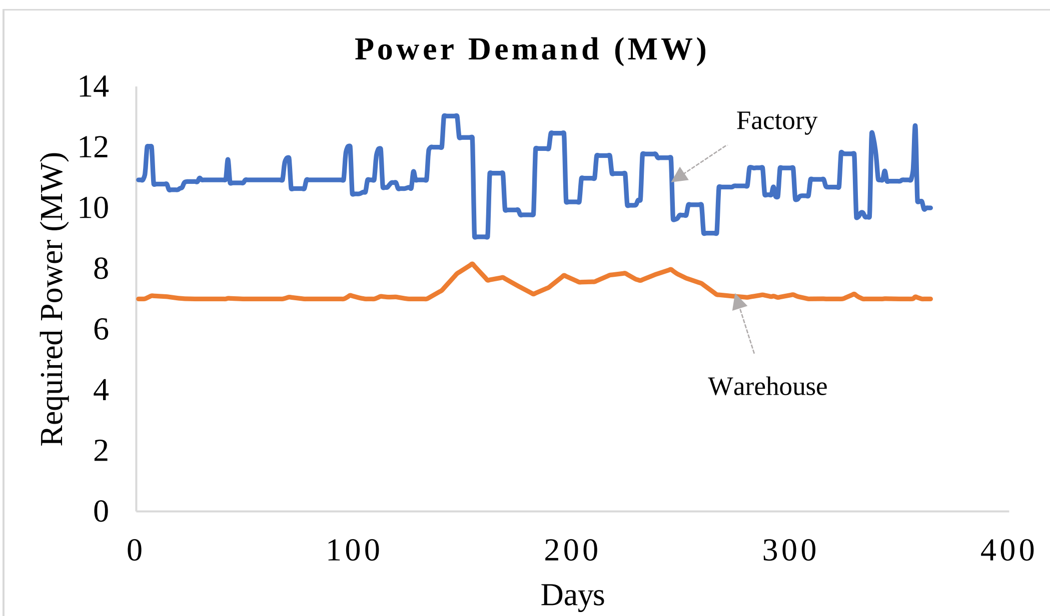

Figure 2.7:Power demand in MW for both factory and warehouse.

We have calculated the curtailment load by considering 5%, 10%, 15% and 20% of DR event and the power demand of each time-period for both factory and warehouse, respectively. The curtailment load for DR of both factory and warehouse in each time-period is plotted in Figure 2.8.

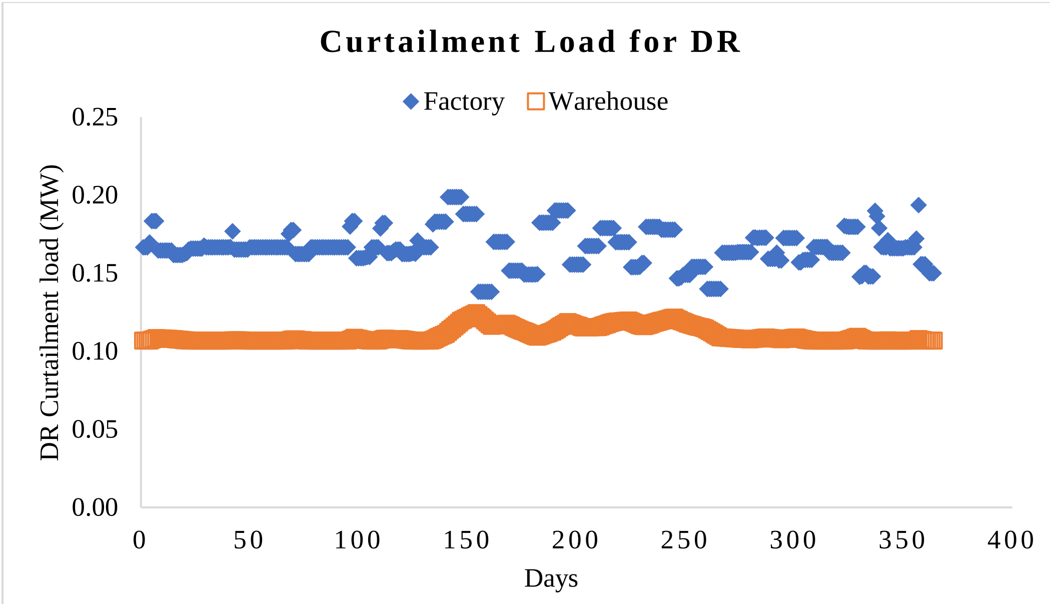

Figure 2.8:Curtailment load of DR in MW for both factory and warehouse.

At present, the efficiency of commercial PV panels is considered as η=0.15. In general, the PV is aligned with an azimuth angle α=0 rad, to the south in the northern hemisphere and to the north in the southern hemisphere. The data related to the cost and operation parameters of WT and PV are shown in Table 2.2.

Table 2.2: Operation and cost parameters of WT and PV systems from Pham et al. (2018).

WT system			**PV system**		
Notation	**Value**	**Unit**	**Notation**	**Value**	**Unit**
a_g	1.5×10^6	$/MW	a_g	3×10^6	$/MW
b_g	10	$/MWh	b_g	8	$/MWh
c_g	0	$/MWh	c_g	35	$/MWh
τ_g	24	hour/period	τ_g	12	hour/period
v_c	3	m/s	η	0.15	n/a
v_r	12	m/s	T_0	45	^{0}C
v_s	25	m/s	α	0	rad
n_e	20	year	n_e	20	year
i_e	0.05	n/a	i_e	0.05	n/a

To solve Problem 2.2, we must consider the factory is located at a particular geographical location. To test the model in different climatic conditions, we consider the location in three aspects such as large wind, strong sunshine and mixed wind and sunshine conditions. Thus, we consider the windier cities in the world. For instance, factory in Wellington, and a warehouse in Christchurch. For sunnier cities, we consider the factory at Aswan and the warehouse at Luxor. For mixed climatic conditions, we consider the factory at Yuma and the warehouse at San Francisco. To solve Problem 2.2, the capacity factors of WT and PV for each city is required. By considering the estimation data of WT and PV capacity factors from Pham et al. (2018), we estimate the WT and PV capacity factors on a daily basis. Thus, the process of estimating the capacity factors for WT and PV and calculating the energy intensity rate of an electric vehicle are explained in subsections **a**, **b** and **c** below.

a) Estimating the WT Capacity Factor

Generally, Automated Surface Observing Systems (ASOS) are installed 8-10 meters above the ground in the local airports of a city to record the wind speed (WU, 2017). At height h_g, Weather Underground measure the wind speed as v_g (m/s). As mentioned in Heier (2005), the calculation of wind speed at height h is given by

$$v_h = v_g \left(\frac{h}{h_g}\right)^k ; \qquad \text{for } h \geq h_g \tag{2.10}$$

where, 'k' is the Hellman exponent that is calculated by considering the seaside location, terrain shape, and the air stability. We assume the k- value between 0.27-0.34 in the populated areas (Blackadar et al, 1968; Heier, 2005).

Capacity Factor (CF) is the ratio of average power generated and the rated peak power. By considering Equation (2.11), the capacity factor of WT is calculated. (Pham et al, 2018)

$$\lambda_w = \frac{E[P_w(V)] \times T}{P_w \times T} = \frac{1}{v_r^3}\int_{v_c}^{v_r} v^3 f_w(v)dv + \left(F_w(vs\quad) - F_w(v_r)\right) \qquad (2.11)$$

$'\lambda_w'$ value lies in the range [0,1].

- $P_w(V)$ is the instantaneous output of WT at wind speed *v* and is formulated as: (Thringer et al, 1993)

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

where, v_c, v_r *and* v_s are cut-in-speed, the rated speed and the cut-off speed, respectively and P_m is the rated power capacity.

- The probability density function $f_w(v)$ and cumulative distribution function $F_w(v)$ for Weibull wind speeds are calculated as follows:

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

$$F_w(v) = e^{-\left(\frac{v}{c}\right)^k} \text{, for } v \ge 0.$$

where *k* and *c* are the shape and scale parameters, respectively.

We re-use the values of WT capacity factors for six cities such as Wellington, Christchurch, Aswan, Luxor, Yuma and San Francisco from Section 4.2 of Pham et al.

(2018). Thus, the capacity factors for WT are estimated for 364 days and are plotted as it is shown in Figure 2.9.

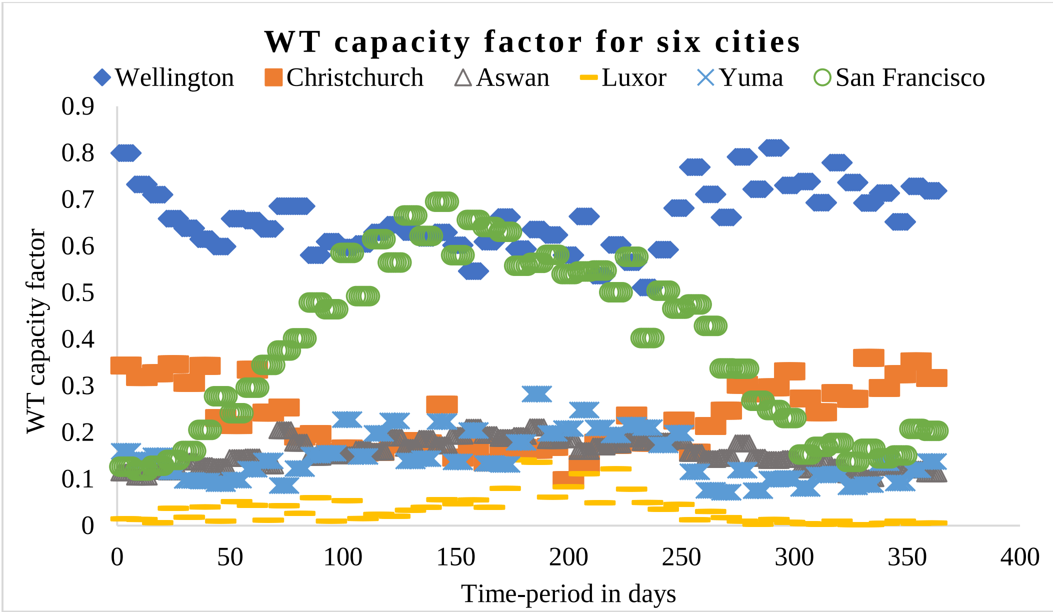

Figure 2.9: Estimated capacity factors of WT for six cities from Pham et al, 2018.

b) Estimating the PV Capacity Factor

Solar Irradiance I_t (W/m^2) is calculated when the solar radiation gets on the PV surface at time t in a clear sky day. The formula to calculate the solar irradiance is as follows: (Pham et al, 2018)

$$I_t = 1370\left(0.7^{(\cos\phi)^{0.678}}\right)\left(1 + 0.034\cos\left(\frac{2\pi(d-4)}{365}\right)\right)\left(\cos\theta + 0.1\left(1 - \frac{\beta}{\pi}\right)\right) \quad (2.12)$$

where,

$$\cos\phi = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi$$

$$\cos\theta = \cos\delta\cos\omega$$

The actual power output of a PV system, 'P_t', considering the uncertain weather conditions can be calculated as follows:

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

where W_t is a weather coefficient that varies from 0 and 1;

Thus, the capacity factor of PV is calculated by using the following formula:

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

where P_{PV}^{max} is the PV system rated capacity and T is the number of hours; In southern hemisphere, we assume $\alpha = \pi$ and convert ϕ to a native angle.

Using the formulas above, which are the same as in Section 4.3 of Pham et al. (2018), the values for the PV capacity factors are calculated for six cities: Wellington, Christchurch, Aswan, Luxor, Yuma and San Francisco. The capacity factors for PV are estimated for 364 days and they are shown in the Figure 2.10.

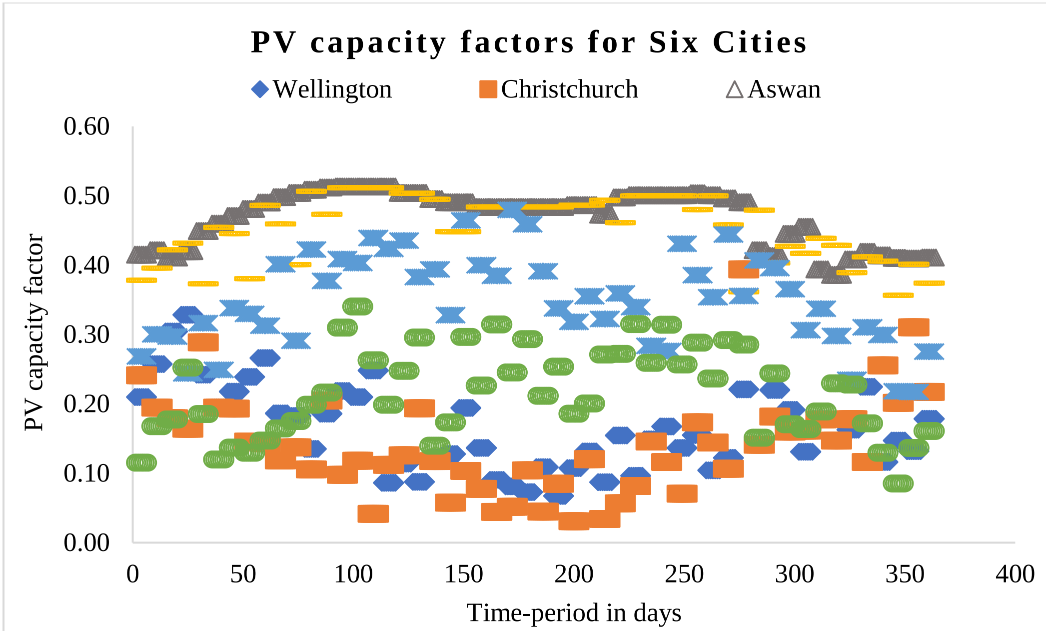

Figure 2.10:Estimated capacity factors of PV for six cities from Pham et al. 2018.

c) Electric Vehicle Energy Intensity Rate

An electric vehicle requires power to transport the product from one place to the other place by considering the product weight, the travel distance and the vehicle speed. Thus, the energy intensity rate of the vehicle is the amount of energy consumed to transport one-kilogram product over one kilometer at a certain speed and is denoted as follows:

$$q_v = \frac{E_{EV}}{m \times d_{max}} \tag{2.13}$$

where E_{EV} is a battery capacity in MWh, d_{max} (km) is the driving range at speed v, and m is the vehicle weight in addition to the load weight.

2. Results and Analysis

Problem 2.2 is coded using the AMPL programming language and the CPLEX solver running in an Intel(R) Core (TM) i7-8550U processor, which runs at 1.8 GHz 1.99 GHz, and 12 GB DRAM. The current model has four continuous decision variables and six constraints. We have solved Problem 2.2 by considering the output of Problem 2.1 and all the input parameters presented in Section 2.1.3. After solving Problem 2.2, the results were shown in the three cases and shown in Table 2.3.

Table 2.3: The output of carbon-neutral production inventory model with DR model

		Case 1	**Case 2**	**Case 3**
		Wellington (F), Christchurch (WH)	Aswan (F), Luxor (WH)	Yuma (F), San Francisco (WH)
	Cost ($)	54,037,167	61,317,877	59,698,137
Factory	WT (MW)	16.65	0	75.63
	PV (MW)	0	46.81	0
Warehouse	WT (MW)	30.19	0	18.25
	PV (MW)	0	31.08	0

** F – Factory, WH – Warehouse **

As shown in Table 2.3, we consider three cases in which each case is related to the one factory and one warehouse. After solving Problem 2.2 for three cases, we obtain the outputs like the total cost of the system and the capacity of required generation technology at a particular location for both factory and warehouse. The results are explained in detail as follows:

- Case 1 is related to the Wellington (factory) and Christchurch (warehouse). In Case 1, the total cost required for the system is $54,037,167 and the WT system is preferred by both factory and warehouse with a capacity of 16.65MW and 30.19MW, respectively. There is no PV installation for both factory and warehouse because of the windy climatic conditions in both cities.

- Case 2 is related to the Aswan (factory) and Luxor (warehouse). In Case 2, the total required cost for the system installation is $ 61,317,877. In Aswan and Luxor, only PV system is installed with a capacity of 46.81MW and 31.08MW, respectively. Due to their sunny climate, wind generation is not competitive compared with PV.

- Case 3 is related to the Yuma (factory) and San Francisco (warehouse). In Case 3, the total system investment cost is $ 59,698,137. Only WT system is used for both Yuma and San Francisco with an installed capacity of 75.63MW and 18.25MW, respectively. There is no PV installation for both cities due to the windy climatic conditions in both cities.

2.1.4 Comparison of the Results with DR and without DR

In this section of the research, we compare the results between the system considering DR and without DR. The comparison of both systems for three cases is shown in Table 2.4.

Table 2.4: Comparison of Problem 2.2 results with DR and without DR.

				Factory		Warehouse	
Case		DR	Cost ($)	WT (MW)	PV (MW)	WT (MW)	PV (MW)
1	Wellington (F), Christchurch (WH)	No	54,009,372	16.59	0	30.07	0
		Yes	54,037,167	16.65	0	30.19	0
2	Aswan (F), Luxor (WH)	No	61,262,101	0	46.63	0	30.96
		Yes	61,317,877	0	46.81	0	31.08
3	Yuma (F), San Francisco (WH)	No	59,648,754	75.35	0	18.19	0
		Yes	59,698,137	75.63	0	18.25	0

In Table 2.4, results between the system with DR and without DR are compared for three cases considering the single factory with single warehouse. In Case 1, it is clearly shown that the total cost of the system with DR is only 0.005% higher than the system without DR and it installs almost the same WT capacity with average of 16.5MW in

Wellington and 30.1MW in Christchurch. In Case 2, the total cost of the system with DR is only 0.09% higher than the system without DR and consumes almost the same PV capacities of an average 46.5MW and 31MW in Aswan and Luxor, respectively. The total cost of the system with DR is only 0.06% higher than the total cost of the system without DR and consumes almost the same WT capacities of 75.5MW and 18.2MW in Yuma and San Francisco, which is shown in Case 3 of Table 2.4.

2.2 Multi-Factory and Single Warehouse System

2.2.1 System Setting

In this section, we consider that there are two factories and one warehouse, and an electric truck is used to transport the products between the factories and the warehouse. Onsite renewable energy generators like WT and PV systems are installed at both factories and warehouse.

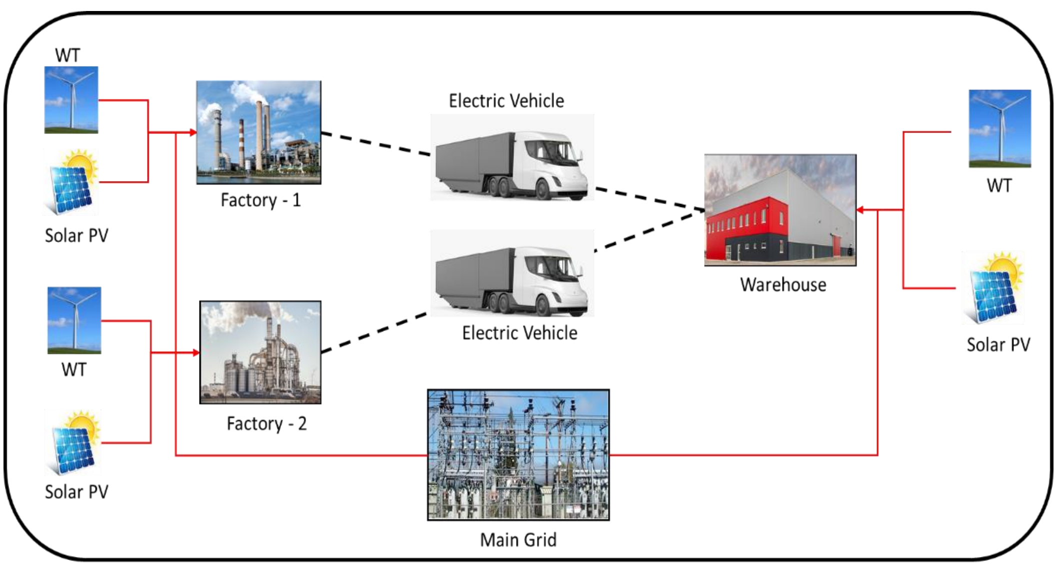

Figure 2.11:A multi-factory with single warehouse integrated with onsite generation

In this system, all facilities are connected to the main grid to receive the energy during its low generation period due to low outputs of renewable energy resources and to fed back energy to the grid during the surplus renewable energy generation period. Same as a single factory and single warehouse system, we consider two grid pricing policy, namely, net-metering and feed-in-tariff in exchanging of energy between the facilities and the main grid.

2.2.2 Numerical Experiments

a) Production-Inventory Planning Model

1. Input Parameters

For multi-factory with single warehouse, we use the same input parameters that are used in the single factory and single warehouse model. But the availability of two resources like labor and machine for the multi-factory case will differ from the single factory. We use the weekly availability of resources data for two-factory and single warehouse from Pham et al. (2018) and break the weekly data into a daily basis. The availability of labor and machine resources for 364 days are now duplicated in Figures 2.12 and 2.13.

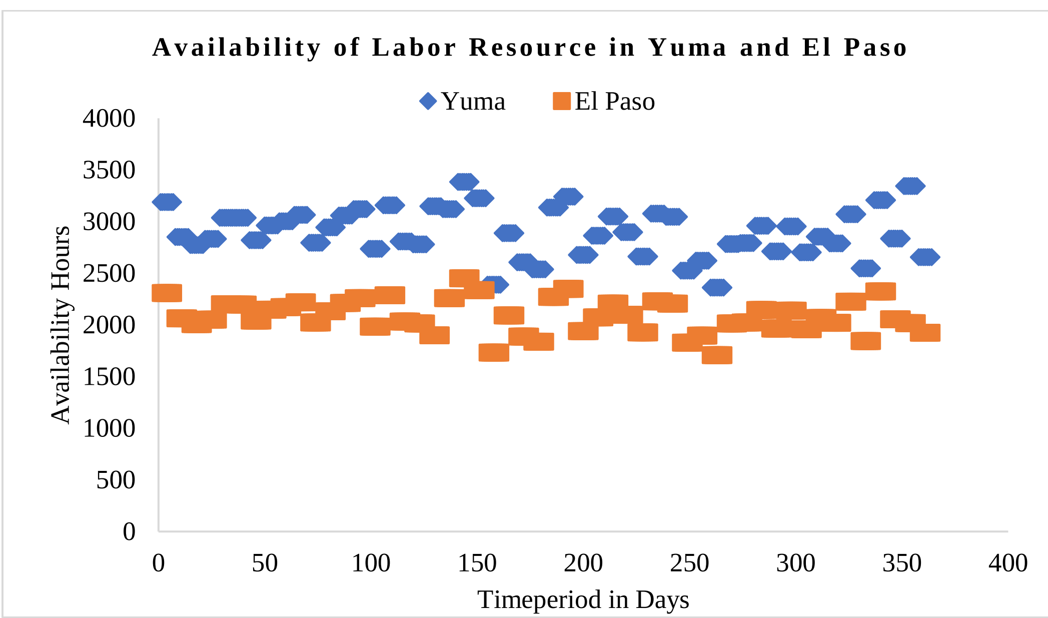

Figure 2.12: Availability of labor resource in Yuma and El Paso

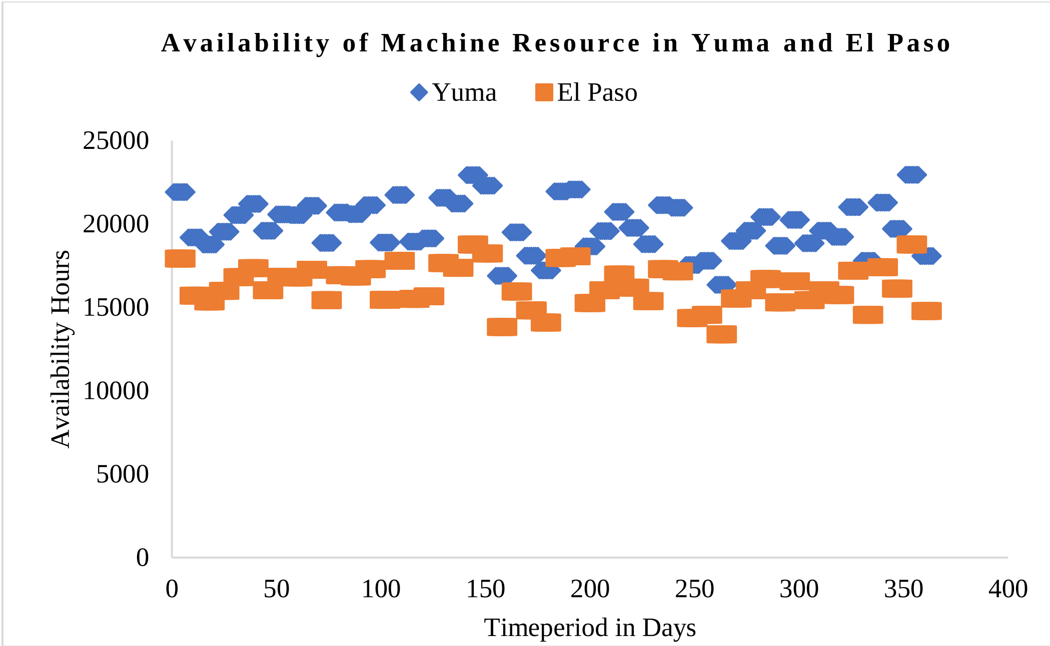

Figure 2.13: Availability of machine resource in Yuma and El Paso

2. Results and Analysis

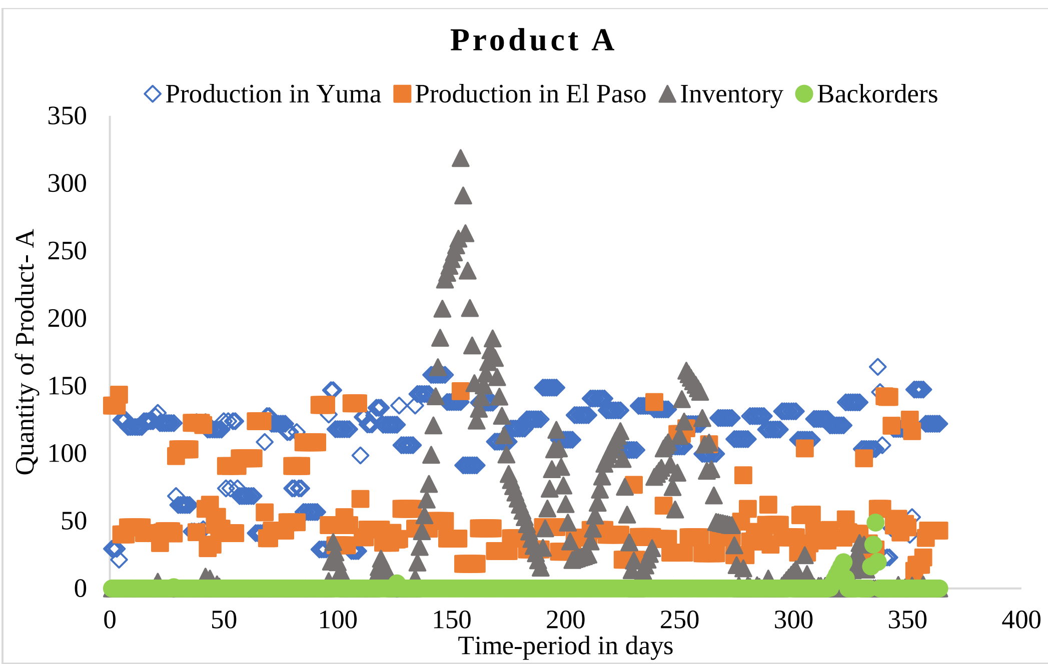

Figure 2.14:The production, inventory and backorders at each time-period for Product A in multi-factory and single warehouse.

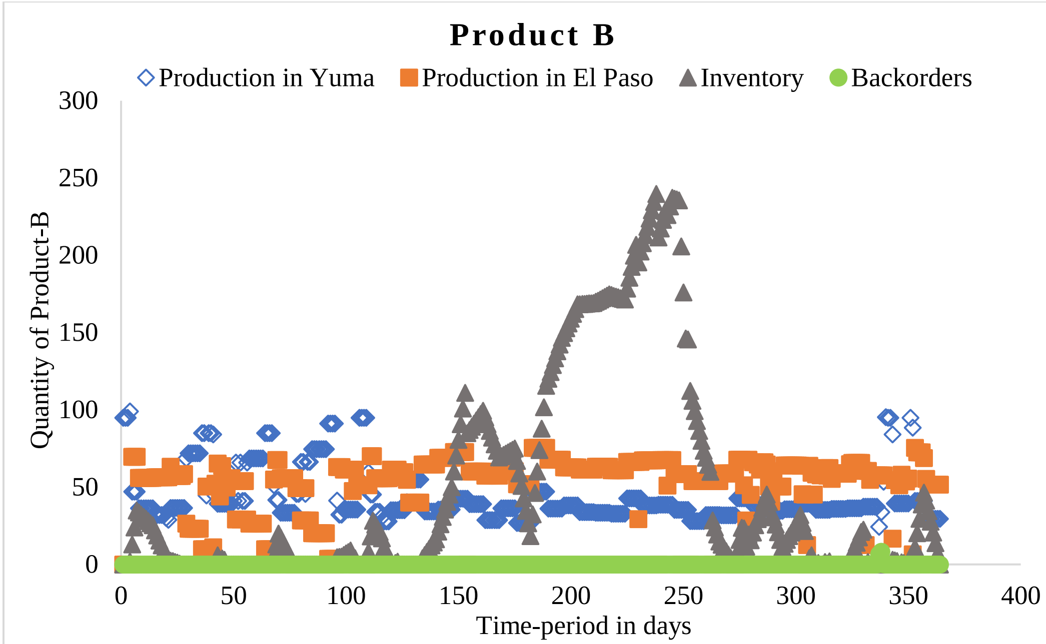

Figure 2.15: The production, inventory and backorders at each time-period for Product B in multi-factory and single warehouse.

b) Carbon-Neutral Production Inventory Planning with Demand Response Model

1. Input Parameters

To optimize carbon-neutral production inventory system subject to random demand response, we assume that Factory 1 is in Yuma, Arizona, Factory 2 is located in El Paso, Texas, and the warehouse is sited in Phoenix, Arizona. Similarly, the capacity factors of WT and PV corresponding to three cities are plotted in Figures 2.16 and 2.17, respectively.

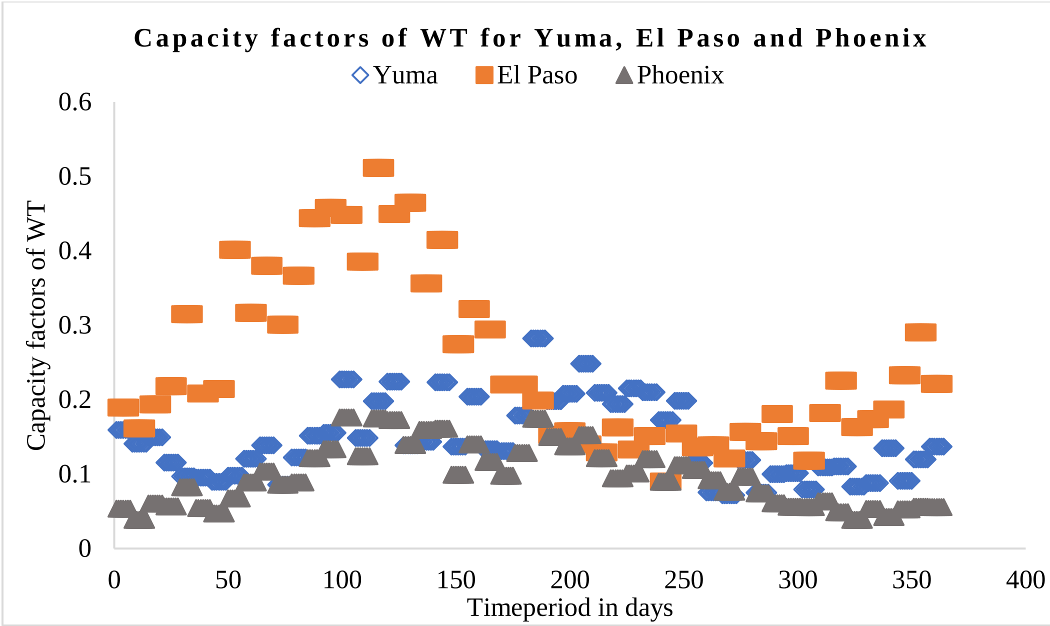

Figure 2.16: Capacity factors of WT for Yuma, El Paso and Phoenix from Pham et al., 2015.

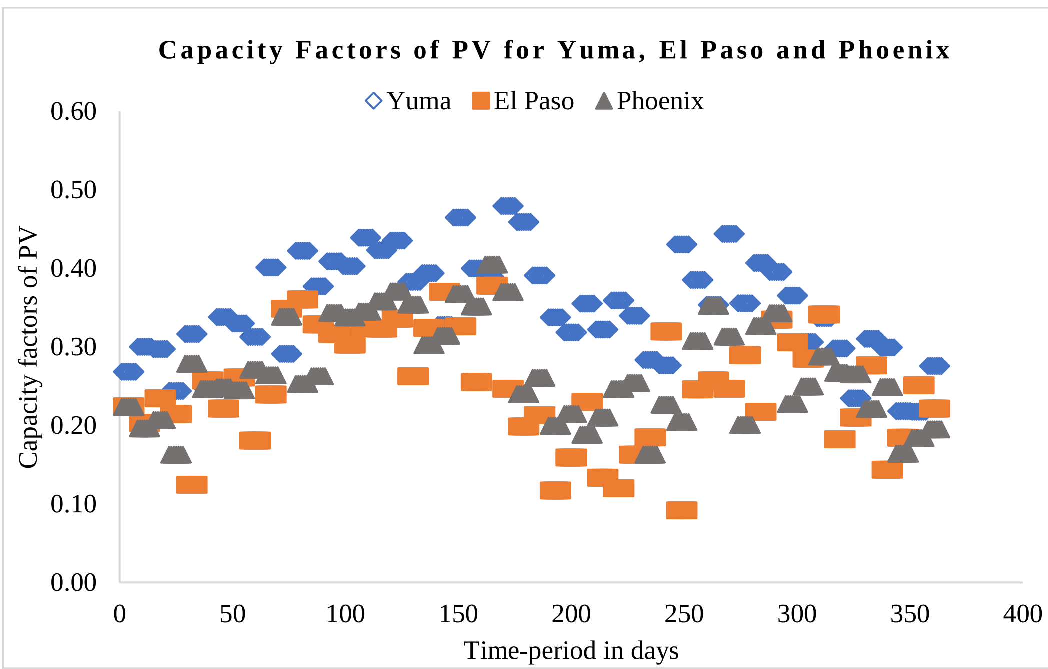

Figure 2.17: Capacity factors of PV for Yuma, El Paso and Phoenix from Pham et al., 2015.

2. Results and Analysis

We solved Problem 2.2 for multi-factory with single warehouse considering Yuma and El Paso, where two factories are located, and Phoenix where the warehouse is located. Three different cases, namely Cases 4, 5 and 6, capturing the PV cost variation and the carbon credits are considered as shown in Table 2.5. Problem 2.2 is coded using the AMPL programming language and the CPLEX solver running in Intel(R) Core (TM) i7-8550U processor, which runs at 1.8 GHz 1.99 GHz, and 12 GB DRAM. The current model has six continuous decision variables and 9 constraints, and the results were shown in Table 2.5.

Table 2.5: The output of carbon-neutral production inventory model with DR model

	Case 4		Case 5		Case 6	
PV Capacity Cost ($)	3M/MW		2M/MW		1.5M/MW	
Carbon Credit ($/MWh)	35		0		0	
Total Cost ($)	64,083,974		63,663,550		60,553,929	
City	RES (MW)	Capacity	RES (MW)	Capacity	RES (MW)	Capacity
Yuma (factory 1)	WT	43.45	WT	43.45	PV	36.07
El Paso (factory 2)	WT	18.43	WT	18.43	WT	18.43
Phoenix (warehouse)	WT	72.69	PV	52.66	PV	52.66

In Table 2.5, as mentioned in Case 4, if we consider the PV capacity cost of $3M/MW with a carbon credit of $35/MWh, then the system consumes WT system in both factories as well as in the warehouse with a capacity of 43.45MW in Yuma (Factory 1), 18.43MW in El Paso (Factory 2) and 72.69MW in Phoenix (warehouse), and the total cost of the system is $64,083,974. As shown in Case 5, if we reduce the PV cost to $2M/MW with zero-carbon credit, then still system consumes the same WT capacities in both factories, but in warehouse the system consumes PV instead of WT with a capacity of 52.66MW and the total cost of the system is reduced to $63,663,550. In Case 6, if PV capacity cost still reduced to $1.5M/MW, then the system considers PV system with a capacity of 36.07 MW in Yuma, WT system with the same capacity of 18.43 MW in El Paso and PV system with a same capacity of 52.66 MW in Phoenix. The total cost of the system is reduced to $ 60,553,929 in Case 6.

3. CARBON-NEUTRAL PRODUCTION-INVENTORY MODEL WITH ENERGY STORAGE

3.1 A Single Factory and Single Warehouse System with Battery Storage

3.1.1 System Setting

In this chapter, we consider a single factory and a single warehouse system in which the microgrid system is equipped with battery storage system (BSS). The whole system is connected to the main grid through the local substation as shown in Figure 3.1. An electric truck is used to ship the products from the factory to the warehouse.

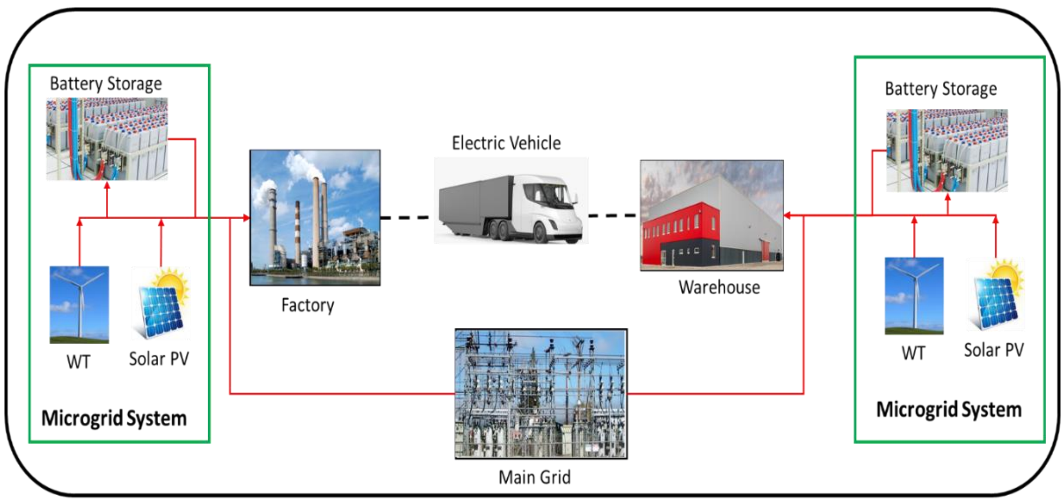

Figure 3.1: A single factory and single warehouse integrated with microgrid system.

As shown in Figure 3.1, the factory and the warehouse both are connected to a microgrid system that are comprised of WT, solar PV and BSS, respectively. The microgrid systems are connected to the main grid that supplies the power when the power demand is higher than the microgrid output. If surplus power is produced by the microgrid system, it will be fed back to the main grid through net metering or feed-in tariff scheme.

3.1.2 Production Inventory Planning Model

In this section, we solve the production inventory model as we did in Section 2.1.2 and we got the same results for two products of a factory and they were shown in the following graphs of Figures 3.2 and 3.3, respectively.

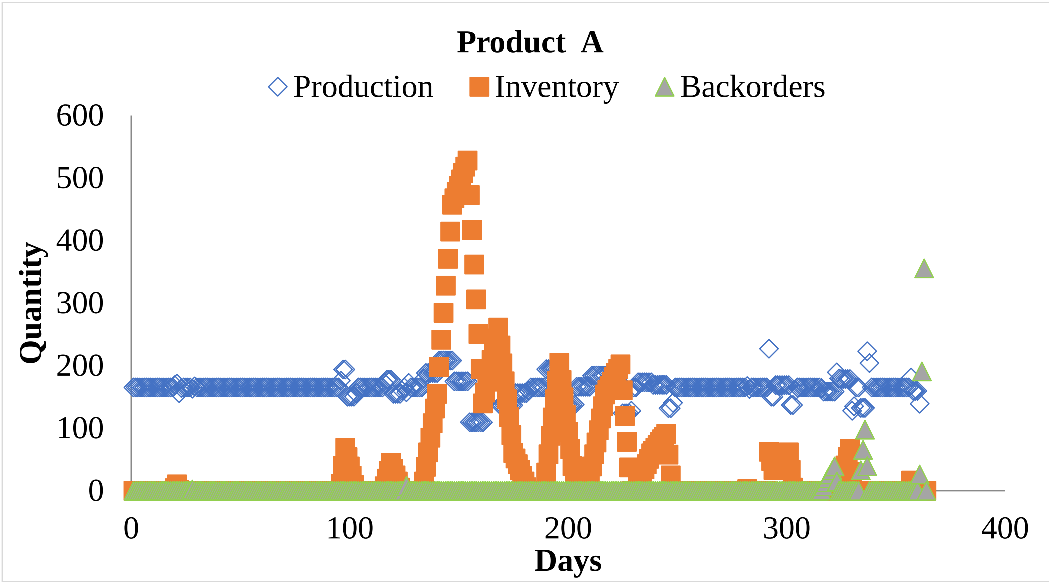

Figure 3.2:The production, inventory and backorders at each time-period for Product A.

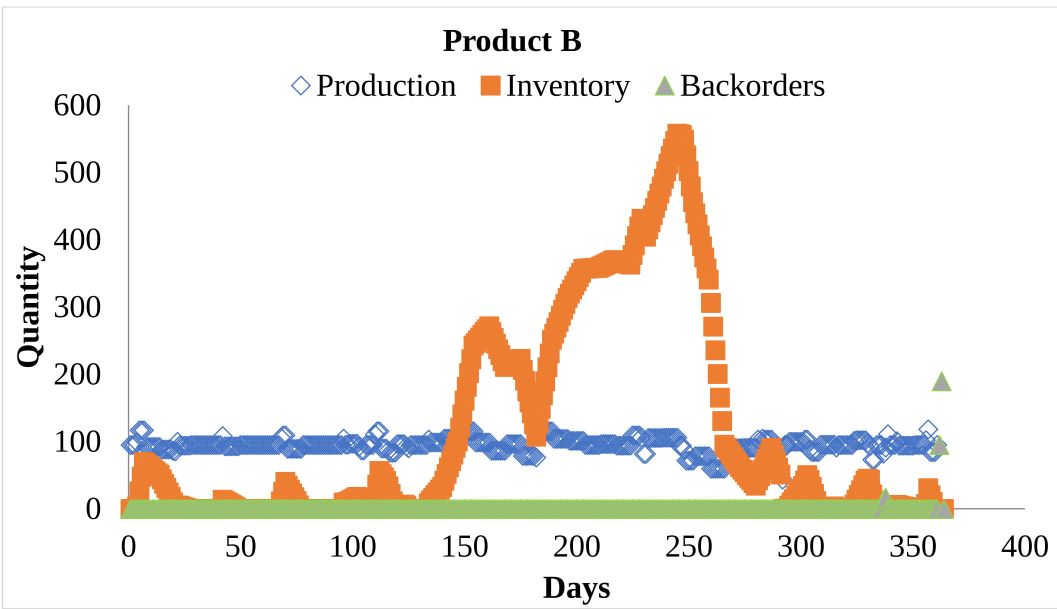

Figure 3.3: The production, inventory and backorders at each time-period for Product B.

3.1.3 Carbon-Neutral Production-Inventory with Battery Storage Model

I. Mathematical Model

We expand Problem 2.2 from Pham et al. (2018) by adding the battery storage systems, and the following notation were used to formulate the carbon-neutral production-inventory planning with battery storage option.

Notation

Parameter	**Definition**
q_v	Electric vehicle energy intensity rate (MWh/kg/km)
w_v	Vehicle self-weight (kg)
d_k	Distance between factory *k* and the warehouse (km)
m_i	Unit weight of product type *i* (kg/unit)
n_k	Number of yearly trips between factory *k* and the warehouse
τ_{gk}	Number of generation hours of technology *g* per period in facility *k*
t_w	Annual operating hours of the warehouse (hours)
a_g	Capacity cost for generation technology *g* ($/MW)
φ	Capital recovery factor of WT and PV system
γ	Probability of meeting the product demand γ
b_g	Operation and maintenance cost for generation technology *g* ($/MWh)
c_g	Carbon credits for generation technology *g* ($/MWh)
e_{ik}	Energy consumed for producing one unit of product *i* in facility *k* (MWh/unit)
x_{ijk}	Quantity of product *i* produced in period *j* in facility *k*
L_0	Electricity demand (load) of the warehouse (MW)
ζ	Random wind profile and weather conditions,
v_c, v_r, v_s	Cut-in speed, rated speed and cut-off wind speed, respectively
$P_{gk}(\zeta)$	Random power output of generation technology *g* in location *k*

$\lambda_{gjk}(\zeta)$ Capacity factor of generation technology *g* in period *j* in location *k*

E_ζ Expected value operator with respect to ζ

B_{jk}^{s} Energy stored in the battery in period *j* at facility *k*

B_{j-1k}^{s} Energy stored in the battery in period *j-1* at facility *k*, note that $B_{0k}^{s} = 0$

Decision Variable	**Comments**
P_{gk}^{c}	Capacity of generation technology *g* in facility *k*
B_{k}^{c}	Battery storage capacity (unit: MWh) at facility *k*

The main objective of this mathematical model is to minimize the total annual operation cost comprised of non-energy production, renewable generating units and the battery system installed in a factory as well as in the warehouse. Problem 3.1 is formulated as follows.

Problem 3.1:

Minimize:

$$f_2(\mathbf{P^c}, \mathbf{B^c}) = \varphi_g \sum_{g=1}^{G} \sum_{k=0}^{K} a_g P_{gk}^{c} + \varphi_b \sum_{k=0}^{K} B_{k}^{c} + E_\zeta \sum_{g=1}^{G} \sum_{k=0}^{K} \sum_{j=1}^{J} \left(b_g \tau_{gk} \lambda_{gjk}(\zeta) P_{gk}^{c} - c_g \tau_{gk} \lambda_{gjk}(\zeta) P_{gk}^{c} \right) + f_1(x, y, z); \tag{3.1}$$

Subject to:

$$\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (e_{ik} + q_v d_k m_i) x_{ijk} + q_v n_k d_k w_v + B_{jk}^{s} - B_{j-1k}^{s} \leq E_\zeta \sum_{j=1}^{J} \sum_{g=1}^{G} \sum_{k=1}^{K} \tau_{gk} P_{gk}^{c} \lambda_{gjk}(\zeta) \, ; for\ k = 1,2, \dots K \tag{3.2}$$

$$t_w L_0 + \sum_{k=1}^{K} q_v n_k d_k w_v + B_{j0}^s - B_{j-1,0}^s \leq E_\zeta \sum_{j=1}^{J} \sum_{g=1}^{G} \tau_{g0} P_{g0}^c \lambda_{gj0}(\zeta) \quad for \quad k = 0 \tag{3.3}$$

$$0 \leq B_{jk}^s \leq B_k^c; \qquad \forall k \; and \; \forall j \tag{3.4}$$

$$B_{0k}^s = 0; \qquad \forall k \tag{3.5}$$

$$B_{Jk}^s = 0; \qquad \forall k \tag{3.6}$$

$$P_{gk}^c \geq 0; \qquad \forall g \; and \; \forall k \tag{3.7}$$

$$B_k^c \geq 0; \qquad \forall k \tag{3.8}$$

In Problem 3.1, the main objective function (3.1) is to minimize the total cost of the production, inventory, backorder and the energy produced by microgrid systems. Constraint (3.2) is the energy balance equation that shows the annual power consumption by the factory k, e-vehicle and battery storage must be counterbalanced with the onsite generation system energy. Constraint (3.3) indicates the energy used at the warehouse, battery storage and by the e-trucks. As shown in equation (3.4), energy stored in the battery should not exceed its capacity and must be non-negative. Constraints (3.5) and (3.6) reveal that there is no energy storage in the battery at initial and final periods for both facility k and warehouse. Constraints (3.7) and (3.8) explain the non-negativity of the P_{gk}^c and B_k^c.

II. Numerical Experiments

1. Input Parameters

To solve Problem 3.1 of this Chapter 3, we use the same input parameters that we used in Section 2.1.3. In addition to that, we use the following input parameters in Table 3.1 as they are required for the battery system under study.

Table 3.1: Input parameters for the optimization of Problem 3.2

Comments	Notation	PV System	WT System	Battery System
Capital Recovery Factor	ϕ	0.0802	0.0802	0.1295
Cost	a	$ 3×10^6 – 1×10^6/MW	$ 1.5×10^6/MW - $$3\times10^6$/MW	$ 0.5×10^6 – 0.01×10^6/ MWh

As shown in Table 3.1, we perform sensitivity analysis for Problem 3.1 by changing the capacity costs of battery storage, WT and PV systems. Particularly we change the capacity costs of PV system from $3M/MW to $1M/MW, WT system from $1.5M/MW to $3M/MW and, battery storage system from $0.5M/MWh to $0.01M/MWh.

2. Results and Analysis

Problem 3.1 is coded using the AMPL programming language and the CPLEX solver running in an Intel(R) Core (TM) i7-8550U processor, which runs at 1.8 GHz 1.99 GHz, and 12 GB DRAM. The current model has six continuous decision variables and 742 constraints. The results obtained in AMPL are plotted, including the levelized cost of energy (LCOE) explained in Section 1.3 and the optimal capacities of WT, PV and BSS. To capture the diverse climate conditions world-wide, Problem 3.1 is solved for three city pairs, namely Wellington and Christchurch, Aswan and Luxor, and Yuma and San Francisco. The different battery capacity costs for both factory and warehouse are denoted in X-axis. The LCOE and the power and battery capacities are presented in the Y-axis of the graphs.

a) Wellington (Factory) – Christchurch (Warehouse):

After solving Problem 3.1 for the factory in Wellington and the warehouse in Christchurch and doing sensitivity analysis, the outputs were drawn into graphs for various input parameters mentioned in Table 3.1 and represented in following Figures 3.4 to 3.7.

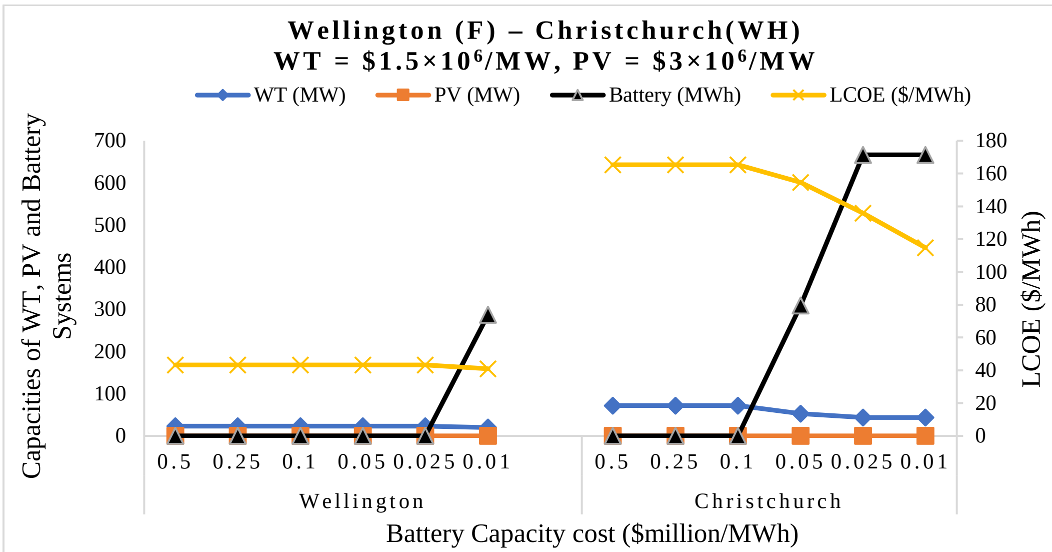

Figure 3.4: Results for the microgrid system of the factory in Wellington and the warehouse in Christchurch, at WT=$1.5M/MW and PV=$3M/MW.

In Figure 3.4, at the capacity costs of WT=$1.5M/MW and PV=$3M/MW, the system considers WT system in both factory and warehouse for all battery capacity costs with an average capacity of 23.04MW and 53.03MW respectively, and there is no PV consumption for both cities. The system consumes the energy from the battery system with a capacity of 287.84MWh at a capacity cost of $0.01M/MWh in Wellington and, 309.15MWh at $0.05M/MWh and 666.6MWh at $0.025M-0.01M/MWh in Christchurch. The average LCOE of the microgrid system in Wellington and Christchurch are $43/MWh and $155/MWh, respectively.

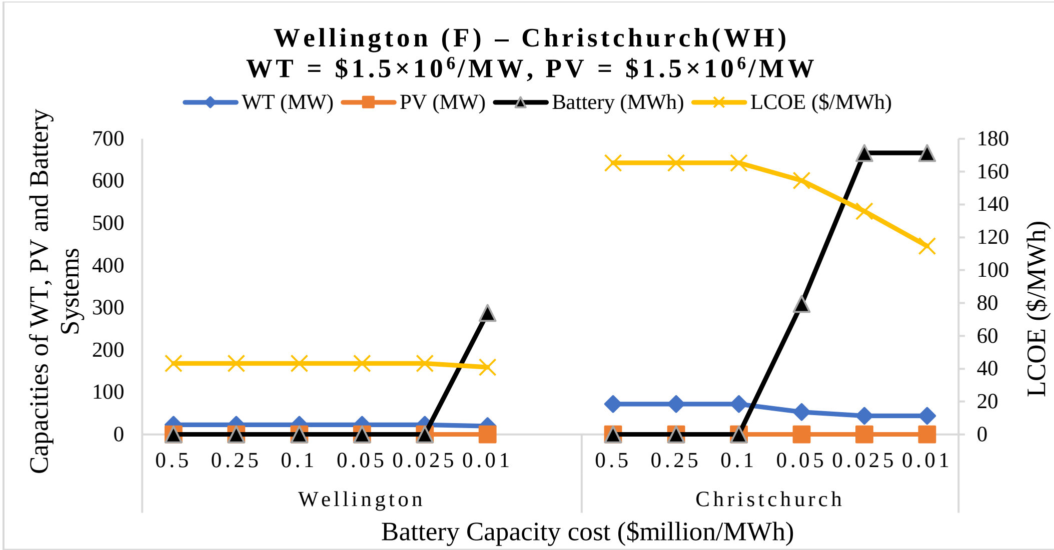

Figure 3.5: Results for the microgrid system of the factory in Wellington and the warehouse in Christchurch, at WT=$1.5M/MW and PV=$1.5M/MW.

As shown in Figure 3.5, even though if we reduce the PV capacity cost to $1.5M/MW and with same WT capacity cost, there is no change in the outputs for different battery capacity costs.

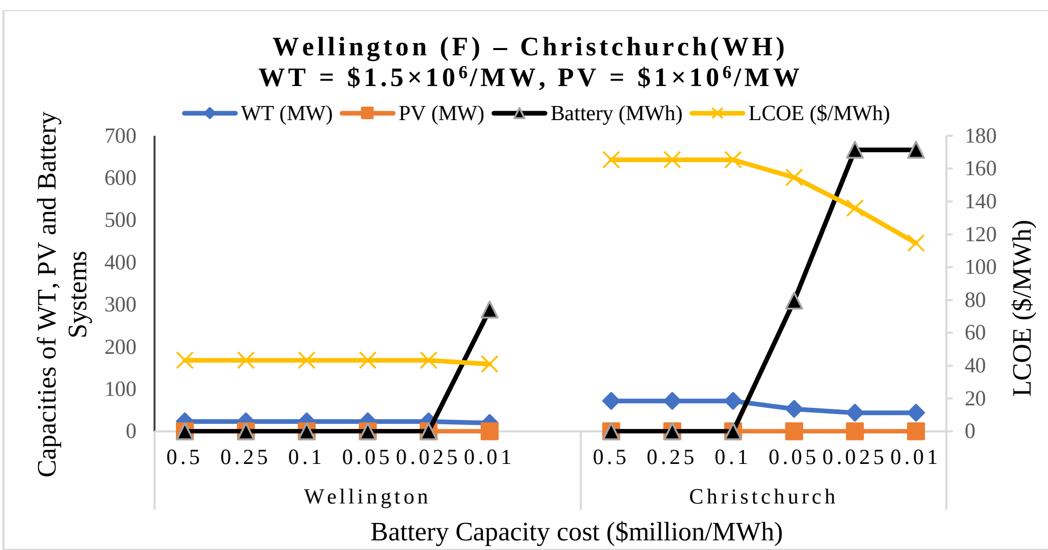

Figure 3.6: Results for the microgrid system of the factory in Wellington and the warehouse in Christchurch, at WT=$1.5M/MW and PV=$1M/MW.

Even if we still reduce the PV capacity cost to $1M/MW and the same WT capacity cost, there is no change in the outputs, which is shown in Figure 3.6.

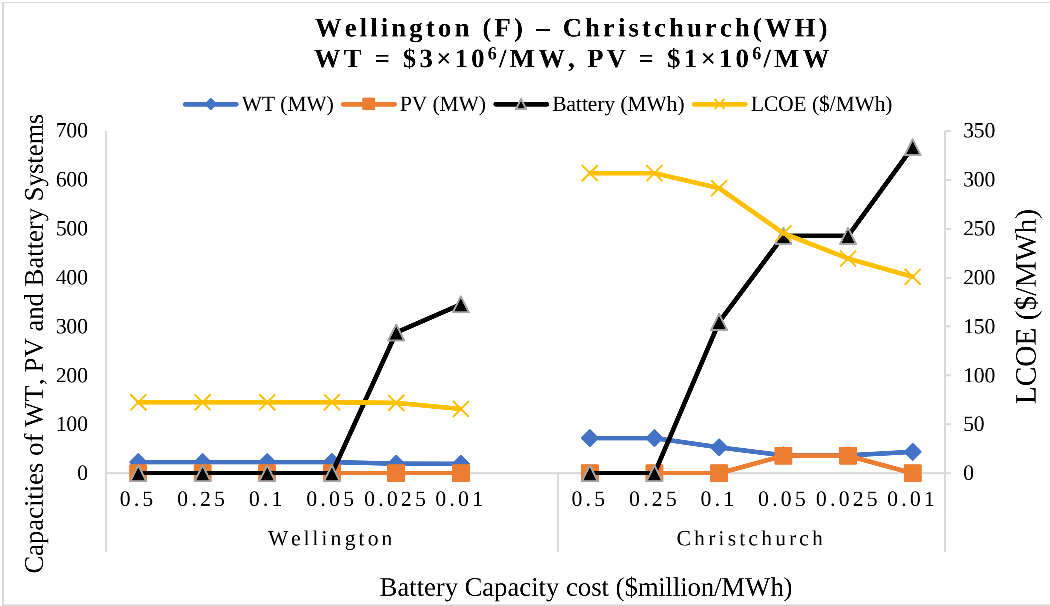

Figure 3.7: Results for the microgrid system of the factory in Wellington and the warehouse in Christchurch, at WT=$3M/MW and PV=$1M/MW.

As shown in Figure 3.7, if we increase the WT capacity cost to $3M/MW and the same PV capacity cost of $1M/MW, the system still chooses the same WT capacity of 23.04 MW and no PV installation in Wellington and in Christchurch, the system chooses the PV with a capacity of 35.93MW when the battery capacity cost is $0.05M/MWh and $0.025M/MWh and if we reduce the battery capacity cost reduced to $0.01M/MWh, then the system doesn't choose PV system. The system receives the energy from the battery system at its capacity cost of $0.025M/MWh in Wellington and at $0.1M/MWh capacity cost in Christchurch. The average LCOE of microgrid system in Wellington and Christchurch are $73/MWh and $245/MWh, respectively.

b) Aswan (Factory) – Luxor (Warehouse):

After solving Problem 3.1 for the factory in Aswan with warehouse in Luxor considering the sensitivity analysis, the outputs were drawn into graphs for various input parameters mentioned in Table 3.1 and represented in Figures 3.8 to 3.11.

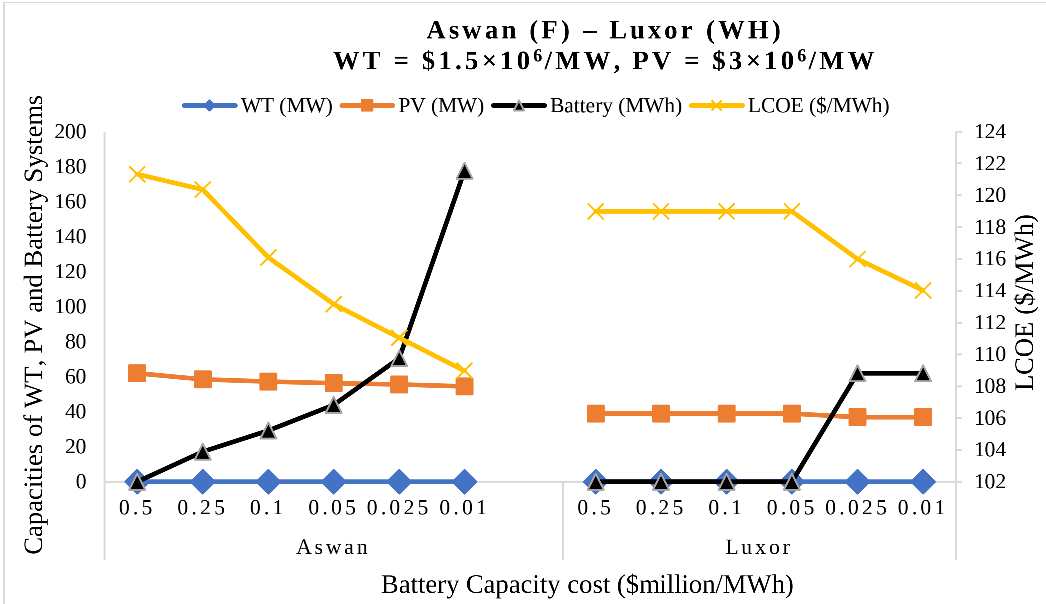

Figure 3.8: Results for the microgrid system of the factory in Aswan and the warehouse in Luxor, at WT=$1.5M/MW and PV=$3M/MW.

In Figure 3.8, when we consider the capacity costs of WT and PV are $1.5M/MW and $3M/MW respectively, then the factory in Aswan and the warehouse in Luxor consume PV system with an average capacity of 56.25MW and 38.9MW, respectively, and there is no WT consumption. In Aswan, energy from the battery system is consumed only when its capacity cost drops to $0.25M/MWh or lower, whereas in Luxor, the battery energy is consumed only when its capacity cost drops to $0.025M/MWh or lower. The average LCOE of the factory and warehouse is $113/MWh and $119/MWh, respectively.

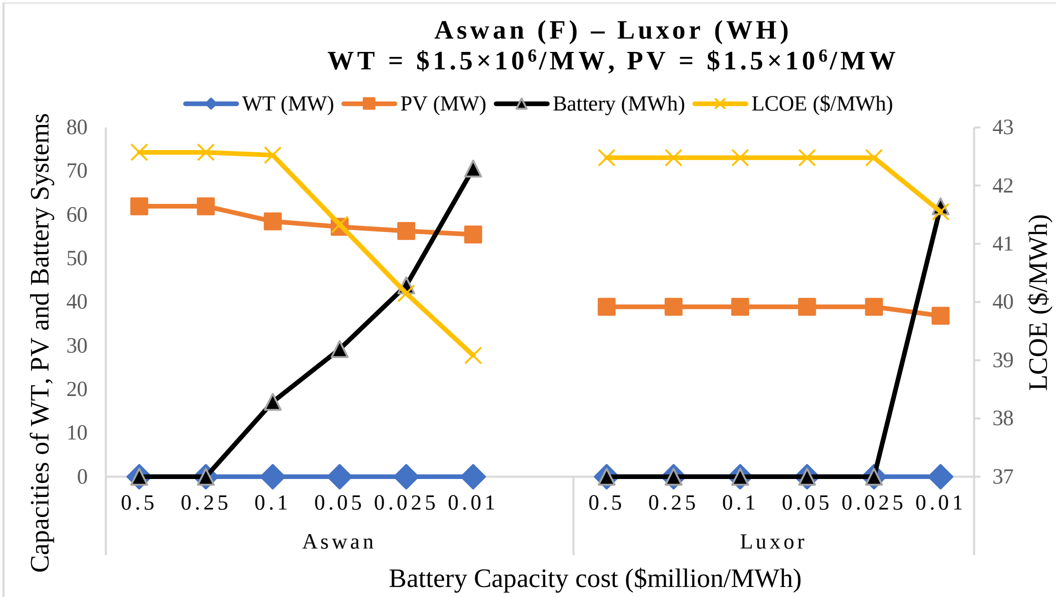

Figure 3.9: Results for the microgrid system of the factory in Aswan and the warehouse in Luxor, at WT=$1.5M/MW and PV=$1.5M/MW.

As shown in Figure 3.9, if we reduce PV capacity cost to $1.5M/MW and the WT capacity cost remains the same, then the factory and warehouse chooses still PV with an average capacity of 57.25MW and 38.9MW, respectively and there is no WT consumption. After reducing the PV capacity cost, battery energy is consumed at a capacity cost $0.1M/MWh for the factory and $0.01M/MWh for the warehouse. The average LCOE of the factory and warehouse is $41/MWh and $42/MWh, respectively.

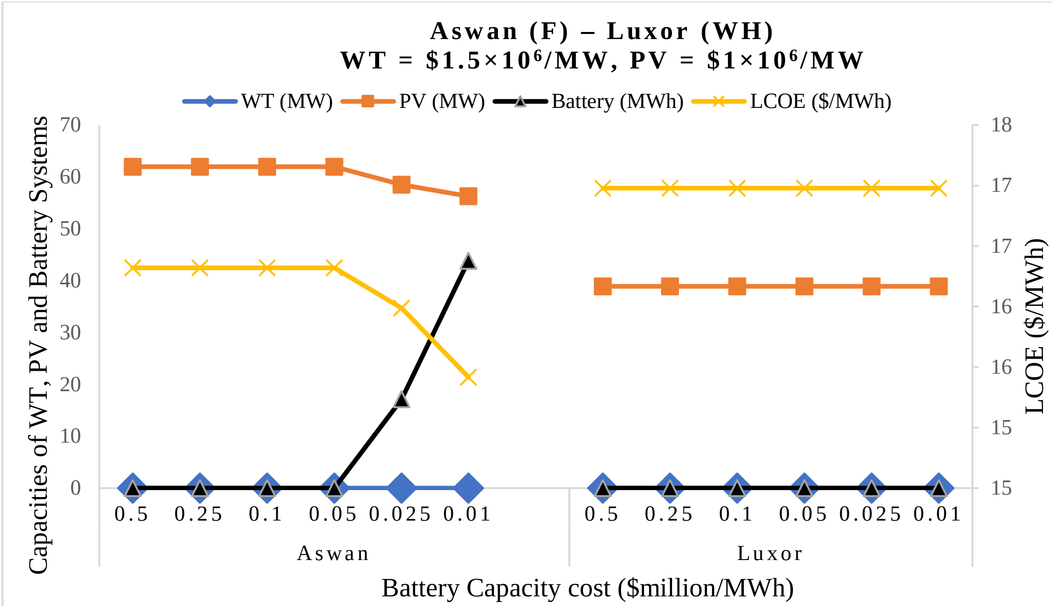

Figure 3.10: Results for the microgrid system of the factory in Aswan and the warehouse in Luxor, at WT=$1.5M/MW and PV=$1M/MW.

Figure 3.10 show that if we still reduce the PV capacity cost to $1M/MW without changing the WT capacity cost, both factory and warehouse consume PV with an average capacity cost of 61.96MW and 38.91MW, respectively and there is no WT consumption. Battery energy is consumed at its capacity cost of $0.025M/MWh for Aswan, whereas in Luxor, no energy from the battery is consumed for all battery capacity costs mentioned in Table 3.1. The average value of LCOE in Aswan and in Luxor is $16/MWh and $17/MWh, respectively.

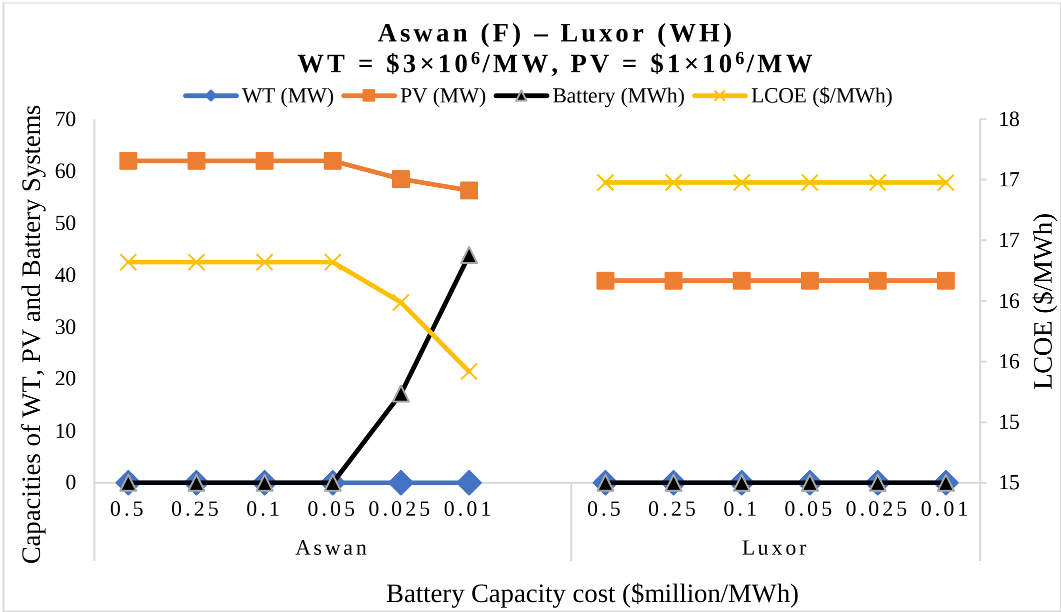

Figure 3.11: Results for the microgrid system of the factory in Aswan and the warehouse in Luxor, at WT=$3M/MW and PV=$1M/MW.

As shown in Figure 3.11, if we increase the WT capacity cost to $3M/MW while keeping the same PV capacity cost, there is no change in the outputs for both the factory and warehouse.

c) Yuma (Factory) – San Francisco (Warehouse):

Based on the input parameters in Table 3.1, Problem 3.1 for the factory in Yuma with warehouse in San Francisco is solved for the sensitivity analysis. The outputs were plotted in Figures 3.12 to 3.15.

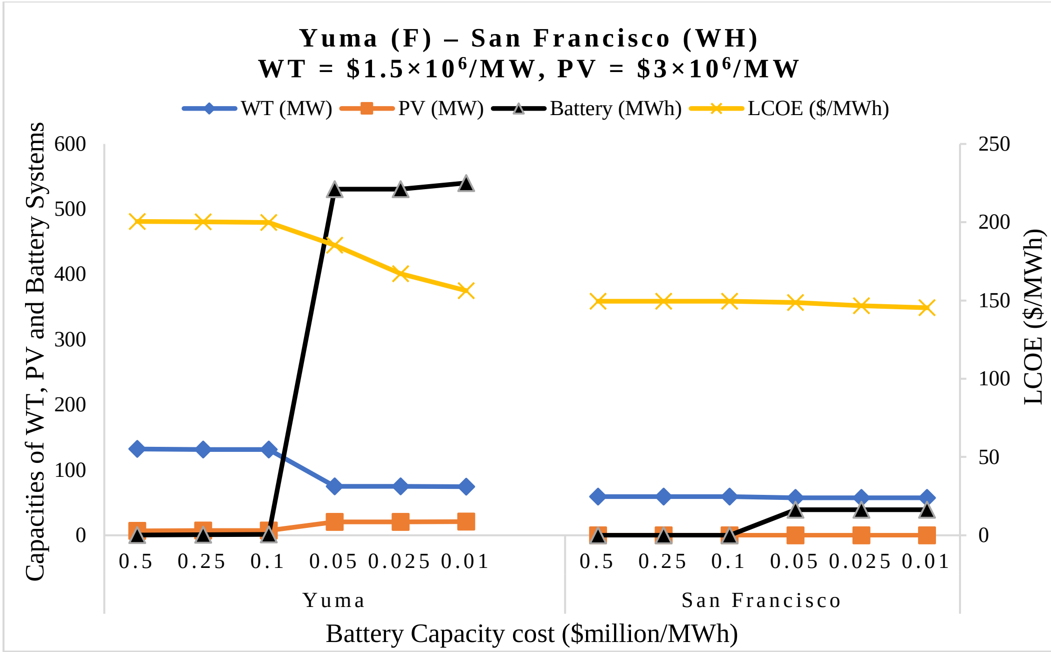

Figure 3.12: Results for the microgrid system of the factory in Yuma and the warehouse in San Francisco, at WT=$1.5M/MW and PV=$3M/MW.

In Figure 3.12, we consider the capacity costs of $1.5M/MW and $3M/MW for WT and PV, respectively. The system adopts both WT and PV units with an average capacity of 75.23MW and 20.65MW, respectively for the factory in Yuma, whereas the warehouse in San Francisco uses WT only with an average capacity of 57.45MW with no PV installation. Energy from the battery is taken when its capacity cost is $0.05M/MWh and lower for both the factory and warehouse. The average LCOE of the microgrid system in the factory and warehouse is $185/MWh and $149/MWh, respectively.

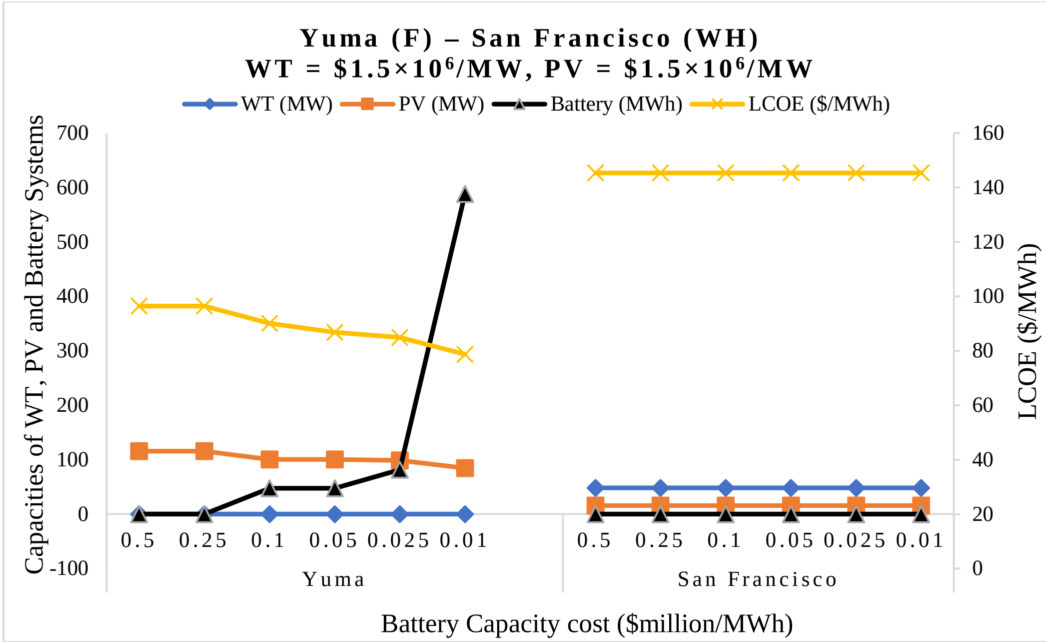

Figure 3.13: Results for the microgrid system of the factory in Yuma and the warehouse in San Francisco, at WT=$1.5M/MW and PV=$1.5M/MW.

As shown in Figure 3.13, if we reduce the PV capacity cost to $1.5M/MW and with same WT capacity cost, the system in the factory chooses only PV with an average capacity of 100.23MW and there is no WT consumption, whereas in warehouse, the system considers both WT and PV with an average capacity of 48.19MW and 15.61MW respectively. The system in the factory receives energy from the battery for all battery capacity costs mentioned in Table 3.1, with an average capacity of 47.2MWh, whereas in warehouse, there is no consumption of battery energy for all battery capacity costs. The average LCOE of the factory and warehouse is $87/MWh and $145/MWh, respectively.

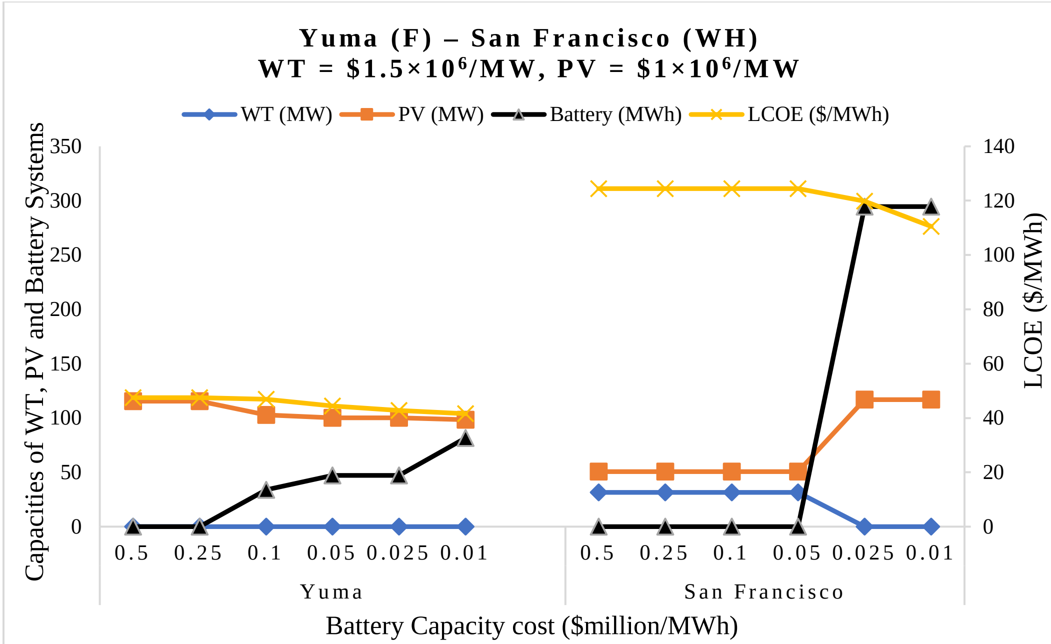

Figure 3.14: Results for the microgrid system of the factory in Yuma and the warehouse in San Francisco, at WT=$1.5M/MW and PV=$1M/MW.

If we still reduce the PV capacity cost to $1M/MW, which is shown in Figure 3.14, then there is no change in the WT and PV consumption for the factory, whereas for the warehouse, the system chooses WT with an average capacity of 31.52MW until the battery capacity cost is $0.05M/MWh and after that the system doesn't choose WT, and PV is chosen for all battery capacity costs mentioned in Table 3.1, with an average capacity of 73MW. Battery energy is chosen at a capacity cost of $0.1M/MWh and lower for the factory in Yuma, and $0.025M/MWh for the warehouse in San Francisco. The average value of LCOE for the factory and warehouse is $44/MWh and $124/MWh, respectively.

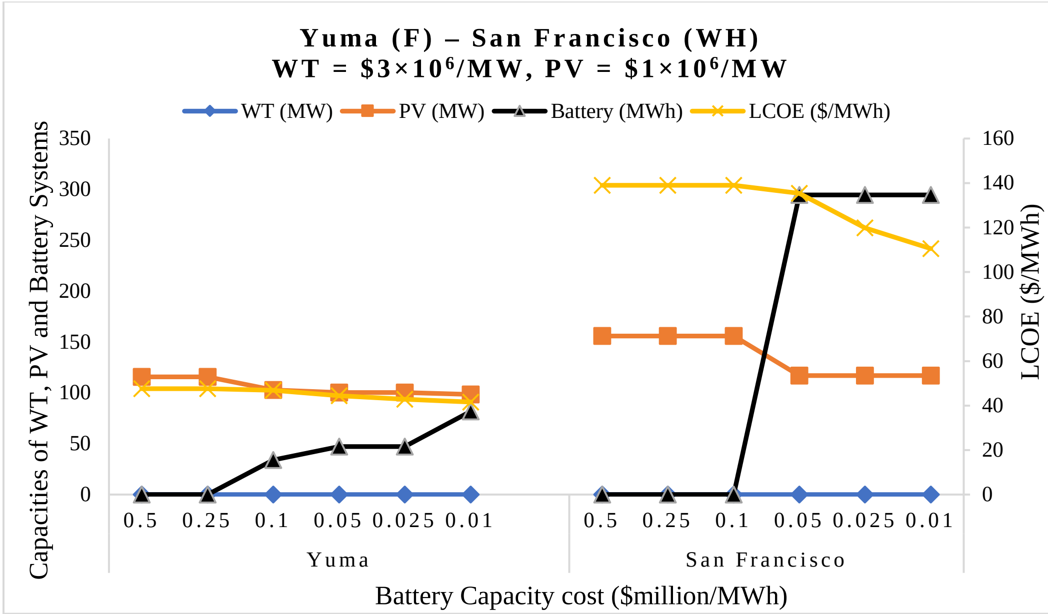

Figure 3.15: Results for the microgrid system of the factory in Yuma and the warehouse in San Francisco, at WT=$3M/MW and PV=$1M/MW.

As shown in Figure 3.15, without changing the PV capacity cost and increasing the WT capacity cost to $3M/MW, the system chooses only PV and not WT for both factory and warehouse with an average capacity of 100.23MW and 116.88MW, respectively. An energy from the battery is chosen at its capacity cost of $0.1M/MWh for the factory and $0.05M/MWh for the warehouse. The average LCOE of the factory and warehouse is $44/MWh and $135/MWh, respectively.

3.2 A Multi-Factory and Single Warehouse System

3.2.1 System Setting

In this section, we consider two factories and one warehouse. Each facility is integrated with microgrid system individually and all are connected to the main grid. Electric vehicle is used to transport the items between the two factories and a warehouse.

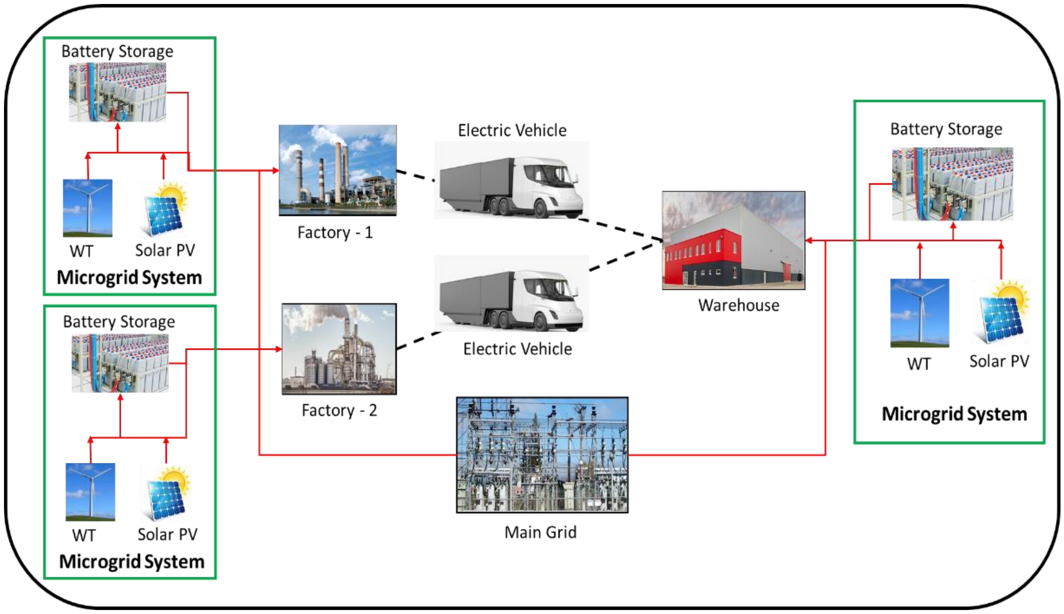

Figure 3.16: A multi-factory and single warehouse integrated with microgrid system.

In Figure 3.16, we consider two factories and a single warehouse system integrated with microgrid system in each site. Electric vehicle travels between the factories and the warehouse to ship the finished products. The system is connected to the main grid.

3.2.2 Production Inventory Planning Model

In this section we consider the same input parameters that we used to solve Problem 2.1 in Chapter 2 for the multi-factory and single warehouse case. We adapt values from Section 2.2.2 and solve Problem 2.1 in Chapter 2. After solving Problem 2.1, we obtain the same results for the quantity of production, inventory and backorders of both products for multi-factory and single warehouse system. The results were shown in Figures 3.17 and 3.18, respectively.

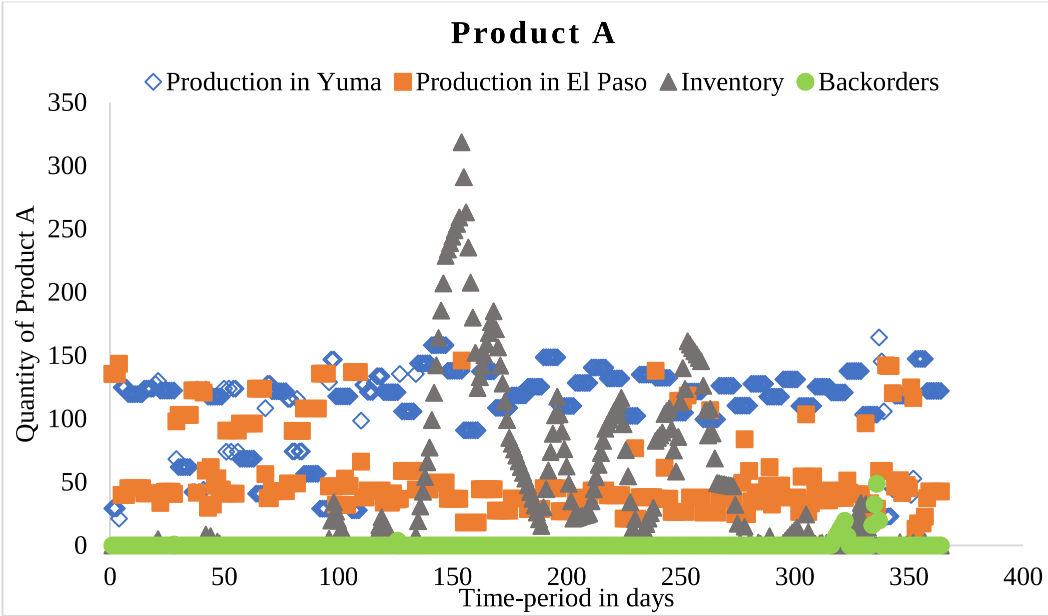

Figure 3.17: The production, inventory and backorders at each time-period for Product A in two-factory and single warehouse.

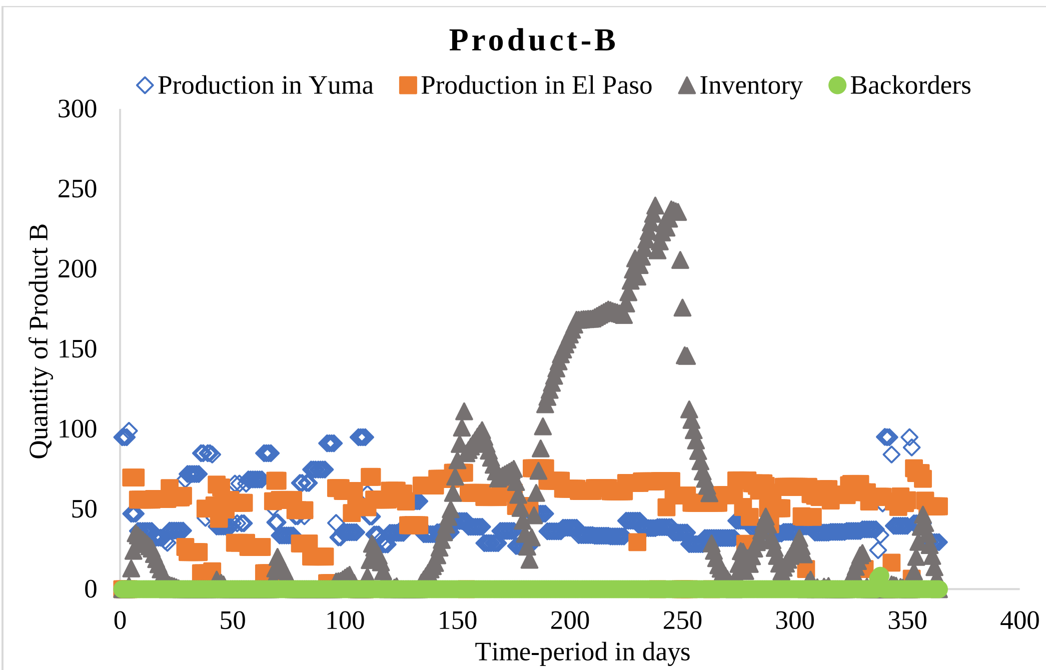

Figure 3.18: The production, inventory and backorders at each time-period for Product B in two-factory and single warehouse.

3.2.3 Carbon-Neutral Production-Inventory with Microgrid System Model

1. Input Parameters

In this section, we consider the same input parameters that are used in the Section 2.2.2 of Chapter 2, which are required for Problem 3.1. In addition to that, we also consider the same input parameters mentioned in Table 3.1. Again, we perform the sensitivity analysis for Problem 3.1 of multi-factory and single warehouse as same as the single factory and single warehouse problem. We consider the two factories in Yuma and El Paso and warehouse in Phoenix like we considered for multi-factory and single warehouse problem in Chapter 2. We consider the same capacity factors data for these three cities mentioned in Section 2.2.2.

2. Results and Analysis

Problem 3.1 is coded using the AMPL programming language and the CPLEX solver running in an Intel(R) Core (TM) i7-8550U processor, which runs at 1.8 GHz 1.99 GHz, and 12 GB DRAM. The current model has nine continuous decision variables and more than 1,113 constraints. In this section, after doing sensitivity analysis for multi-factory with single warehouse by considering the different capacity costs of PV, WT and battery systems, we have drawn the graphs for the outputs like levelized cost of energy (LCOE) and the consumption capacities of WT, PV and battery systems and are represented in the following figures. The different battery capacity costs for two factories located in Yuma and El Paso, and warehouse in Phoenix are represented in X-axis, and the outputs of the system were mentioned in the Y-axis of the graphs in Figures 3.19, 3.20, 3.21 and 3.22.

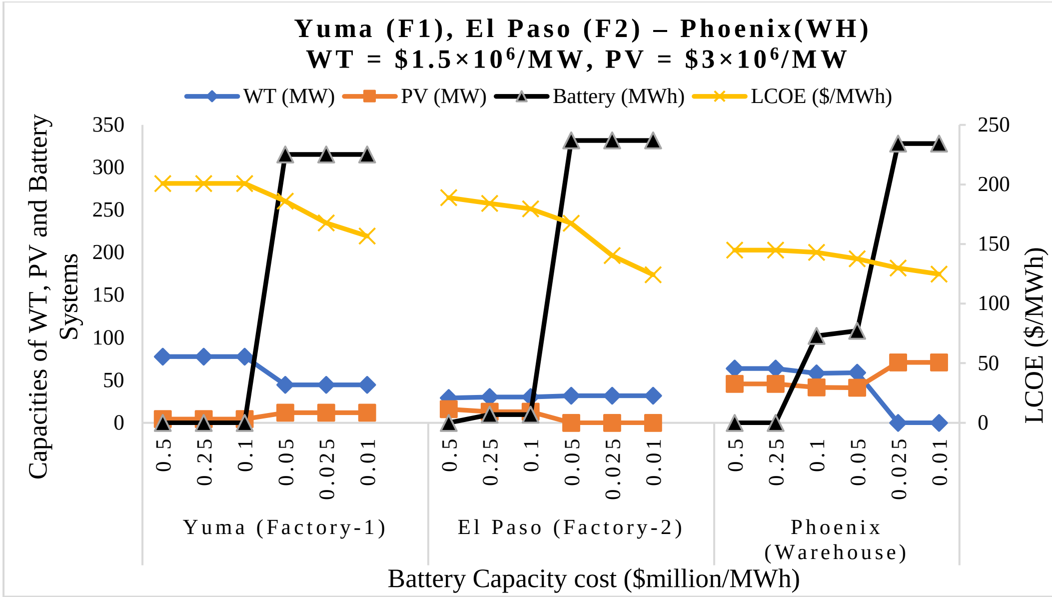

Figure 3.19: Results for the microgrid system with two-factory and single warehouse at WT=$1.5M/MW and PV=$3M/MW.

In Figure 3.19, if we consider the capacity costs of WT and PV are $1.5M/MW and $3M/MW respectively, then the system chooses both WT and PV for two factories and warehouse. For Yuma (Factory 1), an average capacity of 44.53MW of WT and 12.1MW of PV is consumed for all battery capacity costs mentioned in Table 3.1, and battery energy is considered at its capacity cost of $0.05M/MWh. For El Paso (Factory 2), an average capacity of 31.83MW of WT for all battery capacity costs and 12.1MW of PV is considered until the battery capacity is $0.1M/MWh and after that there is no PV consumption, and the battery energy is considered at its capacity cost of $0.25M/MWh. For the warehouse in Phoenix, the system chooses an average capacity of 102MW of WT only until the battery capacity cost is 0.05 and higher and 42MW of PV for all battery capacity costs, and battery energy is consumed at its capacity cost of $0.1M/MWh and lower. The average LCOE of the microgrid system in Yuma, El Paso and Phoenix is $186/MWh, $167/MWh and $138/MWh, respectively.

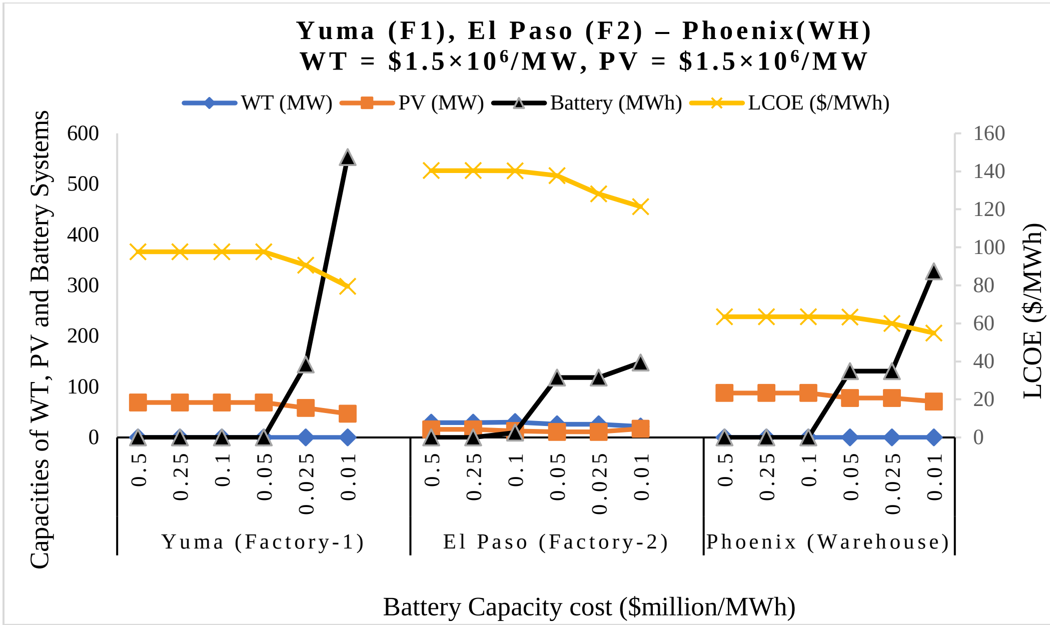

Figure 3.20: Results for the microgrid system with two-factory and single warehouse at WT=$1.5M/MW and PV=$1.5M/MW.

If we reduce only the PV capacity cost to $1.5M/MW as shown in Figure 3.20, the system in Yuma only chooses PV with an average capacity of 69MW and no WT for all battery capacity costs, and the battery energy is chosen at a battery capacity cost of $0.025M/MWh. The system in El Paso chooses both WT and PV with an average capacity costs of 26MW of WT and 11.2MW of PV for all battery capacity costs, and battery energy is consumed at its capacity cost of $0.1M/MWh and lower. The system in Phoenix installs only PV with an average capacity of 78MW and no wind generation regardless of battery capacity costs in Table 3, and battery energy is consumed at its capacity cost of $0.05M/MWh and lower. The average LCOE of the microgrid system in Yuma, El Paso and Phoenix is $98/MWh, $138/MWh and $63/MWh, respectively.

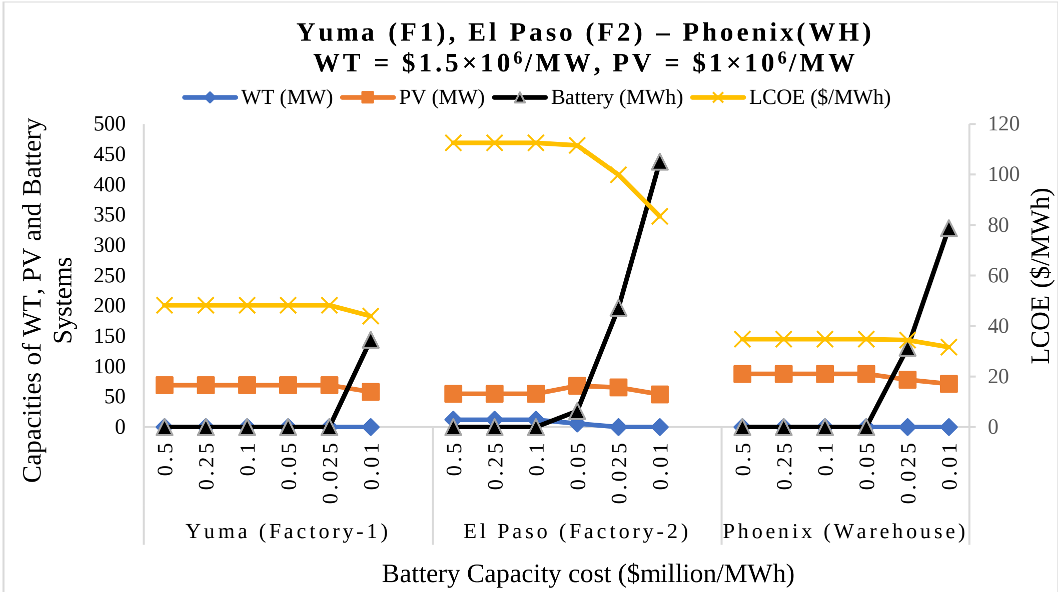

Figure 3.21: Results for the microgrid system with two-factory and single warehouse at WT=$1.5M/MW and PV=$1M/MW.

As shown in Figure 3.21, if we continue to reduce PV capacity cost to $1M/MW, there are no changes in the installed capacities of PV and battery, but the average LCOE decreases to $48/MWh. The system in El Paso still chooses PV with an average capacity of 67.8MW for all battery capacity costs and WT is chosen with an average capacity of 10MW until the battery capacity cost becomes $0.05M/MWh and higher, and battery energy is used at its capacity cost of $0.05M/MWh and lower. For the system in Phoenix, there are also no changes in consumption capacities for PV and battery, but the average LCOE of the microgrid system is decreased to $35/MWh.

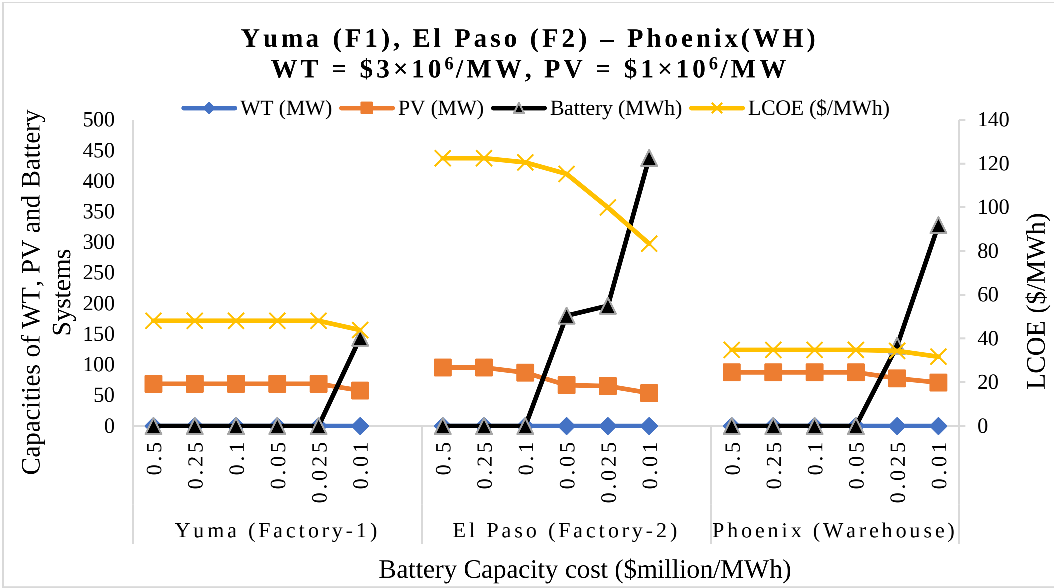

Figure 3.22: Results for the microgrid system with two-factory and single warehouse at WT=$3M/MW and PV=$1M/MW.

As shown in Figure 3.22, if we increase the capacity cost of WT to $3M/MW, then there are no changes in the outputs of Yuma and Phoenix, but in El Paso, the system chooses only PV instead of WT with an average capacity of 67.1MW for all battery capacity costs.

4. FLOW SHOP MODEL WITH MICROGRID SYSTEM INTEGRATION

4.1 Flow Shop Model

4.1.1 Model Setting

In this chapter, we consider a multi-stage flow shop scheduling problem in which each stage consists two unrelated parallel machines. At the end of each stage, a buffer is placed to store the jobs or work-in-processes (WIPs) that have processed in that stage and to feed the jobs to the next stage. The main aim of this model is to estimate the power demand and provide necessary electricity to process the jobs in each time-period.

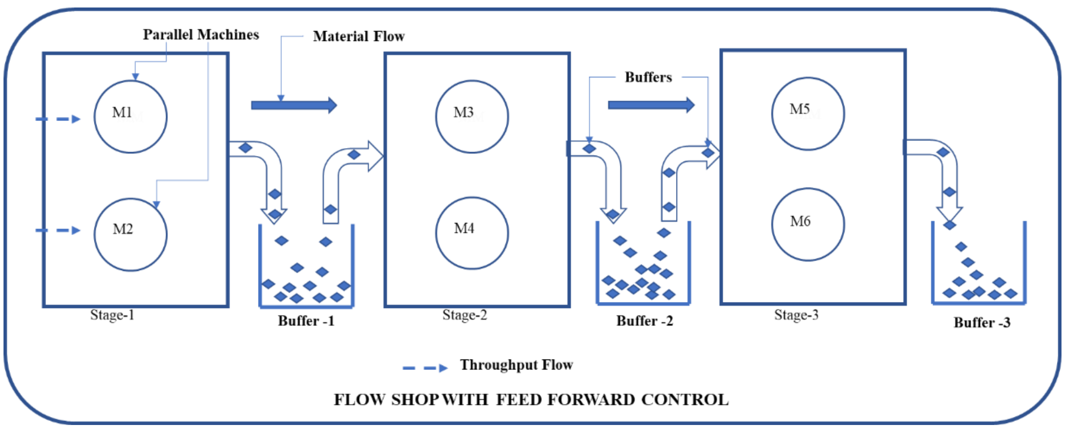

Figure 4.1: Flow shop with feed forward control

Figure 4.1 shows that the machine flow shop with a feedforward control mechanism. The processed jobs of Stage 1, which are processed in machines 1 and 2 are stored in buffer and they are fed to Stage 2 to process in the machines 3 and 4. The processed jobs of Stage 2 are stored in buffer and then fed to the machines 5 and 6 of Stage 3. The finished jobs that are finally processed in Stage 3 machines are placed in buffer. The materials are fed to the machines in forward motion with no reverse. Hence, once a job is fed to the next stage machines, it cannot be returned to the previous stage or previous buffer.

4.1.2 Mathematical Model

In this research we consider the factory that has a hybrid flow shop with number of stages *s*. Each stage has unrelated parallel machines M_h that process *n* jobs at each stage *s*. Here we assume time-period $\mathcal{T}_f$ in a set of time instances like $\mathcal{T}_f = \{t_0, t_0 + 1, .., t_0 + T_f\}$, where t_0 is the initial time at which machine starts operating the job and T_f is the total operating time of the facility. We assume the required throughput Th_{j0} for job $j \in J$ in a given time-period $\mathcal{T}_f$. At each stage, buffer box with a capacity of BC_s is located and the total number of stages is denoted as 'd'. All machines in every stage has two modes, i.e., on-mode and off-mode. Even though the formulated model in this research can handle the machines with different speeds, we assume that all machines run with same speed. We denote the processing time and power needed for job j are PT_{smj} and PP_{smj}, respectively. In this model we consider the maintenance scheduling that has maintenance time MT_{sm} for machine m in stage s and the setup time between any two jobs are ignored. The nomenclature required for the model are denoted as follows:

Notation

Parameter	**Definition**
s	Stage index
d	Number of stages
m	Machine index
M_h	Number of unrelated parallel machines in each stage s
j	Job type index
n	Number of jobs
$\mathcal{T}_f$	Set of time instances within the machine operational interval i.e., $\mathcal{T}_f = \{ t_0,\ t_0 + 1, \dots, t_0 + T_f \}$ where t_0 starts operating time and T_f ends operating time

Th_{j0}	Required production throughput for job j
PT_{smj}	Processing time for job j on mth machine
PP_{smj}	Processing power required for job j on mth machine
x_{smjt}	= 1, if machine m is operating job j at time instant t, and 0 otherwise
y_{smjt}	= 1, if machine m starts processing job j at time instant t, and 0 otherwise
N_{smjt}	Number of products of type j that have processed at machine m by time instant t
$\bar{x}_{smt}$	= 1, if machine m is maintained at time instant t, and 0 otherwise
$\bar{y}_{smt}$	= 1, if machine m starts maintenance at time instant t, and 0 otherwise
MT_{sm}	Maintenance time for machine m in stage s
BC_s	Buffer capacity after stage s

The decision variables in the model are represented as follows:

- x_{smjt} is equal to 1, if machine *m* at stage *s* is operating job *j* at time instant *t*, and 0 otherwise;

  Thus, x_{smjt} is represented as a vector, $\vec{x} = \langle x_{1,1,1,1}, \dots, x_{3,2,2,8640} \rangle$

- y_{smjt} is equal to 1, if machine *m* at stage *s* starts operating job *j* at time instant *t*, and 0 otherwise;

  Thus, y_{smjt} is represented as a vector, $\vec{y} = \langle y_{1,1,1,1}, \dots, y_{3,2,2,8640} \rangle$

- N_{smjt} are the number of products of type *j* that have been processed in machine *m* of stage *s* at time instant *t*;

  Thus, N_{smjt} is represented as a vector, $\vec{N} = \langle N_{1,1,1,1}, \dots, N_{3,2,2,8640} \rangle$

- $\bar{x}_{smt}$ is equal to 1, if machine *m* at stage *s* is maintained at time instant *t*, and 0 otherwise;

  Thus, $\bar{x}_{smt}$ is represented as a vector, $\vec{\bar{x}} = \langle \bar{x}_{1,1,1}, \dots, \bar{x}_{3,2,8640} \rangle$

- $\bar{y}_{smt}$ is equal to 1, if machine *m* at stage *s* starts maintenance at time instant *t*, and 0 otherwise;

Thus, $\bar{y}_{smt}$ is represented as a vector, $\vec{\bar{y}} = \langle \bar{y}_{1,1,1}, \dots, \bar{y}_{3,2,8640} \rangle$

We formulate a time-indexed mixed integer programming model to estimate the required power demand at each time-period and the total energy consumed by the factory.

Problem 4.1:

Minimize:

$$f_1(\vec{\mathbf{x}}, \vec{\mathbf{y}}, \vec{\bar{\mathbf{x}}}, \vec{\bar{\mathbf{y}}}, \vec{\mathbf{N}}) = \sum_{t=1}^{T_p} \sum_{s=1}^{d} \sum_{m=1}^{M_h} \sum_{j=1}^{n} PP_{smj} x_{smjt} \quad (4.1)$$

Subject to:

$$N_{sjt} = 0 \quad \text{for} \quad j \in J; s \in S; t = t_0 \dots, t_0 + PT_{smj} - 1; \quad (4.2)$$

$$N_{sjt} = \sum_{k=0}^{t-PT_{smj}+1} y_{smjk} \quad \text{for} \quad j \in J; s \in S; t = t_0 + PT_{smj}, \dots, t_0 + T_f; \quad (4.3)$$

$$N_{sjt} \geq N_{s+1,j,t} + x_{s+1,m,j,t} \quad \text{for} \quad j \in J; s \in S \backslash \{d\}; t \in \mathcal{T}_f; \quad (4.4)$$

$$N_{sjt} \leq N_{s+1,j,t} + BC_s \quad \text{for} \quad j \in J; s \in S \backslash \{d\}; t \in \mathcal{T}_f; \quad (4.5)$$

$$N_{djT_f} = Th_{j0} \quad \text{for} \quad j \in J; \quad (4.6)$$

$$x_{smjt} = \sum_{k=0}^{t} y_{smjk} \quad \text{for} \quad j \in J; s \in S; m \in M_h; t = t_0 \dots, t_0 + PT_{smj} - 1; \quad (4.7)$$

$$x_{smjt} = \sum_{k=t-PT_{smj}+1}^{t} y_{smjk} \quad \text{for} \quad j \in J; s \in S; m \in M_h; t$$

$$= t_0 + PT_{smj}, \dots, t_0 + T_f; \tag{4.8}$$

$$\sum_{k=t}^{t+PT_{smj}-1} x_{smjk} \geq y_{smjt} PT_{smj} \quad \text{for} \quad j \in J; s \in S; m \in M_h; t$$

$$= t_0 \dots, t_0 + T_f - PT_{smj} + 1; \tag{4.9}$$

$$\sum_{j \in J} x_{smjt} \leq 1 \quad \text{for} \quad s \in S; m \in M_h; t \in \mathcal{T}_f; \tag{4.10}$$

$$\sum_{j \in J} y_{smjt} \leq 1 \quad \text{for} \quad s \in S; m \in M_h; t \in \mathcal{T}_f; \tag{4.11}$$

$$\bar{x}_{smt} = \sum_{k=0}^{t} \bar{y}_{smk} \quad \text{for} \quad m \in M; t = t_0 \dots, t_0 + MT_{sm} - 1; \tag{4.12}$$

$$\bar{x}_{smt} = \sum_{k=t-MT_{sm}+1}^{t} \bar{y}_{smk} \quad \text{for} \quad s \in S; m \in M_h; t = t_0 + MT_{sm}, \dots, t_0 + T_f; \tag{4.13}$$

$$\sum_{k=t}^{t+MT_m-1} \bar{x}_{smk} \geq \bar{y}_{smt} MT_{sm} \quad \text{for} \quad s \in S; m \in M_h; t$$

$$= t_0 \dots, t_0 + T_f - MT_m + 1; \tag{4.14}$$

$$\bar{x}_{smt} + \sum_{j \in J} x_{smjt} \leq 1 \quad \text{for } s \in S; m \in M_h;\ t \in \mathcal{T}_f; \tag{4.15}$$

$$x_{smjt}, y_{smjt} \in \{0,1\} \text{ for } j \in J; s \in S; m \in M_h; t \in \mathcal{T}_f; \tag{4.16}$$

$$\bar{x}_{smt}, \bar{y}_{smt} \in \{0,1\} \quad \text{for } s \in S; m \in M_h; t \in \mathcal{T}_f; \tag{4.17}$$

$N_{sjt} \in Z$ for $j \in J; s \in S; t \in \mathcal{T}_f;$ (4.18)

The number of processed items at stage *s* at time instance *t* is assured by constraints (4.2) and (4.3). Constraints (4.4) and (4.5) show that the jobs are made in hybrid flow shop that has buffer capacities at each stage *s*. At the end time $t_0 + T_f$, the finished job *j* is equal to Th_{j0}, which is stated in constraint (4.6). No interruption occurs in between the beginning and ending of job processing on machine *m*, which is shown in continuous constraints (4.7), (4.8) and (4.9). Constraints (4.10) and (4.11) explain that the machine *m* can only process at most one product at any time instance *t*. Constraints (4.12), (4.13) and (4.14) are also continuous, and no interruption occurs until the maintenance is completed. Constraint (4.15) states that machine can only be in either processing or maintenance. Constraints (4.16) and (4.17) reveal the machine status that is denoted as binary. Production throughput is represented as integer, which is shown in the last constraint (4.18).

4.1.3 Numerical Experiments

Let us consider that the facility produces two jobs in this hybrid flow shop and runs in three shifts per day i.e., 8 hours each shift and 24 hours in total. We assume that the maintenance downtime for each machine is two hours. And we consider that factory operates 24 hours in a day, 30 days in a month and 12 months in a year (i.e., 8640 hours/year). Thus, the total set of time instants in time-period is $\mathcal{T}_f = \{0,1,..,8640\}$. The processing power and the processing time for each job in each machine at each stage are represented in Table 4.1.

Table 4.1: Processing power and processing time for each job in each machine at each stage.

{Job, Stage, Machine}	Processing Power (MW)	Processing Time (hours/Job)
{1, 1, 1}	3	40
{1, 1, 2}	4	40
{1, 2, 1}	3	60
{1, 2, 2}	3	60
{1, 3, 1}	3	40
{1, 3, 2}	4	40
{2, 1, 1}	4	40
{2, 1, 2}	3	40
{2, 2, 1}	4	60
{2, 2, 2}	5	60
{2, 3, 1}	3	40
{2, 3, 2}	4	40

In Table 4.1, we assume that the average processing power and processing time required for each machine to process a job is 3.58MW and 46.66 hours/job. The machines in Stage 2 requires more processing time of 60 hours/job when compared to the machines in other stages that requires 40 hours/job.

1. Case Study

In this research we solve the above mixed integer linear programming model by considering two cases whereas Case 1 serves as the benchmark analysis.

I. Case 1 (Benchmark):

We assume that two jobs have same throughput in this benchmark case and estimate the required throughput for each month in a year of 12 months and are listed in Table 4.2.

Table 4.2: Throughput data for each month required for Case 1

Month	1	2	3	4	5	6	7	8	9	10	11	12
Throughput for Job 1	**4**	**4**	**5**	**5**	**5**	**6**	**6**	**7**	**7**	**6**	**5**	**4**
Throughput for Job 2	**4**	**4**	**5**	**5**	**5**	**6**	**6**	**7**	**7**	**6**	**5**	**4**

II. Case 2

In Case 2, the throughput is twice of the Case 1 for each month of total 12 months and again the two jobs maintain the same throughput. Thus, the throughput required to process each job in each month is presented in Table 4.3.

Table 4.3: Throughput data for each month required for Case 2

Month	1	2	3	4	5	6	7	8	9	10	11	12
Throughput for Job 1	**8**	**8**	**10**	**10**	**10**	**12**	**12**	**14**	**14**	**12**	**10**	**8**
Throughput for Job 2	**8**	**8**	**10**	**10**	**10**	**12**	**12**	**14**	**14**	**12**	**10**	**8**

4.1.4 Results and Analysis

The mathematical model formulated in Problem 4.1 is coded using the AMPL programming language and the CPLEX solver running in an Intel(R) Core (TM) i7-8550U processor, which runs at 1.8 GHz 1.99 GHz, and 12 GB DRAM. The current model has a total of 673,998 integer decision variables and more than 952,144 constraints across the planning horizon of T_p=8,640 hours. Since AMPL consumes more time to solve Problem 4.1 for 12-month period (i.e., 8640 hours), we consider 3-month period (i.e., 2160 hours) and we add up all the power demand that we obtained for every 3-month period of total 12-month period. We also add up the throughput for each month consecutively while solving Problem 4.1 in both cases that are mentioned in Section 4.1.3. As we are solving Problem 4.1 on an hourly basis, the power consumption in each time-period is equal to the energy consumption per period. The results for two cases are represented and explained as follows:

I. Case 1 (Benchmark):

In this benchmark case, the model is solved by considering the input parameters in Tables 4.1 and 4.2 in Chapter 4, and the results obtained are shown in Figure 4.2 below.

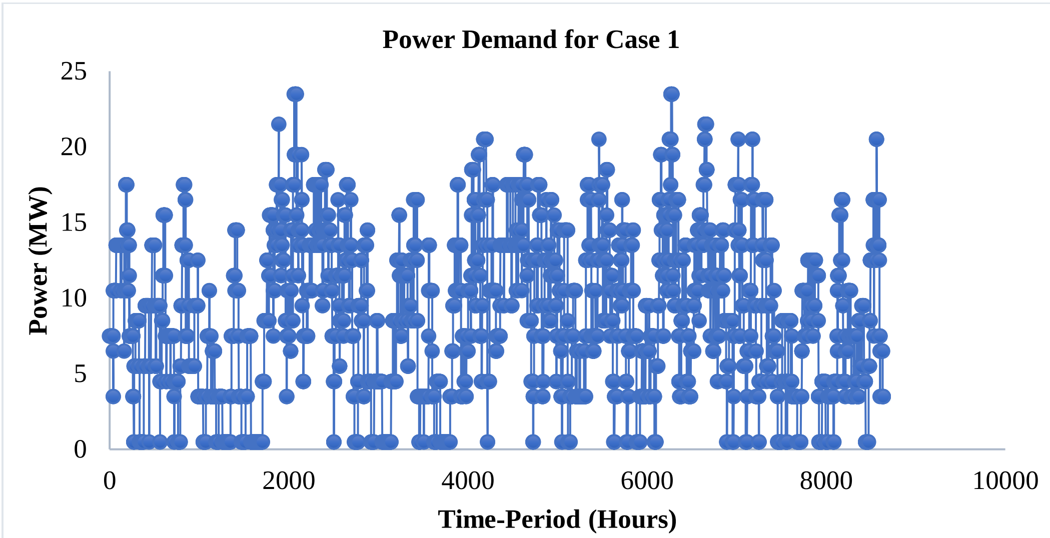

Figure 4.2: Power demand for one year using flow shop model considering Case 1

In Figure 4.2, the graph represents the power demand required for each period over one year, i.e. 8640 hours. As the power demand and energy use for each period is the same, the total energy required for whole year in this benchmark is 75,928.5MWh. The data in Figure 4.2 also shows that two periods i.e., 2074th and 6268th periods require highest power of 23.5MW where as some of the periods require minimum power of 0.5MW for maintaining the machines.

II. Case 2:

In this Case 2, we consider the input parameters that are mentioned in Tables 4.1 and 4.3 in Chapter 4. The results are shown in Figure 4.3 below.

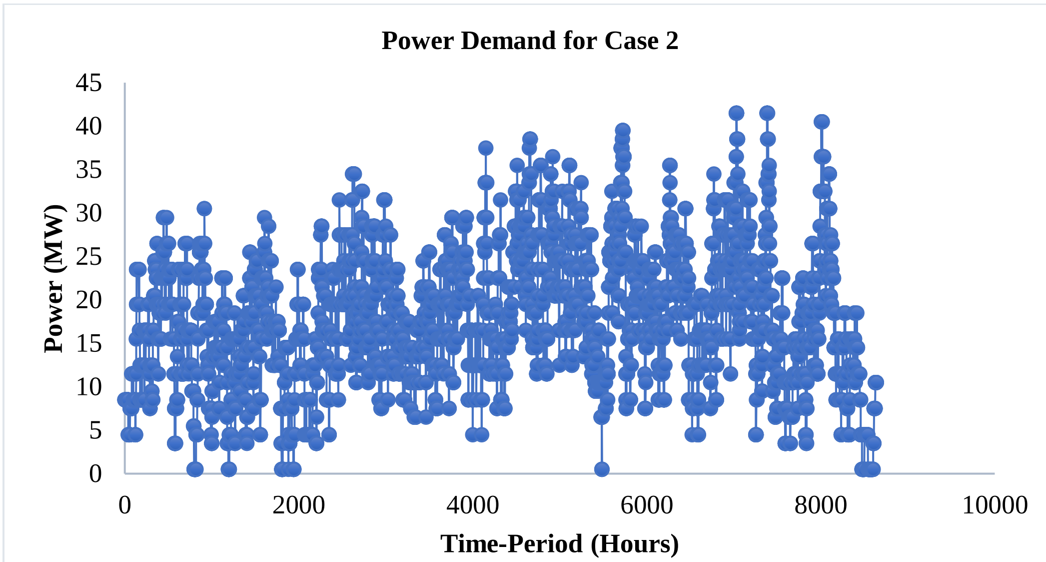

Figure 4.3: Power demand for one year using flow shop model considering Case 2

Figure 4.3 shows that the power demand required for each time-period, which is equal to the energy demand per period. Thus, by adding up all the energies of each period, the total energy use is 153,720.5MWh, which is almost double than the total energy demand of the benchmark case due to the doubling of throughput. Figure 4.3 also reveals that the two periods i.e., 7032th and 7382th periods requires the largest power of 41.5MW and some periods requires only 0.5MW for the maintenance of machines.

4.2 Allocation of Microgrid System for Flow Shop Manufacturing

4.2.1 System Setting

In this section, we design the machine flow shop factory that is connected to the microgrid and main grid systems. To maintain the production, the factory consumes the energy from both two sources. Figure 4.4 shows that the factory with machine flow shop interconnected to the microgrid and power grid systems.

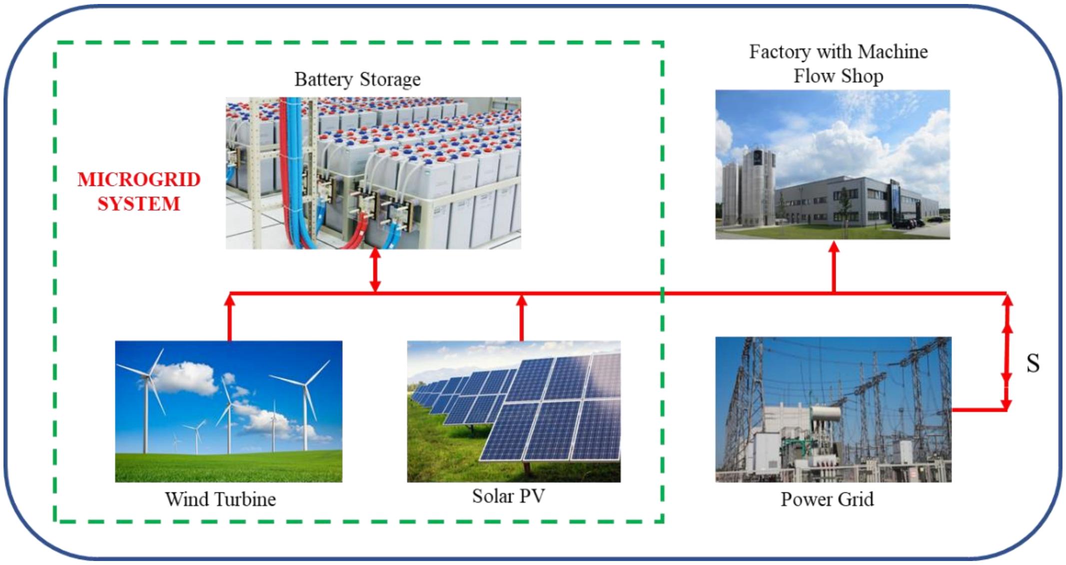

Figure 4.4: The layout of the interconnected microgrid connected to the factory and main grid.

In the microgrid system, there is a battery storage system to store the excess energy and to provide the energy during power shortage. This battery storage system is connected to the two renewable energy resources (RES) like wind and solar PV. Depending on the excessive energy produced by these two RES, the flow of power is directional in the battery storage system. Figure 4.5 also shows that microgrid system is also connected to the main grid that supplies energy when the power demand of flow shop factory exceeds the available microgrid power. There is a switch 'S' located between the main grid and the flow shop factory that has microgrid system. The switch 'S' is always closed, when the factory with inter-connected microgrid system is connected to main power grid. But, in island microgrid system, switch 'S' is always open, and the factory doesn't consume any power from the main grid. The main characteristics between the two operational modes are differentiated in Table 4.4.

Table 4.4: Differentiation in characteristics between the interconnected and island microgrid operations

Characteristics	**Interconnected Microgrid**	**Island Microgrid**
Net-metering Rate	Yes	No
TOU Rate	Yes	No
Energy Independence	Not Really	Yes
Zero-Carbon Emission	Not Really	Yes
Probability of Power shortage in the Facility	No	Yes
Prosumer Economy to UC	Yes	No
Stakeholders	Facility and Utility	Facility

In Chapter 4, we discuss only about the interconnected microgrid system whereas an island microgrid system is discussed in Chapter 5.

4.2.2 Mathematical Model

In this section, we develop a mathematical model to incorporate the flow of energy between the all the resources and users. Thus, we introduce a linear programming model to solve the flow of energy and the total electricity cost required to be invested by the factory. The nomenclature required for the model is mentioned as follows:

Notation

Parameter	**Definition**
P_i^t	Power input to the battery within time interval t
P_o^t	Power output to the battery within time interval t
P_g^t	Power drawn from the grid at time interval t
P_D^t	Power demand of the factory at time interval t
P_{PV}^t	Power generated by the PV system at time interval t
P_{WT}^t	Power generated by the WT system at time interval t
P_S^t	Power stored in the battery at the end of time interval associated with t

CS_t	Charging status during time interval t. CS_t =1 if the battery is charging for time interval t, and 0 otherwise
DS_t	Discharging status during time interval t. DS_t =1 if the battery is discharging for time interval t, and 0 otherwise
R_g^t	Given TOU power rate at time interval t
$Pmax_{CS}$	The maximum power that the battery can charge at each time step
$Pmax_{DS}$	The maximum power that the battery can discharge at each time step
η_{CS}	Efficiency losses associated with battery charging
η_{DS}	Efficiency losses associated with battery discharging
ϕ_1	Capital recovery factor for PV and WT systems
ϕ_2	Capital recovery factor for battery system
a_{PV}	Capacity cost for PV system
a_{WT}	Capacity cost for WT system
a_B	Capacity cost for battery system
CF_{PV}^t	Capacity factor of the PV system at time instant t
CF_{WT}^t	Capacity factor of the WT system at time instant t

Decision Variable	**Definition**
P_B^c	Capacity of the battery system (unit MWh)
P_{PV}^c	Capacity of the PV system (unit MW)
P_{WT}^c	Capacity of the WT system (unit MW)

In this model, we consider the time-period as T_f = {1,2, …, T_p} that has set of time instants that are adjacent and very specific, which starts from 0. The decision variables in model are represented and explained as follows:

- P_g^t, P_{PV}^t *and* P_{WT}^t (unit kWh) are the power drawn from the grid, PV and Wind Turbine systems at time interval '*t'*, respectively;

- P_i^t *and* P_o^t are the power input to and output from the battery respectively, and P_S^t is the power stored in the battery at the end of each time interval related with 't', considering that $P_S^t = 0$, if $t = T_p$;

- CS_t represents the charging status during time interval 't'. $CS_t = 1$, if the battery is charging for time interval 't', otherwise 0;

- DS_t represents the discharging status during time interval 't'. $DS_t = 1$, if the battery is charging for time interval 't', otherwise 0;

Thus, we have formulated the following linear integer programming model in which we consider the time-period as 24 hours per day, 360 days in a year i.e., total T_p=8640 hours per year. The main objective function of this model is to minimize the total electricity cost over T_p hours. The model is formulated as follows:

Problem 4.2:

Minimize

$$f_2(\mathbf{P_{PV}^c}, \mathbf{P_{WT}^c}, \mathbf{P_B^c}) = \sum_{t=1}^{T_p}(R_g^t \times P_g^t) + \phi_1(a_{PV}P_{PV}^c + a_{WT}P_{WT}^c) + \phi_2(a_B P_B^c) \qquad (4.19)$$

Subject to:

$$P_g^t + P_{PV}^t + P_{WT}^t - \frac{P_i^t}{\eta_{CS}} + P_o^t.\eta_{DS} = P_D^t \qquad for \quad t = 0, \ldots, T_p; \qquad (4.20)$$

$$P_{PV}^t = CF_{PV}^t \, P_{PV}^c \qquad for \quad t = 0, \ldots, T_p; \qquad (4.21)$$

$$P_{WT}^t = CF_{WT}^t \, P_{WT}^c \qquad for \quad t = 0, \ldots, T_p; \qquad (4.22)$$

$$0 \leq P_S^t \leq P_B^c \qquad for \quad t = 0, \ldots, T_p; \qquad (4.23)$$

$$P_i^t \leq Pmax_{CS}.CS_t \qquad for \quad t = 0, \ldots, T_p; \qquad (4.24)$$

$$P_o^t \leq Pmax_{DS}.DS_t \qquad for \quad t = 0, \dots, T_p; \tag{4.25}$$

$$P_S^{t-1} - P_S^t = P_o^t - P_i^t \qquad for \quad t = 0, \dots, T_p; \tag{4.26}$$

$$CS_t + DS_t \leq 1 \qquad for \quad t = 0, \dots, T_p; \tag{4.27}$$

$$CS_t, DS_t \ \epsilon \ \{0,1\} \qquad for \quad t = 0, \dots, T_p; \tag{4.28}$$

$$P_0^t = 0 \qquad for \quad t = 0; \tag{4.29}$$

$$P_s^t = 0 \qquad for \quad t = 0 \ and \ 8640\ ; \tag{4.30}$$

$$P_g^t \geq 0 \qquad for \quad t = 1, \dots, T_p; \tag{4.31}$$

$$P_{PV}^c \geq 0 \tag{4.32}$$

$$P_{WT}^c \geq 0 \tag{4.33}$$

$$P_B^c \geq 0 \tag{4.34}$$

In constraint (4.20), power demand required by the facility at time 't' is compensated by the total power received from the grid, WT, PV and battery systems. Constraints (4.21) and (4.22) states that the power drawn from the RES is always equal to their total capacities of RES by considering capacity factors respectively at a time instant 't'. Constraint (4.23) explains that the amount of stored energy in the battery should not exceed its capacity at any time instant 't'. In the battery system, the maximum amount of energy for charging and discharging at any time instant 't' are indicated in constraints (4.24) and (4.25). Constraint (4.26) reveals the battery balancing process. Constraint (4.27) helps to avoid the danger in battery charging and discharging simultaneously at time instant 't'. Constraint (4.29) states that there is no output from the battery at initial period. Constraint (4.30) shows that there is no battery storage at initial and final periods.

Flow chart of Figure 4.5 is depicted to illustrate the steps for solving Problem 4.2. The main purpose of this flow chart is to make the reader to easily understand the process of solving Problem 4.2.

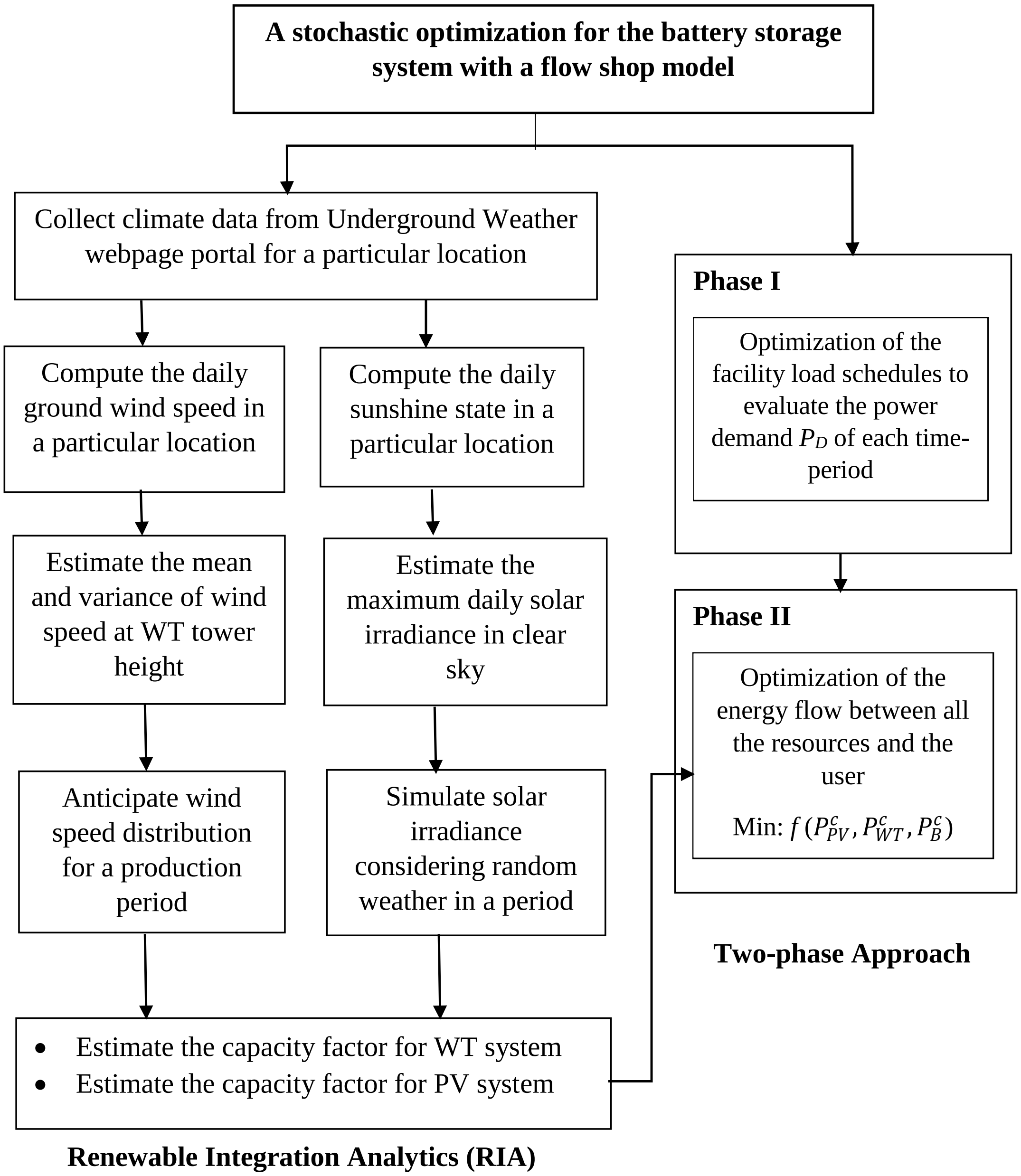

Figure 4.5: Flow chart to show the process involved in solving Problem 4.2.

4.2.3 Numerical Experiments

To solve the above model mentioned in Section 4.2.2., we consider the machine flow shop facility has interconnected microgrid system in four locations such as Wellington in New Zealand, Aswan in Egypt, Yuma in Arizona and San Francisco in California. The reason for selecting these four cities is that Wellington has windier climate, Aswan and Yuma has sunnier climate, and San Francisco has moderate windy and sunny climates. Thus, we can test the model by considering these four cities by verifying whether the model can choose maximum amount of power drawn from a certain RES at a minimum cost for each city according to their climatic conditions.

I. Climate Data

We have already mentioned the climate data for Wellington, Aswan, Yuma and San Francisco in Chapter 2. Thus, we have collected 11 years weather data for these cities and some weather patterns for these two cities are mentioned in Table 4.5.

Table 4.5: Annual weather condition and wind speed at 80-m tower

Cities	Wellington	Aswan	Yuma	San Francisco
Wind Speed Profile	High	Low	Low	Medium
Sunshine	Low	High	High	Medium
Latitude (Degree)	41.29	24.09	32.69	37.77
Average Wind Speed (m/s)	13.61	5.93	6.02	8.21
Clear Days	6	356	165	28
Scattered Cloud (SC)	68	5	109	95
Partially Cloud (PC)	109	3	65	136
Mostly Cloud (MC)	5	0	0	13
Overcast	1	0	0	2
Rain	170	0	13	65
Fog	2	0	1	24
Strom/T-storms	3	0	11	3
Snow	0	0	0	0

We have defined and rated the wind speed and sunny weather profiles that are to be justified in Table 4.6.

Table 4.6: The definition of wind speed and sunny weather profiles

Win Speed	Rate	Weather (sunny days	Rate
>6 m/s	High	>200	High
<3 m/s	Low	<100	Low
(3, 6)	Medium	(100, 200)	Medium

By considering the wind speed and solar irradiance of these four cities, we have estimated the capacity factors for WT and PV systems, which is discussed clearly in Chapter 2. By considering the capacity factors of WT and PV for Wellington, Aswan, Yuma and San Francisco, which are mentioned in Chapter 2, we are estimating the capacity factors for one year on an hourly basis. Thus, we estimate the capacity factors for WT and PV of Wellington, Aswan, Yuma and San Francisco for 8640 hours and were represented in the graphs that are shown in following figures. As to represent the PV capacity factor data clearly in a graph for all cities, we remove the data for the time-periods that has zero PV power consumption, shown in Figure 4.7.

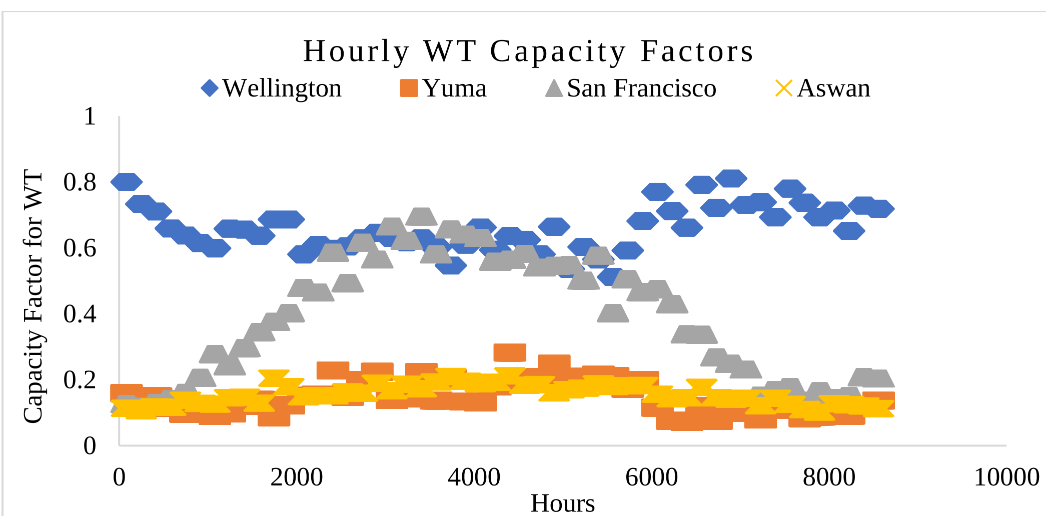

Figure 4.6: Hourly WT capacity factors for Wellington, Aswan, Yuma and San Francisco.

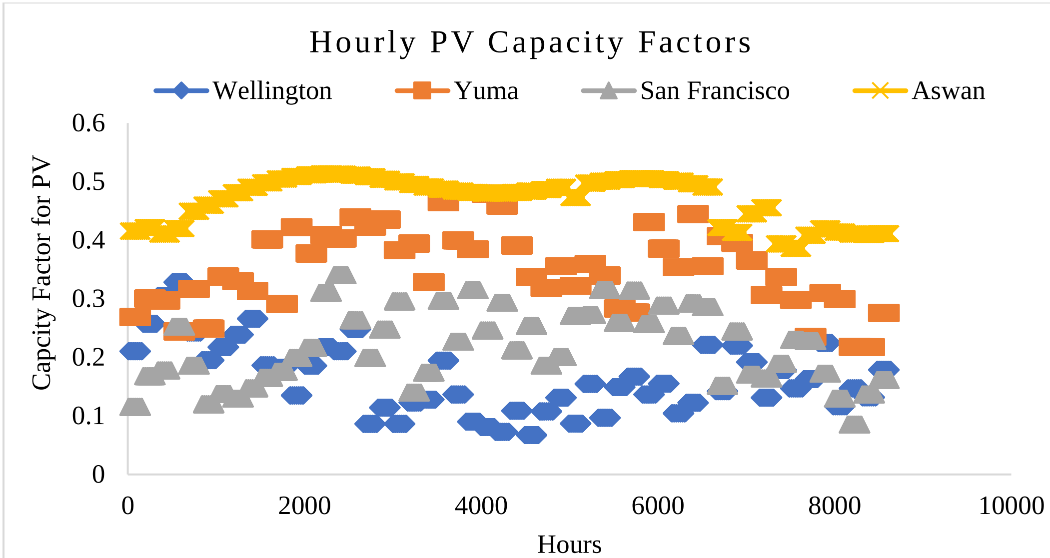

Figure 4.7: Hourly PV capacity factors for Wellington, Aswan, Yuma and San Francisco.

II. Input Data

We consider the production data related to the electricity-intensive manufacturing factory that operates 24 hours in a day and 360 days in a year i.e., 8640 hours in total. The input parameters required to solve the Problem 4.2 mentioned in Section 4.2.2 are represented in Table 4.7.

Table 4.7: Input parameters for the optimization of Problem 4.2

Comments	**Notation**	**PV System**	**WT System**	**Battery System**
Capital Recovery Factor	ϕ	0.0802	0.0802	0.1295
Cost	a	\$3M-1.5M/MW	\$1.5M/MW	\$0.5M–0.01M/MWh
Rate of power	R_g	\$70/MWh, \$140/MWh		
Efficiency of battery Charging	η_c	0.9		
Efficiency of battery Discharging	η_d	0.9		

In Table 4.7, we estimate the capital recovery factor for RES and battery system as 0.0802 and 0.1295, respectively. We consider the capacity cost of \$1.5M/MW for WT, \$3M-1.5M/MW for PV and \$0.5M-0.01M/MWh for battery systems, respectively. While battery charging and discharging, we assume 90% efficiency losses.

In this section of research, we consider two types of rates for the power drawn from the grid. One is net-metering rate of \$70/MWh and other is TOU rate of \$70/MWh at 10PM–6AM and \$140/MWh at 7AM–9PM for everyday in a year. The required power demand data is taken from the two cases results of flow shop model, which is mentioned in the Section 4.1.4. Thus, in this section we solve the model for Wellington, Aswan, Yuma and San Francisco in two cases.

Therefore, by considering all the above-mentioned input data, we have solved the model AMPL software using the CPLEX solver. By solving the Problem 4.2, we find out the minimum total cost that need to be invested by the facility for the total required power. After finding total cost, we calculate the Levelized Cost of Energy (LCOE) by applying the following formula.

$$LCOE\ (\$/\text{MWh}) = \frac{Total\ Cost\ (\$)}{Total\ Energy\ Demand\ (\text{MWh})}$$

** *Total Energy Demand* is taken from the two cases of flow shop model results mentioned in Section 4.1.4.

Thus, by solving Problem 4.2, we find out the following considering both net-metering and TOU rates for a factory located in Wellington, Aswan, Yuma and San Francisco in both cases and the results were discussed in Section 4.2.4.

- ❖ Levelized Cost of Energy ($/MWh)
- ❖ Capacities of WT (MW), PV (MW) and Battery Systems (MWh).

4.2.4 Results and Analysis

Problem 4.2 is coded using the AMPL programming language and the CPLEX solver running in an Intel(R) Core (TM) i7-8550U processor, which runs at 1.8 GHz 1.99 GHz, and 12 GB DRAM. The current model has three continuous decision variables and more than 77,762 constraints. In this research, we do sensitivity analysis for each city in all cases by considering the different battery capacity costs ranging from $0.01M/MWh to $0.5M/MWh. In Case 1, we solve Problem 4.2 for the factory in each city we consider the required power demand and total energy demand data from the benchmark case of flow shop model, which is mentioned in Section 4.1.4. In Case 2, we consider the required power demand and total energy demand data from Case 2 of flow shop model, which is represented in Section 4.1.4. For all cities, we compare the results like LCOE and capacities of WT, PV and battery systems between the net-metering and TOU rates. The comparison of the results for each city is represented in graphs that are shown in the following figures. In each graph, the outputs like LCOE and capacities of WT, PV and battery systems are represented in Y-axis, whereas the different battery capacity costs are represented in X-axis.

Case 1

I. Wellington:

We solved the Problem 4.2 for the factory in Wellington city and after doing the sensitivity analysis, the results were plotted, and they were compared between two rates, which are shown in following figures.

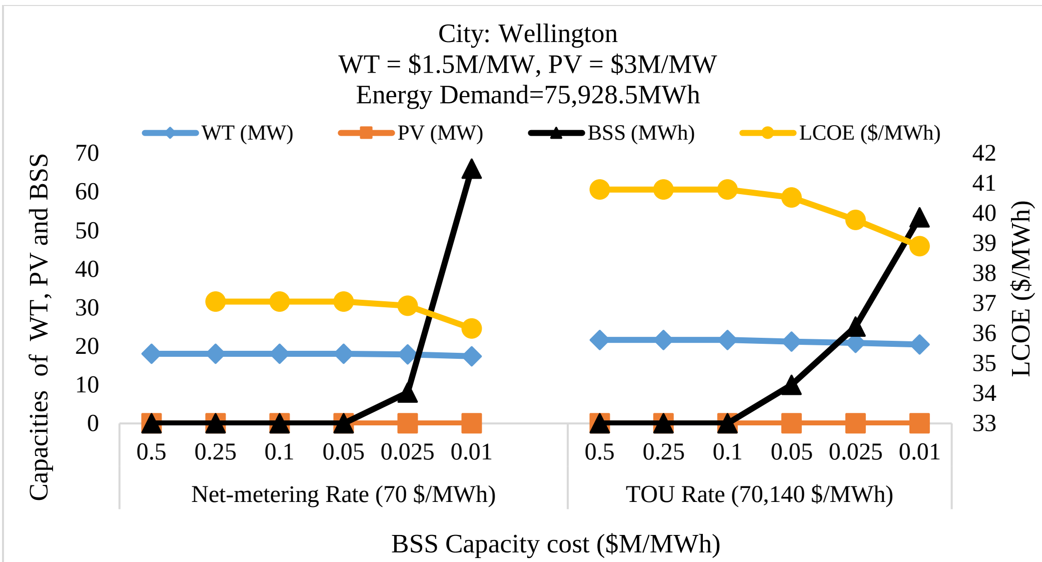

Figure 4.8: Results for the interconnected microgrid in Wellington at WT = $1.5M/MW and PV = $3M/MW.

Figure 4.8 show that the LCOE and the capacities of WT, PV and battery systems for Wellington city at different battery capacity costs ranging from $0.5M/MWh-$0.01M/MWh. When we consider the capacity cost of $1.5M/MW and $3M/MW for WT and PV systems respectively, the system chooses the power from the WT system with a capacity of 18.05MW for net-metering rate and 21.6MW for TOU rate. Battery energy of 8.03MWh and 10MWh are consumed only when its capacity cost is $0.025M/MWh for net-metering rate and $0.05M/MWh for TOU rate. But there is no power consumption from the PV due to the windier conditions in the Wellington city. The average LCOE of

$40.5/MWh for TOU rate is higher than the net-metering rate LCOE that has an average of $37/MWh.

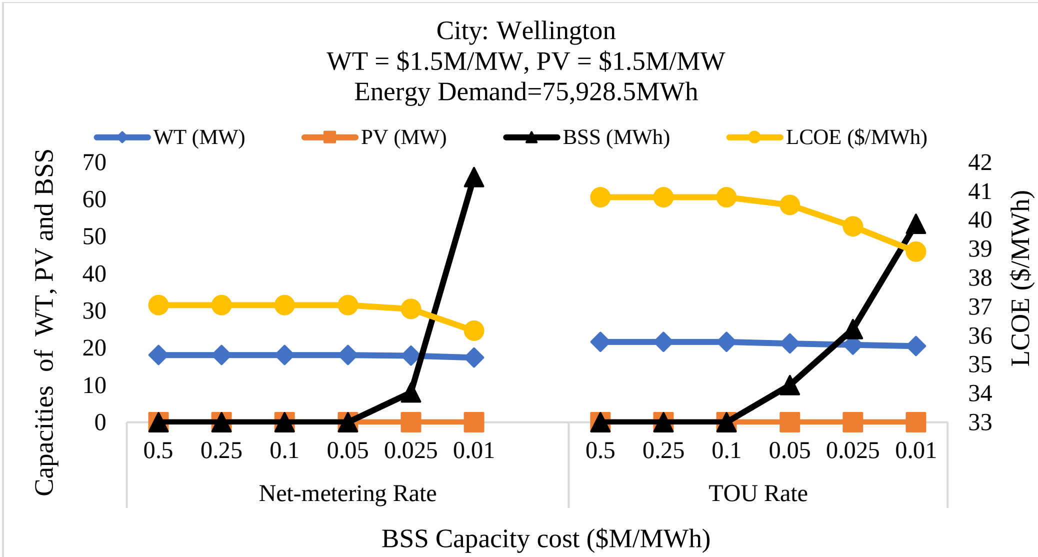

Figure 4.9: Results for the interconnected microgrid in Wellington at WT = $1.5M/MW and PV = $1.5M/MW.

As shown in Figure 4.9, even though if we reduce the PV capacity cost to $1.5M/MW, the system doesn't consider any power from the PV system in both rates and there are no changes in the outputs.

II. Aswan:

After doing the sensitivity analysis for the factory in Aswan, the results were plotted in following graphs.

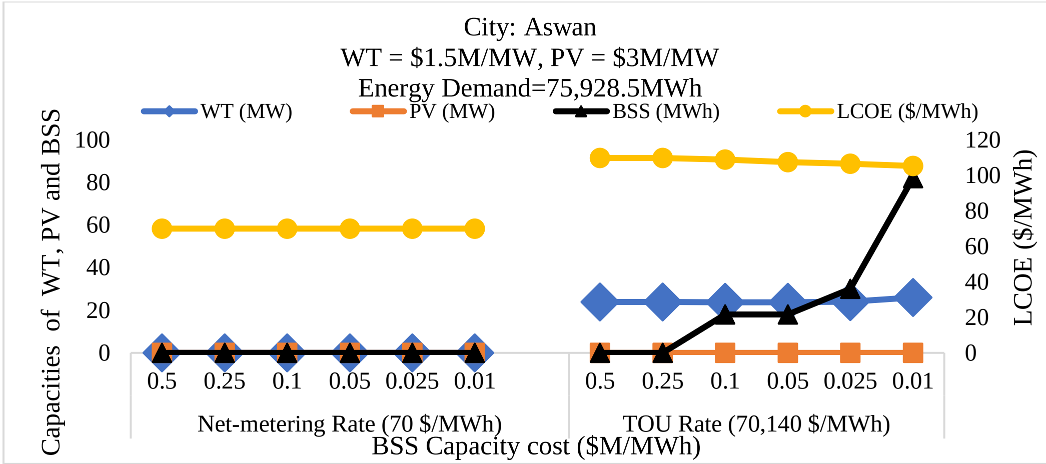

Figure 4.10: Results for the interconnected microgrid in Aswan at WT = $1.5M/MW and PV = $3M/MW.

In Figure 4.10, the graph shows that the system considers only grid power and no power is considered from RES and energy from the battery for net-metering rate. When we consider TOU rate, an average of 24MW wind power is considered and no PV power is consumed. Energy of 18MWh is consumed from the battery at its capacity cost $0.1M/MWh. The average LCOE of $94.2/MWh for TOU rate is higher than an average LCOE of $69.3/MWh for net-metering rate.

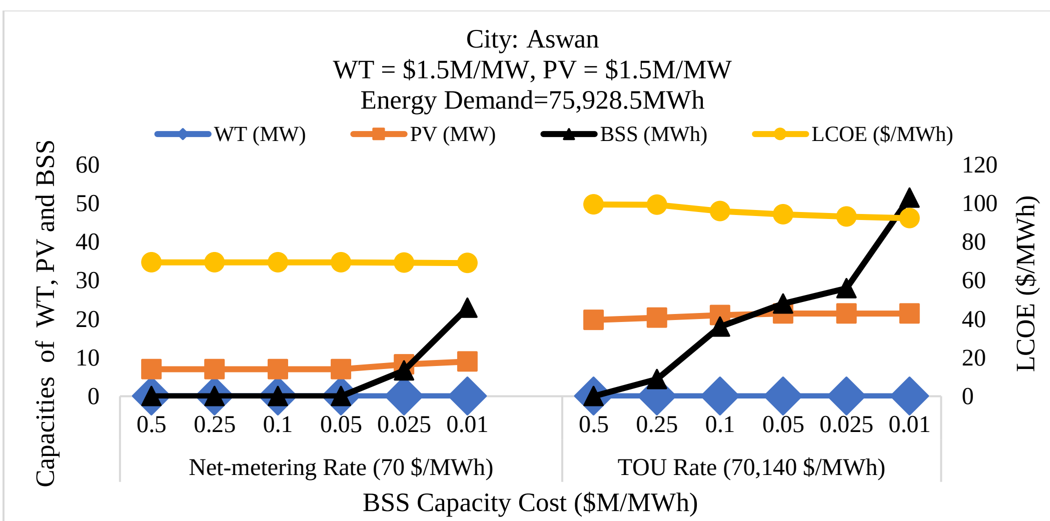

Figure 4.11: Results for the interconnected microgrid in Aswan at WT = $1.5M/MW and PV = $1.5M/MW.

When we reduce the capacity cost of PV system to \$1.5M/MW and by keeping the WT capacity cost constant, system chooses an average PV power of 9.6MW and 6.66 MWh of battery energy at its capacity cost \$0.025M/MWh in net-metering rate. For TOU rate, the system consumes an average PV power of 21MW instead of WT power and battery energy of 4.44MW is consumed at its capacity cost \$0.25M/MWh. The average LCOE of \$94.2/MWh for TOU rate is higher than the net-metering rate LCOE of \$69.3/MWh.

III. Yuma

For Yuma city, we do sensitivity analysis by considering three scenarios, in which first two scenarios have same WT capacity costs of \$1.5M/MW, but PV changes from \$3M/MW to \$1.5M/MW whereas in third scenario we double the both rates of grid power and consider WT and PV capacity costs at \$1.5M/MW. Three scenario's outputs are shown and compared in following graphs.

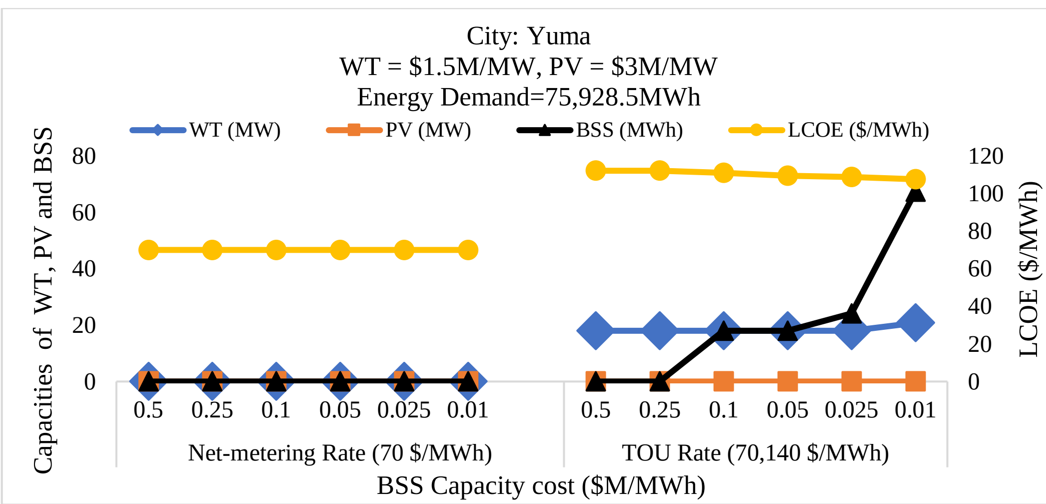

Figure 4.12: Results for the interconnected microgrid in Yuma at WT = \$1.5M/MW and PV = \$3M/MW.

Figure 4.12 reveals the capacities of WT, PV and BSS, and Levelized cost of Energy (LCOE) for Yuma city. If the capacity cost of WT and PV are \$1.5M/MW and

$3M/MW respectively, the system considers only grid power with and no PV and WT power are consumed for net-metering rate and consume WT power of 19MW and no PV power is consumed for TOU rate. If we consider the battery capacity cost ranging from $0.5M/MWh to $0.01M/MWh, then no battery energy is considered for net-metering rate and the battery energy is considered only when the capacity cost is $0.1M–0.01M/MWh. The capacities of WT and BSS, and LCOE for TOU rate are higher than the net-metering rate.

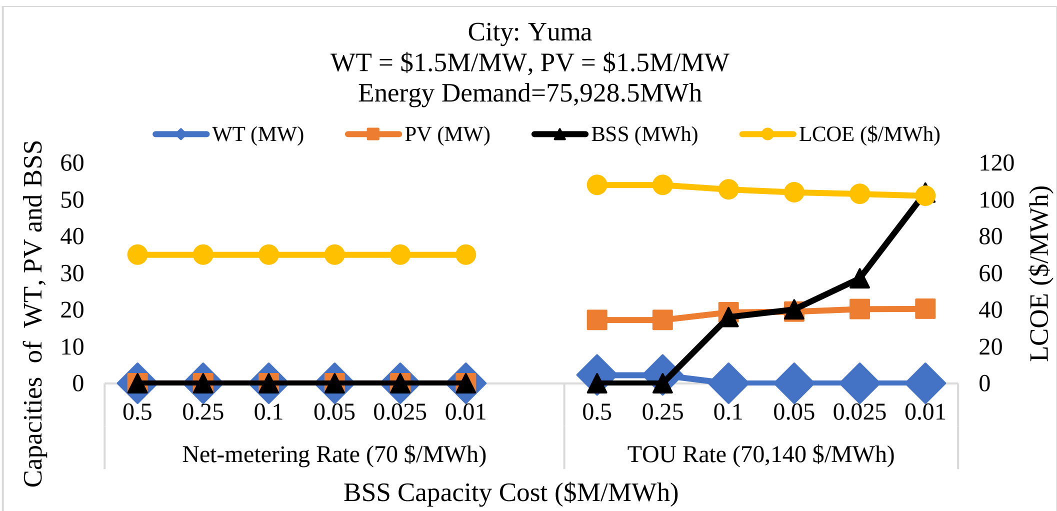

Figure 4.13: Results for the interconnected microgrid in Yuma at WT = $1.5M/MW and PV = $1.5M/MW.

When we reduce the PV capacity cost to $1.5M/MW, the model considers PV power of an average capacity of 19MW instead of WT and there is an increase of battery energy consumption for TOU rate and there is no change in outputs for net-metering rate, which is shown in Figure 4.13.

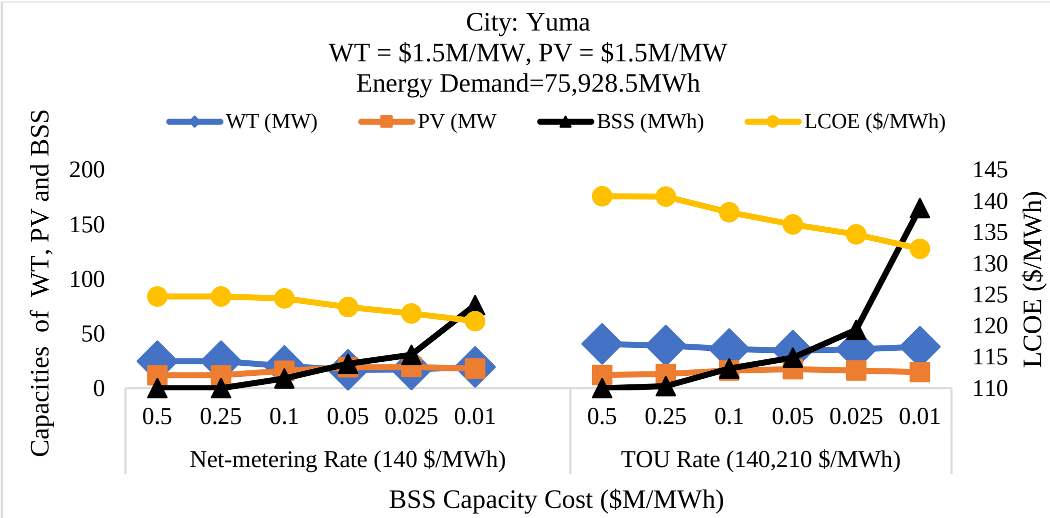

Figure 4.14: Results for the interconnected microgrid in Yuma at WT = \$1.5M/MW and PV = \$1.5M/MW by doubling both rates.

If we double the net-metering rate to \$140 and TOU rate to \$210 and at capacity costs of WT =\$1.5M/MW and PV =\$1.5M/MW, then both WT and PV power are consumed. Battery energy is considered from capacity costs \$0.1M–0.01M/MWh for net-metering rate and \$0.25M-\$0.01M/MWh for TOU rate. As shown in Figure 4.14, for TOU rate, LCOE and WT capacity are higher and PV capacity is lower, when compared to the net-metering rate.

IV. San Francisco

For Aswan city, the sensitivity analysis is done by changing the input parameters and the outputs were drawn into graphs and comparison were done for both rates.

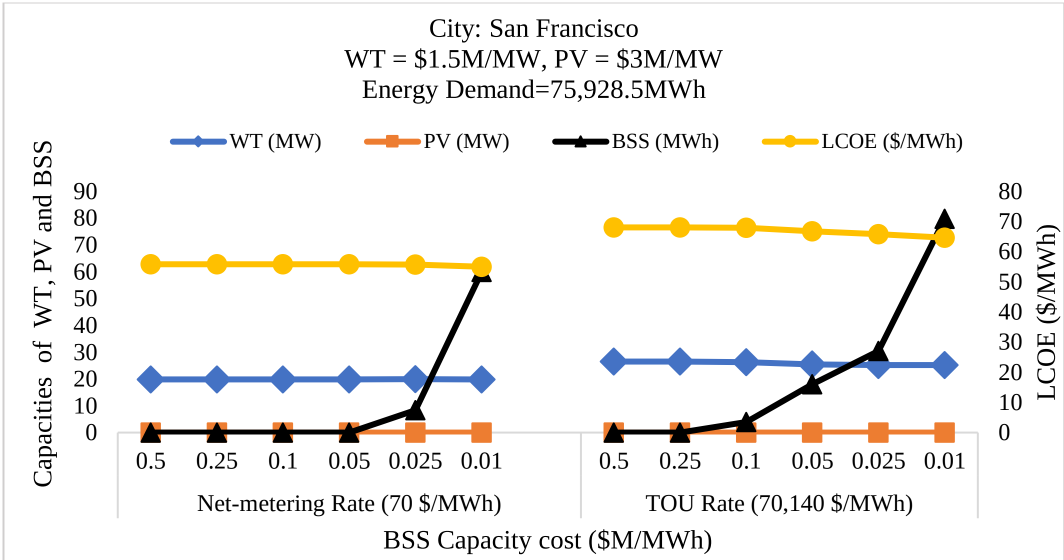

Figure 4.15: Results for the interconnected microgrid in San Francisco at WT = $1.5M/MW and PV = $3M/MW.

In Figure 4.15, the capacities of WT, PV and BSS, and Levelized cost of Energy (LCOE) for San Francisco city are shown. If the capacity cost of WT and PV are $1.5M/MW and $3M/MW respectively, the system considers only WT power with an average capacity of 19.83MW and 25.4MW for net-metering rate and TOU rate, respectively and there is no PV consumption for both net-metering and TOU rates. If we consider the battery capacity cost ranging from $0.5M/MWh to $0.01M/MWh, then the battery energy is considered only when the capacity cost is $0.025M-0.01M/MWh for net-metering rate and $0.1M–0.01M/MWh. The capacities of WT and BSS, and LCOE for TOU rate are higher than the net-metering rate.

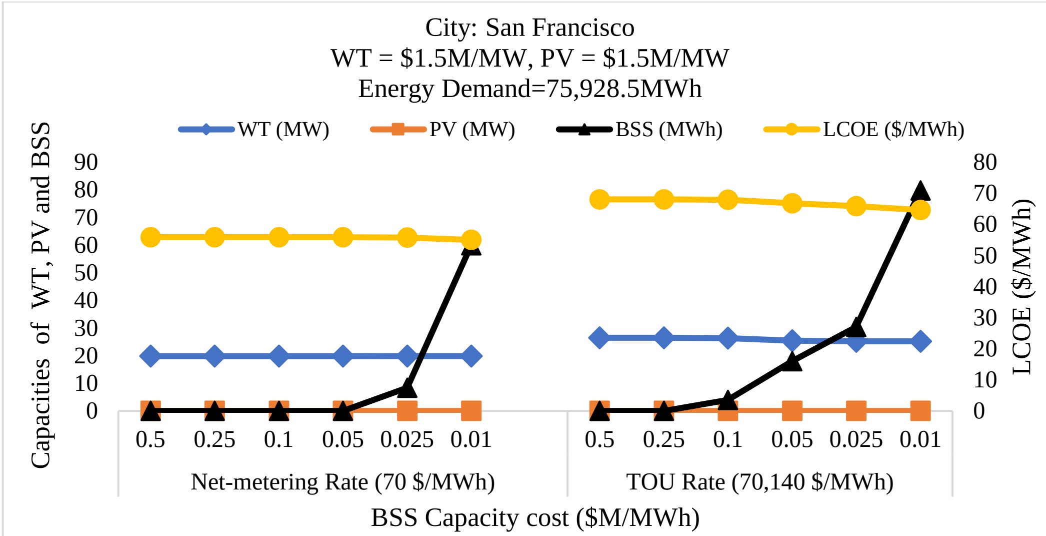

Figure 4.16: Results for the interconnected microgrid in San Francisco at WT = $1.5M/MW and PV = $1.5M/MW.

When we only decrease the capacity cost of PV to $1.5M/MW, there is no change in outputs for both net-metering rate and TOU rate as shown in Figure 4.16.

Case 2

I. Wellington:

By considering the power demand data of the facility from the Case 2 of flow shop model, we solve Problem 4.2 and after doing sensitivity analysis, the results were represented in following figures.

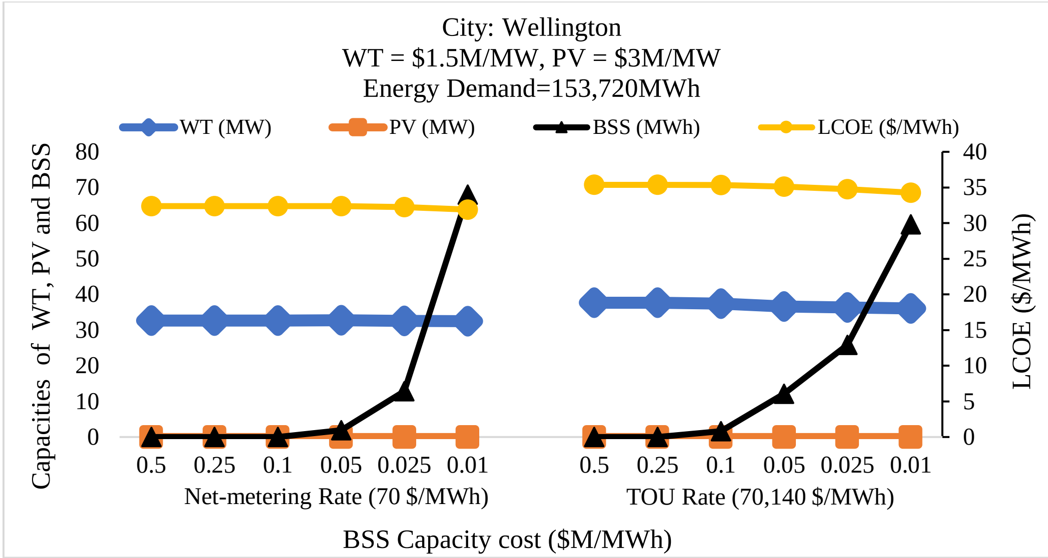

Figure 4.17: Results for the interconnected microgrid in Wellington at WT = $1.5M/MW and PV = $3M/MW.

In Figure 4.17, the system considers WT power of 32.49MW and 37.4MW for net-metering and TOU rates, respectively. No PV power is consumed for both rates. Battery energy of 1.91MWh at $0.05M/MWh and 1.67MWh at $0.1M/MWh is consumed for net-metering and TOU rates, respectively. The LCOE of TOU rate is always higher than the net-metering rate LCOE.

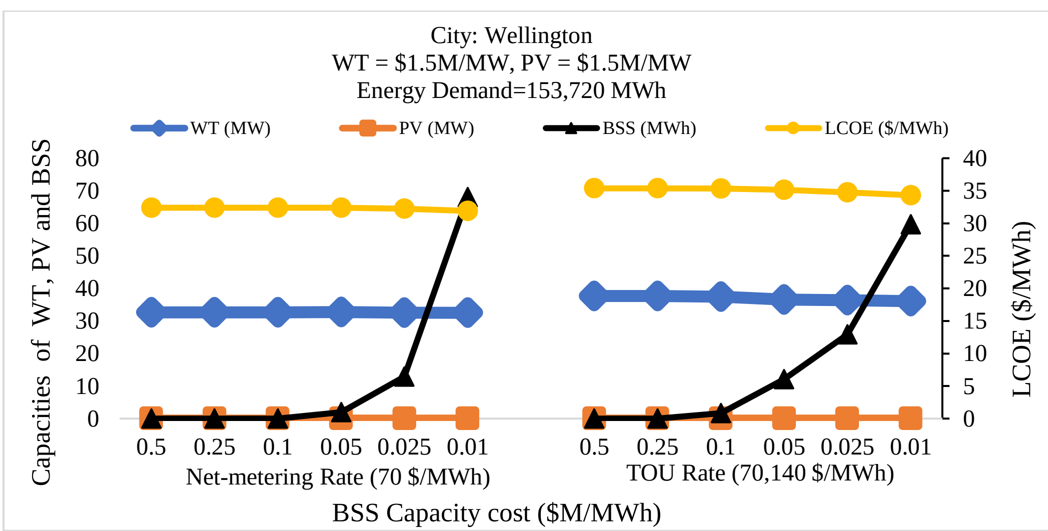

Figure 4.18: Results for the interconnected microgrid in Wellington at WT = $1.5M/MW and PV = $1.5M/MW.

In Figure 4.18, even though we reduce the PV capacity cost to \$1.5M/MW, there is no PV power is consumed. And there is no change in the other outputs.

II. Aswan:

After doing the sensitivity analysis on the model for the factory in Aswan city, the results were shown in following figures.

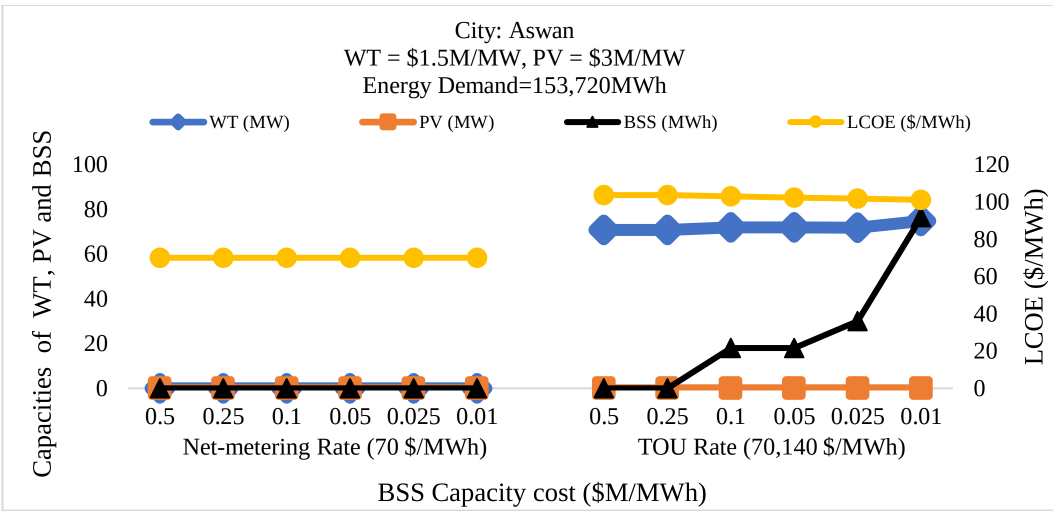

Figure 4.19: Results for the interconnected microgrid in Aswan at WT = \$1.5M/MW and PV = \$3M/MW.

In Figure 4.19, the graph show that there is no power from RES and battery energy is consumed for net-metering rate. For TOU rate, an average of 71.8MW wind power is consumed and battery energy of 18MWh is consumed at its capacity cost \$0.1M/MWh. The LCOE of TOU rate is higher than the net-metering rate LCOE.

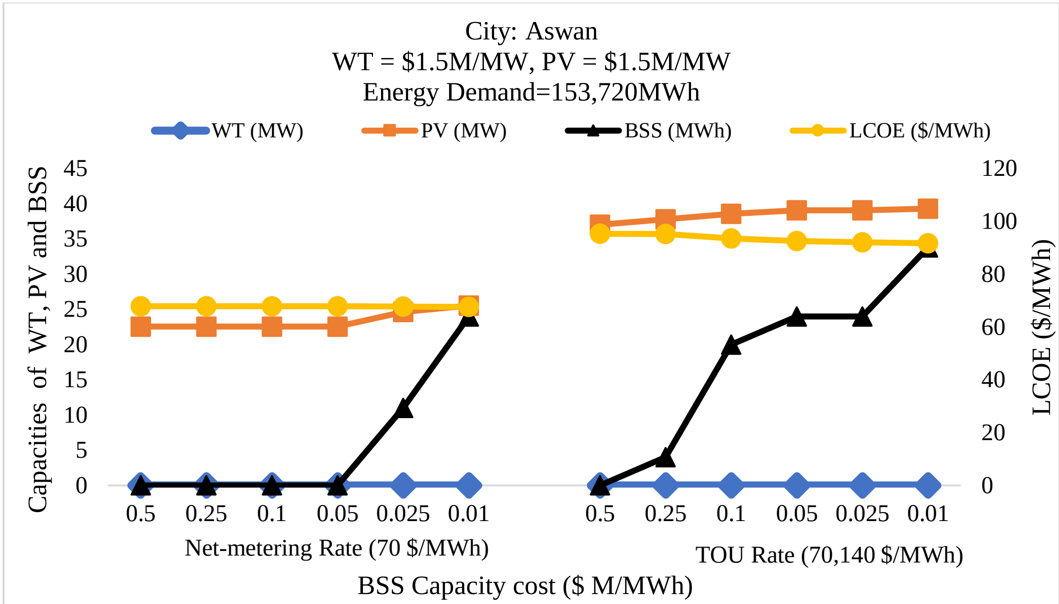

Figure 4.20: Results for the interconnected microgrid in Aswan at WT = $1.5M/MW and PV = $1.5M/MW.

As represented in the above graph of Figure 4.20, an average PV power of 22.5MW and 11MWh of battery energy at $0.025M/MWh for net-metering rate. For TOU rate, an average PV power of 39.06MW and 4MWh of battery energy at $0.25M/MWh is consumed by the system. The average LCOE of net-metering rate is lower than the TOU rate LCOE. But there is no WT power consumed for both rates.

III. Yuma

Same as in Case 1, we consider again three scenarios for the Yuma city and sensitivity analysis is done considering the total energy demand from Case 2 of flow shop model. The outcomes are shown and compared in following graphs.

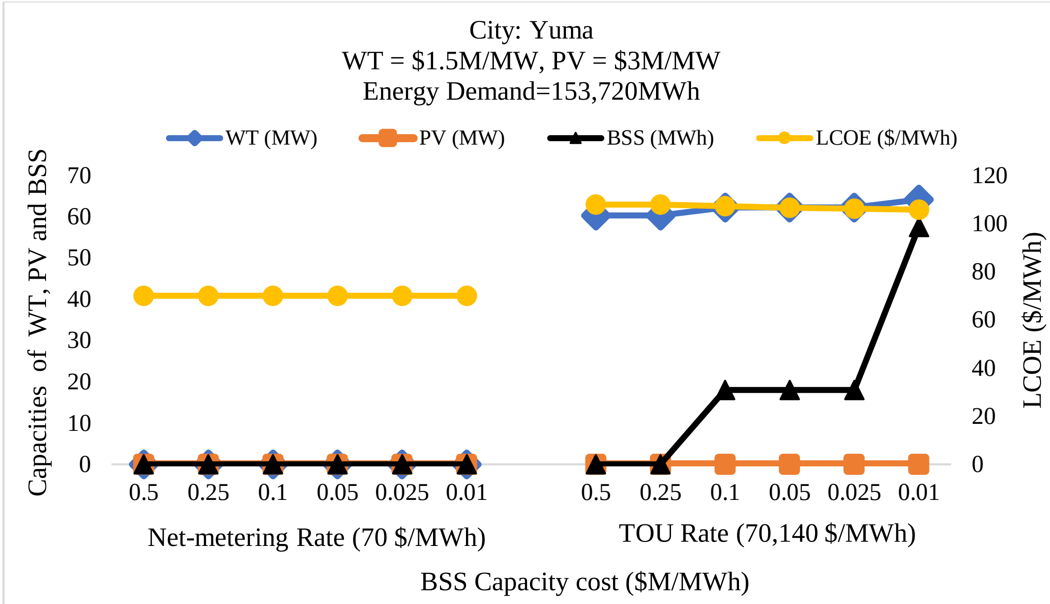

Figure 4.21: Results for the interconnected microgrid in Yuma at WT = $1.5M/MW and PV = $3M/MW.

Figure 4.21 reveals the capacities of WT, PV and BSS and Levelized cost of Energy (LCOE) for Yuma city. If the capacity cost of WT and PV are $1.5M/MW and $3M/MW respectively, the system considers only grid power with and no PV and WT power are consumed for net-metering rate and consume WT power of 62.5MW and no PV power is consumed for TOU rate. If we consider the battery capacity cost ranging from $0.5M/MWh to $0.01M/MWh, then no battery energy is considered for net-metering rate and the battery energy is considered only when the capacity cost is $0.1M–0.01M/MWh. The capacities of WT and BSS, and LCOE for TOU rate are higher than the net-metering rate.

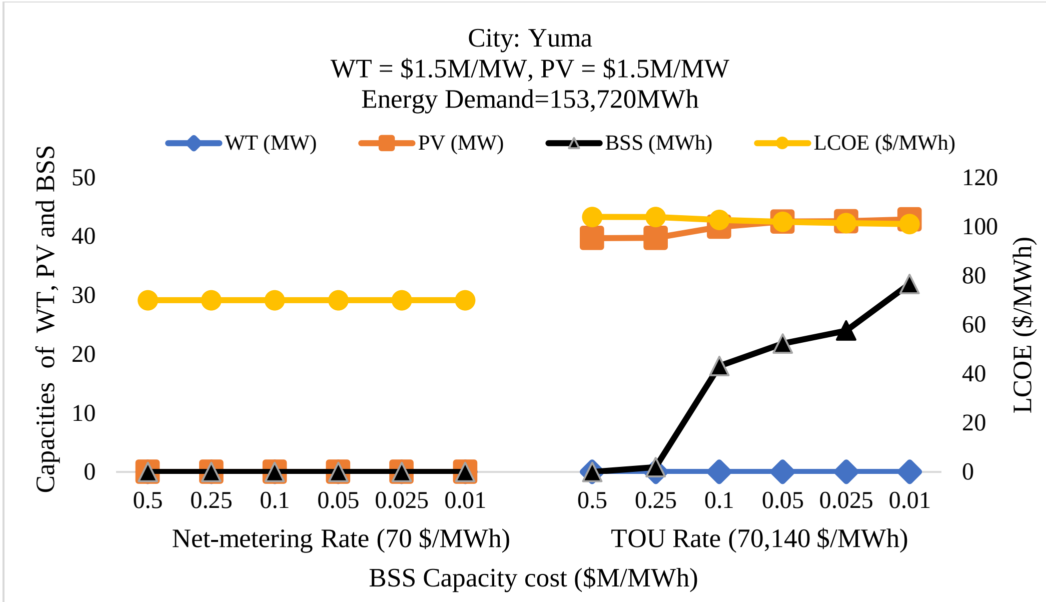

Figure 4.22: Results for the interconnected microgrid in Yuma at WT = $1.5M/MW and PV = $1.5M/MW.

When we reduce the PV capacity cost to $1.5M/MW, the model considers PV power of an average capacity of 41.5MW instead of WT and there is an increase of battery energy consumption for TOU rate and there is no change in outputs for net-metering rate, which is shown in Figure 4.22.

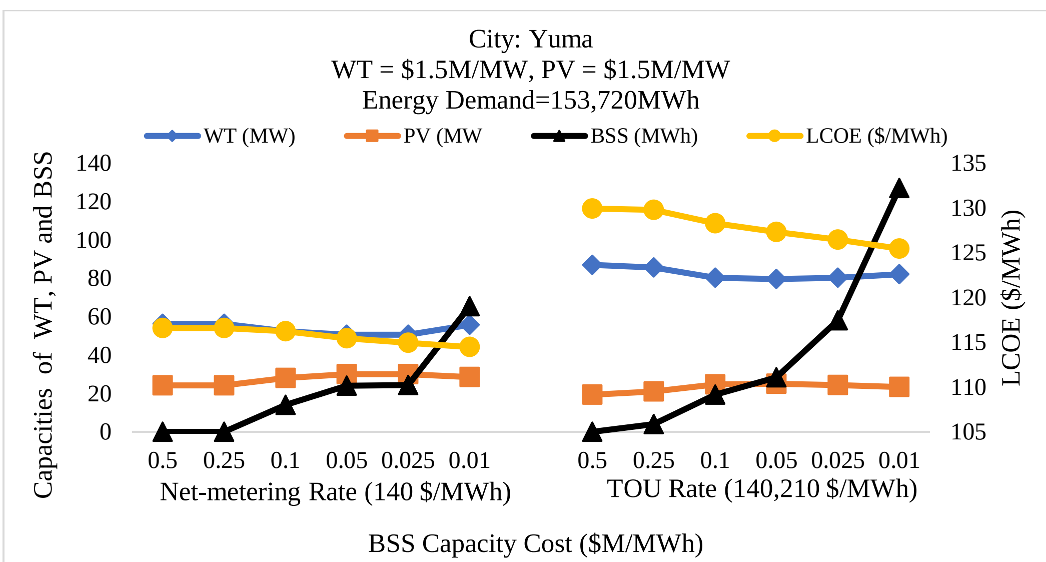

Figure 4.23: Results for the interconnected microgrid in Yuma at WT = $1.5M/MW and PV = $1.5M/MW by doubling both rates.

If we double the net-metering rate to $140 and TOU rate to $140, $210 and at capacity costs of WT =$1.5M/MW and PV =$1.5M/MW, then both WT and PV power are consumed. Battery energy is considered from capacity costs $0.1M–0.01M/MWh for net-metering rate and $0.25M-$0.01M/MWh for TOU rate. As shown in Figure 4.23, for TOU rate, LCOE and WT capacity are higher and PV capacity is lower, when compared to the net-metering rate.

IV. San Francisco

For San Francisco city, we consider total energy demand from Case 2 of flow shop model for sensitivity analysis and the results are represented and compared in following graphs.

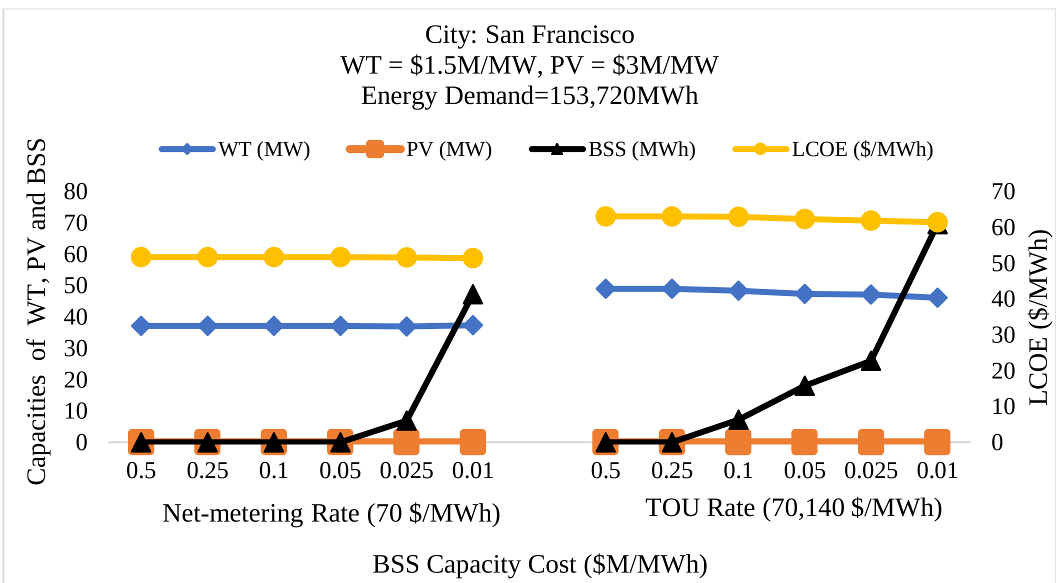

Figure 4.24: Results for the interconnected microgrid in San Francisco at WT = $1.5M/MW and PV = $3M/MW.

In Figure 4.24, the capacities of WT, PV and BSS, and Levelized cost of Energy (LCOE) for San Francisco city are shown. If the capacity cost of WT and PV are $1.5M/MW and $3M/MW respectively, the system considers only WT power with an average capacity of 37MW and 47MW for net-metering rate and TOU rate, respectively and there is no PV consumption for both net-metering and TOU rates. If we consider the battery capacity cost ranging from \$0.5M/MWh to \$0.01M/MWh, then the battery energy is considered only when the capacity cost is \$0.025M - 0.01M/MWh for net-metering rate and \$0.1M–0.01M/MWh. The capacities of WT and BSS, and LCOE for TOU rate are higher than the net-metering rate.

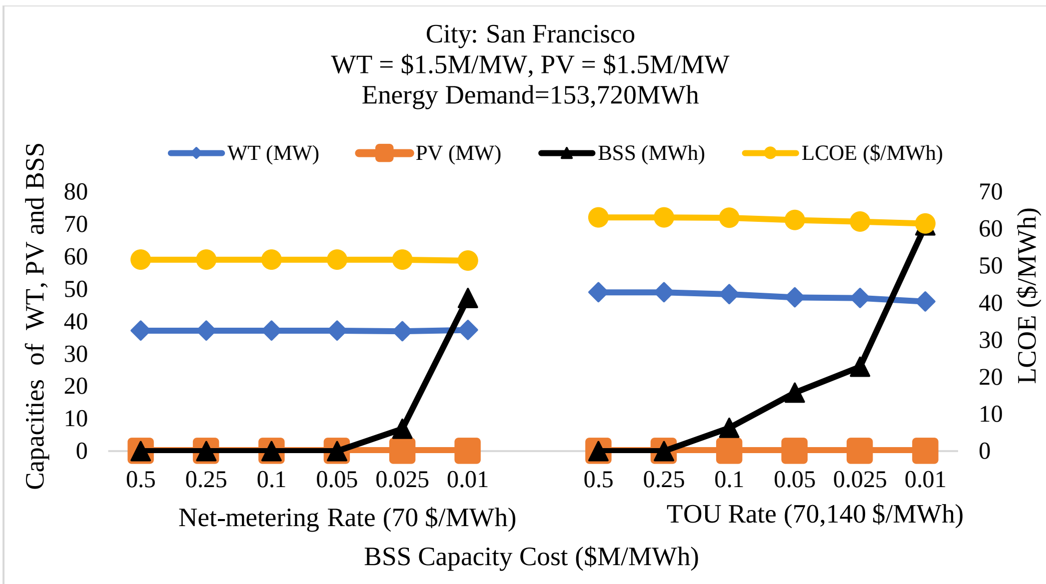

Figure 4.25: Results for the interconnected microgrid in San Francisco at WT = \$1.5M/MW and PV = \$1.5M/MW.

When we only decrease the capacity cost of PV to \$1.5M/MW, there is no change in outputs for both net-metering rate and TOU rate as shown in Figure 4.25.

5. FLOW SHOP MODEL UNDER ISLAND MICROGRID OPERATION

5.1 Allocation of Island Microgrid System for Flow Shop Manufacturing

5.1.1 System Setting

In this section, the microgrid system connected with the factory is isolated from the main power grid. The factory consumes the power only supplied from the microgrid system that has battery storage and RES units like WT and solar PV. The layout of the manufacturing factory with island microgrid system is shown in Figure 5.1.

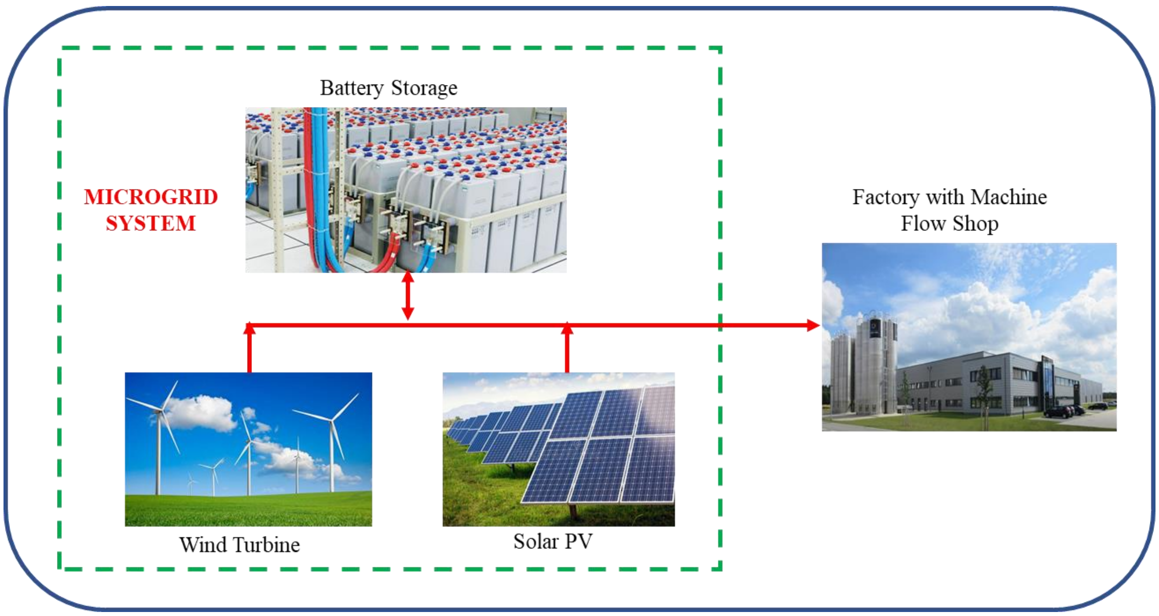

Figure 5.1: The layout of an isolated microgrid system connected to the factory.

As the factory is electrically isolated, the factory consumes the power only from the microgrid system. In this isolated microgrid system, power is produced by only RES such as WT and PV systems. An isolated microgrid system integrated with renewable energy is always ensure zero-carbon emission, which is environment friendly. In this system, the flow of energy is taken place between the user such as factory and the resources like battery system, wind and solar systems.

5.1.2 Numerical Experiments

In this section, we solve the same model formulated in Section 4.2.2 by considering the similar input parameters mentioned in Section 4.2.3. But, due to the isolated microgrid system, we increase the rate of power taken from the grid to highest value, so that system does not choose the grid power. Since the system does not use any grid power, we neither have net-metering nor TOU rates. We use the same climate data that is mentioned in Section 4.2.3.

We solve Problem 4.2 that has formulated in Section 4.2.2 by considering power demand and total energy demand of the benchmark case in flow shop model, which is mentioned in Section 4.1.4. Again, we test the model for the factory located in Wellington, Aswan, Yuma and San Francisco. Problem 4.2 is solved in AMPL software using CPLEX solver and the results were drawn into graphs and discussed in Section 5.1.3.

5.1.3 Results and Analysis

In this section, Problem 4.2 is solved by considering the benchmark case power demand and energy demand of 75928.5MWh in the flow shop model. We do sensitivity analysis by changing the input parameters like capacity costs of WT, PV and battery systems. We consider the same time-period of 8640 hours and the results were drawn in following graphs for four cities. After solving Problem 4.2, we compare the outputs like LCOE and capacities of WT, PV and battery systems for two cities. Same as in the Chapter 4, outputs like LCOE and the capacities of WT, PV and battery systems are represented in Y-axis and the various capacity costs of battery system are mentioned in X-axis for the graphs below.

I. Wellington

After doing sensitivity analysis for a factory in Wellington by considering the power demand and total energy demand of flow shop model benchmark case, the results were presented in following figures.

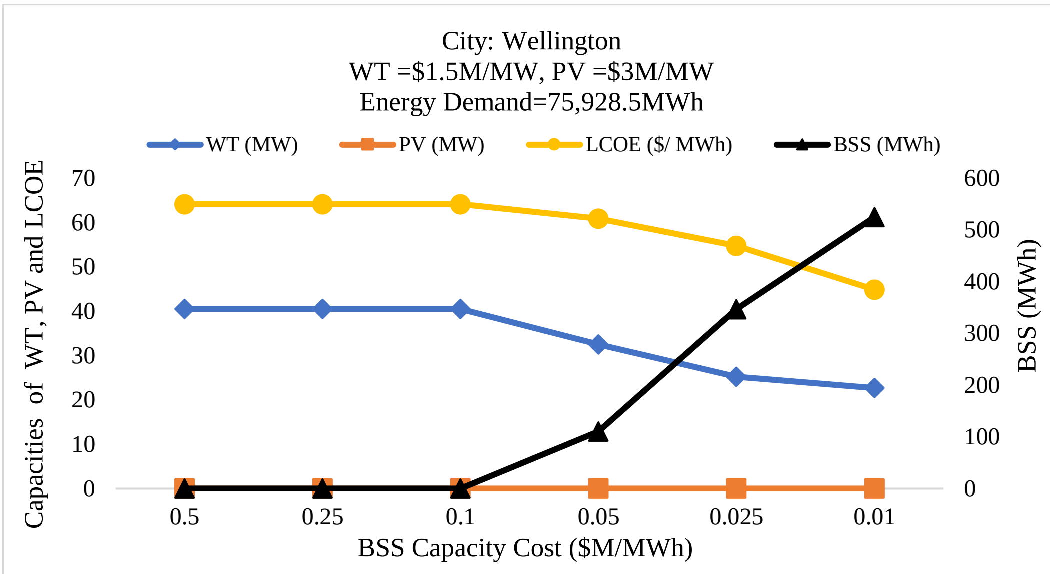

Figure 5.2: Results for the island microgrid in Wellington at WT=$1.5M/MW and PV=$3M/MW.

In Figure 5.2, it shows that system only considers wind power with an average capacity of 32.5MW at its capacity cost $1.5M/MW and no PV power is consumed at its capacity cost $3M/MW. Battery produces with an average capacity of 347MWh is consumed by the system at its capacity cost ranging from $0.05M-$0.01M/MWh and no energy is produced at $0.5M-$0.1M/MWh. The average LCOE of $61/MWh is invested for the factory in Wellington.

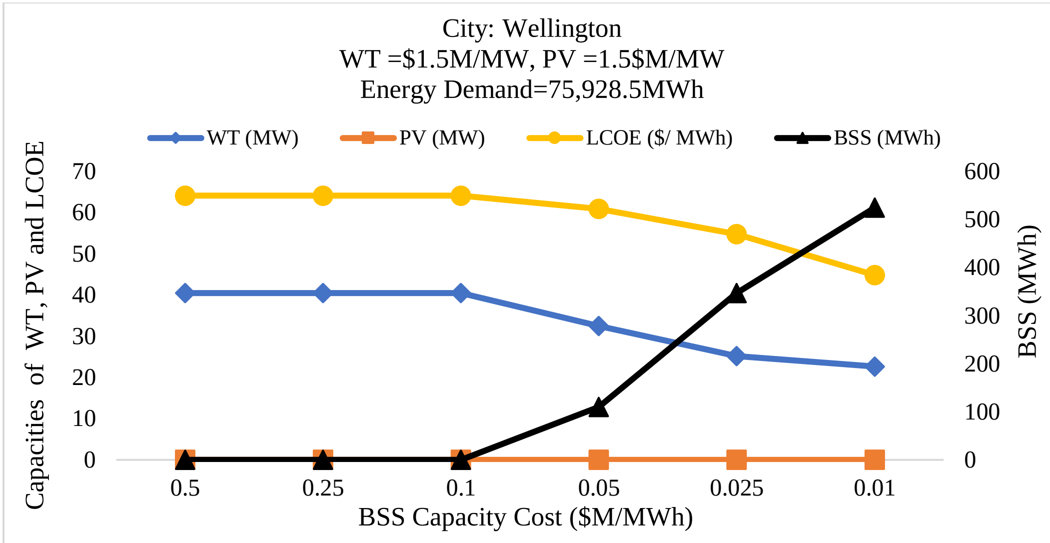

Figure 5.3: Results for the island microgrid in Wellington at WT=$1.5M/MW and PV=$1.5M/MW.

As shown in Figure 5.3, even if we decrease the capacity cost of PV to $1.5M/MW, the system doesn't choose PV power and there are no changes in the other outputs.

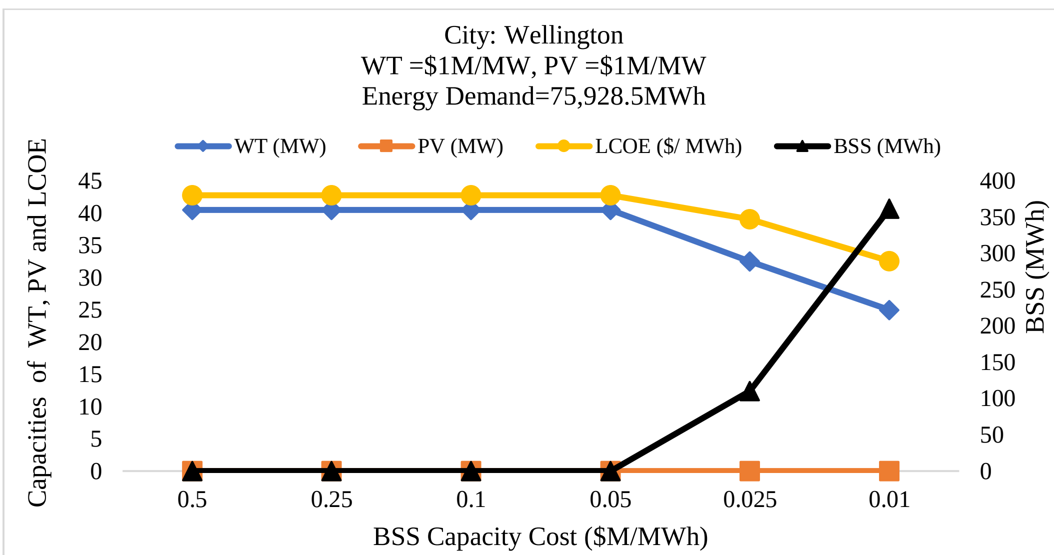

Figure 5.4: Results for the island microgrid in Wellington at WT=$1M/MW and PV=$1M/MW.

If we still reduce the capacity costs of WT and PV to $1M/MW as shown in Figure 5.4, an average WT power of 40.48MW and no PV power is consumed by the system. Battery energy of 110MWh and 362MWh is consumed at its cost of $0.025M/MWh and $0.01M/MWh, respectively. The average LCOE of $43/MWh is invested by the factory.

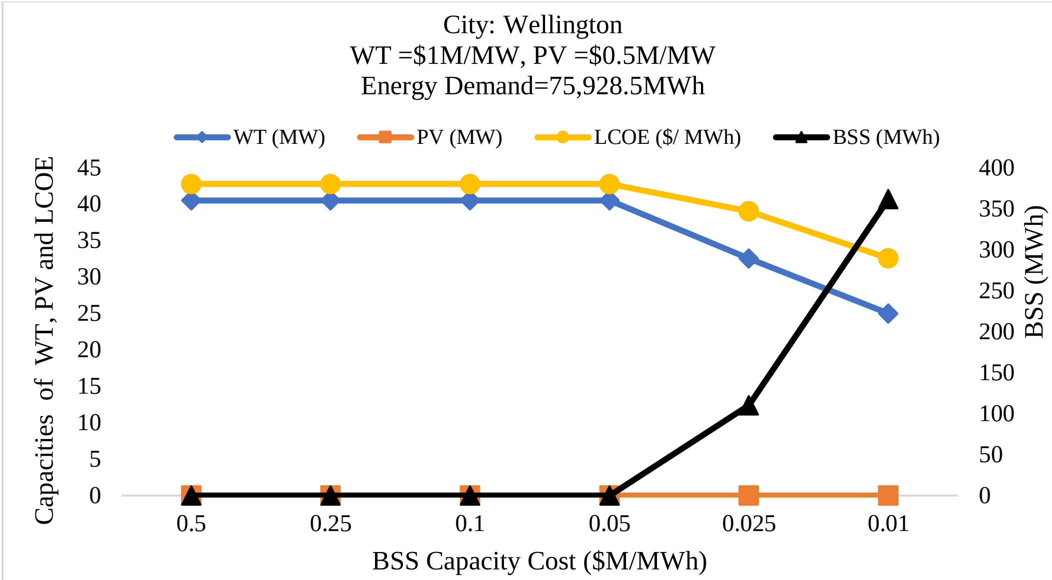

Figure 5.5: Results for the island microgrid in Wellington at WT=$1M/MW and PV=$0.5M/MW.

From the above Figure 5.5, it shows that even if we reduce the PV capacity cost to $0.5M/MWh, there is no PV power consumption and no changes in the other outputs.

II. Aswan

The sensitivity analysis is done on the model for a factory in Aswan and the results were plotted in following figures and discussions are given as well.

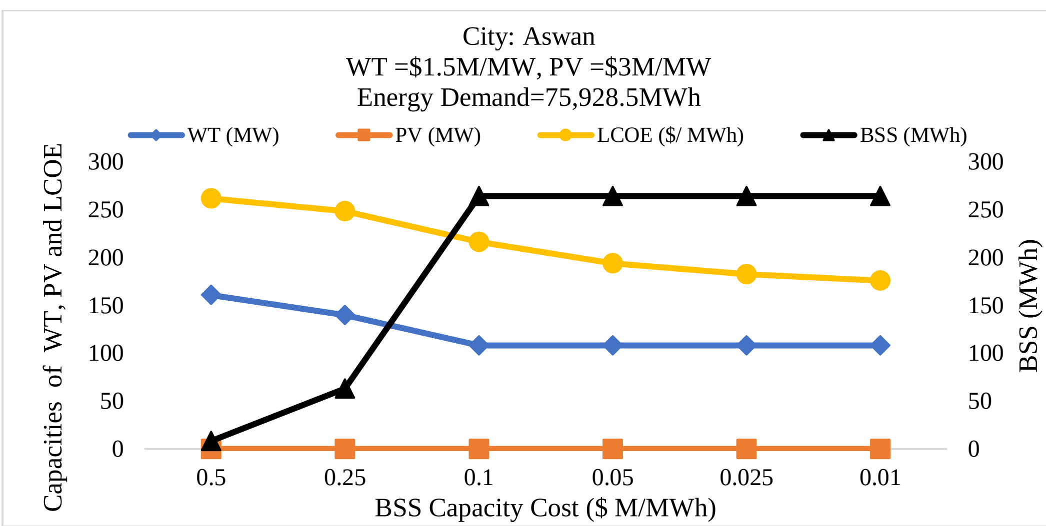

Figure 5.6: Results for the island microgrid in Aswan at WT=$1.5M/MW and PV=$3M/MW.

In above Figure 5.6, in Aswan city even though it has sunnier climate, system chooses only wind power of 122MW at a minimum LCOE of \$194/MWh due to the unavailability of the PV power during night times. Thus, an isolated system in Aswan doesn't consider any PV power. Battery energy of 8.3MWh, 62.97MWh and 264.13MWh is consumed at its capacity costs \$0.5M/MWh, \$0.25M/MWh and \$0.1M-0.01M/MWh, respectively.

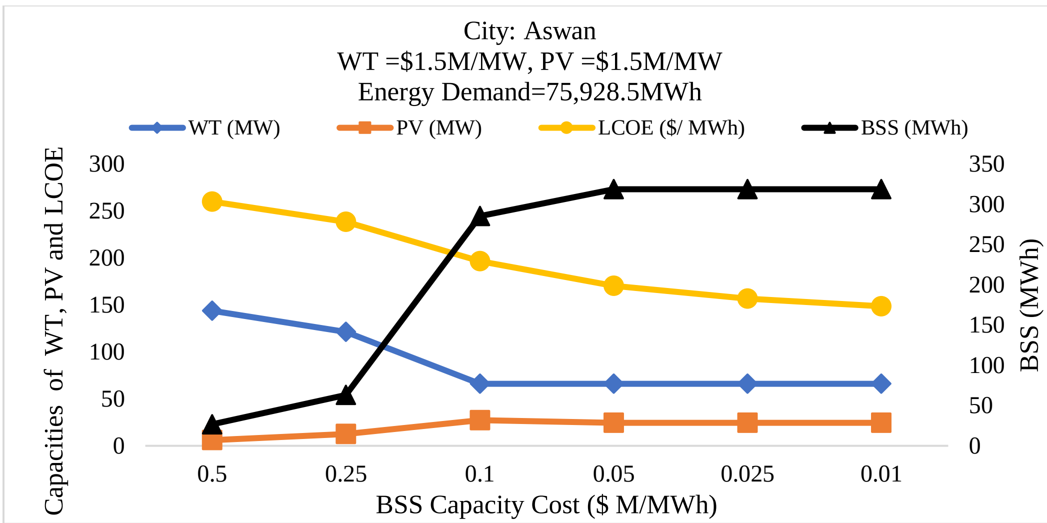

Figure 5.7: Results for the island microgrid in Aswan at WT=\$1.5M/MW and PV=\$1.5M/MW.

From Figure 5.7, it reveals that even if we decrease the PV capacity cost to \$1.5M/MWh, an isolated system chooses an average PV power of 20MW and the capacity of WT consumption is reduced to an average of 88MW and battery consumption is increased at all its capacity costs, respectively.

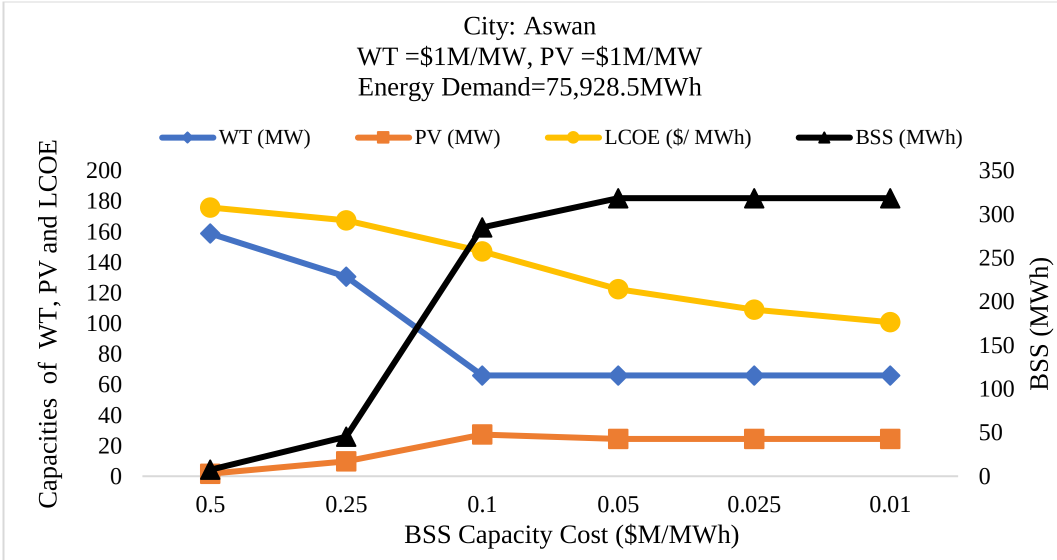

Figure 5.8: Results for the island microgrid in Aswan at WT=$1M/MW and PV=$1M/MW.

As shown in Figure 5.8, when we reduce the capacity costs of PV and WT to $1M/MW, the wind consumption is increased at the high battery capacity costs like $0.5M-0.25M/MWh, whereas PV and battery consumption is decreased. The average LCOE of the system is decreased to $133/MWh.

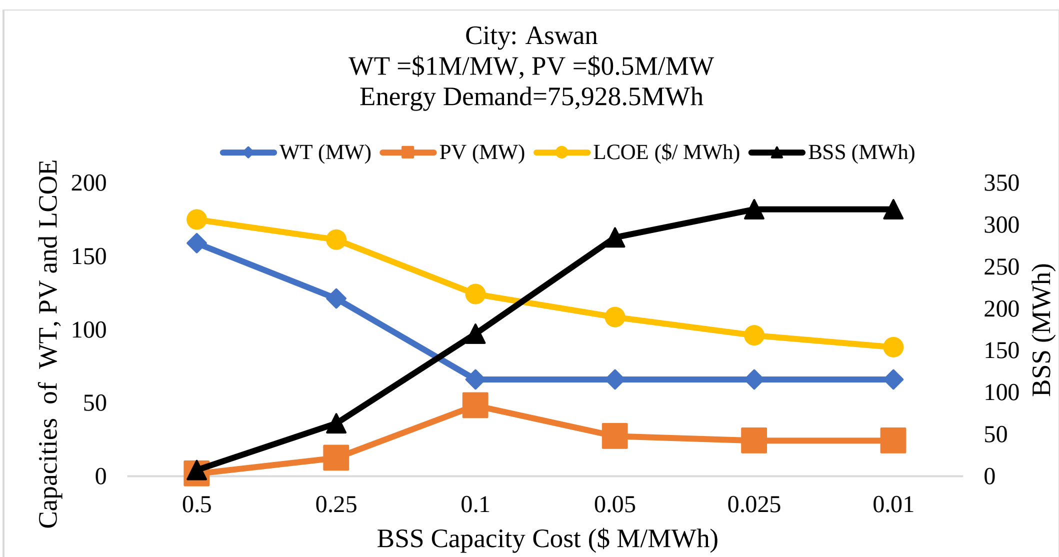

Figure 5.9: Results for the island microgrid in Aswan at WT=$1M/MW and PV=$0.5M/MW.

In Figure 5.9, if we still reduce the PV capacity cost to $0.5M/MW, the PV and battery consumption is increased, and wind consumption is decreased at the battery capacity cost $0.25M/MWh. At battery capacity of $0.1M/MWh, PV consumption is increased to 48.16MW and battery consumption is decreased to 170MW. The average LCOE of the system is decreased to $112/MWh.

III. Yuma

For Yuma city, sensitivity analysis is done on Problem 4.2 for islanded microgrid system by considering the total energy demand of the benchmark case from flow shop model. The calculated results are plotted in following figures.

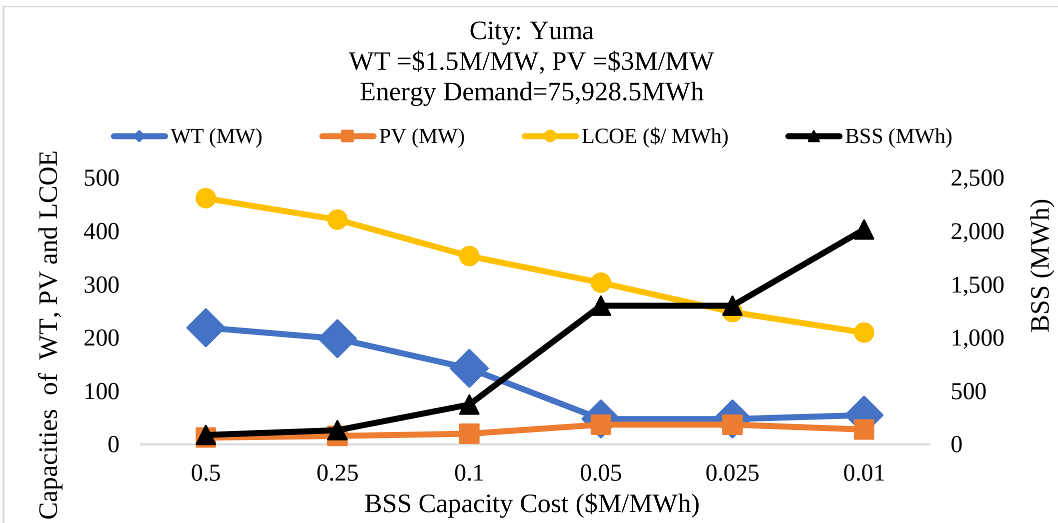

Figure 5.10: Results for the island microgrid in Yuma at WT=$1.5M/MW and PV=$3M/MW.

In Figure 5.10, LCOE and the capacities of WT, PV and BSS for an islanded microgrid system in Yuma city. For the capacity costs of WT and PV with $1.5M/MW and $3M/MW respectively, WT power is consumed with an average capacity of 117MW and average PV power of 25MW is considered. The average battery energy of 870MWh is taken for the capacity costs ranging from $0.5M–0.01M/MWh. The average LCOE of $325/MWh is considered in this system.

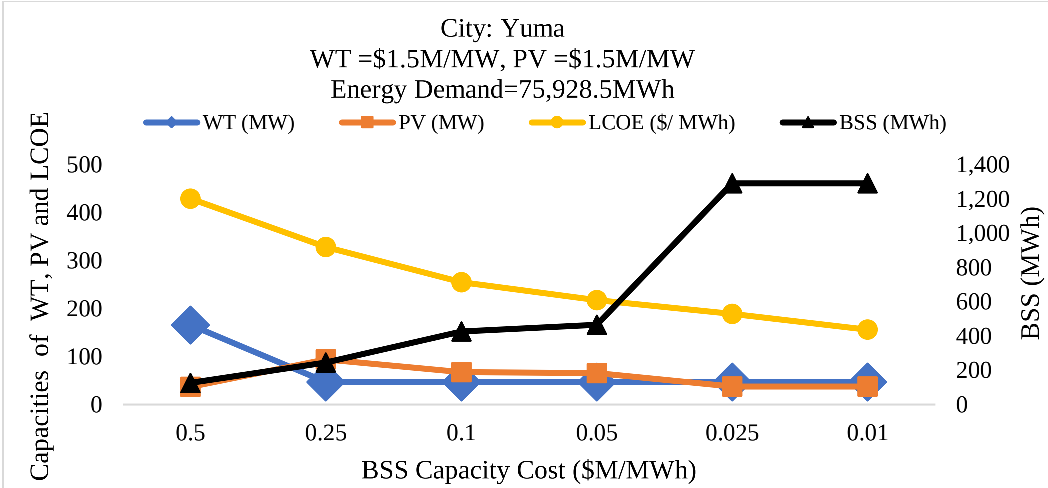

Figure 5.11: Results for the island microgrid in Yuma at WT=$1.5M/MW and PV=$1.5M/MW.

When we reduce the PV capacity cost to $1.5M/MW, wind consumption is decreased, and PV consumption is increased at all battery capacity costs. For the battery capacity costs $0.5M–0.01M/MWh, an average battery energy consumption is decreased to 642MWh. The average LCOE of the system is decreased to $221/MWh.

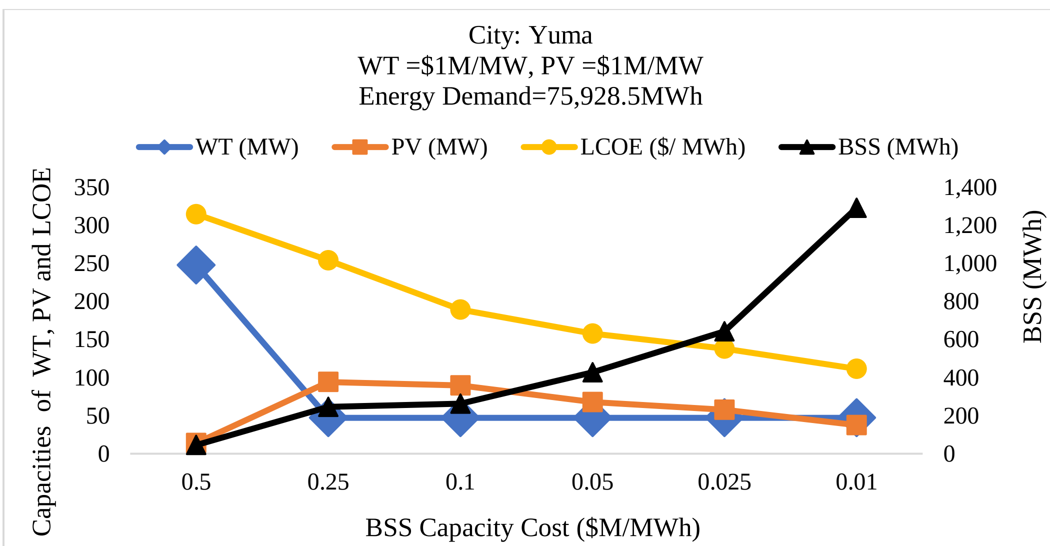

Figure 5.12: Results for the island microgrid in Yuma at WT=$1M/MW and PV=$1M/MW.

If we reduce the capacity costs of WT and PV to $1M/MW each, there is no change in the outputs like energy consumptions at all battery capacity costs except at the $0.025M/MWh. The average LCOE of the system is decreased to $172/MWh.

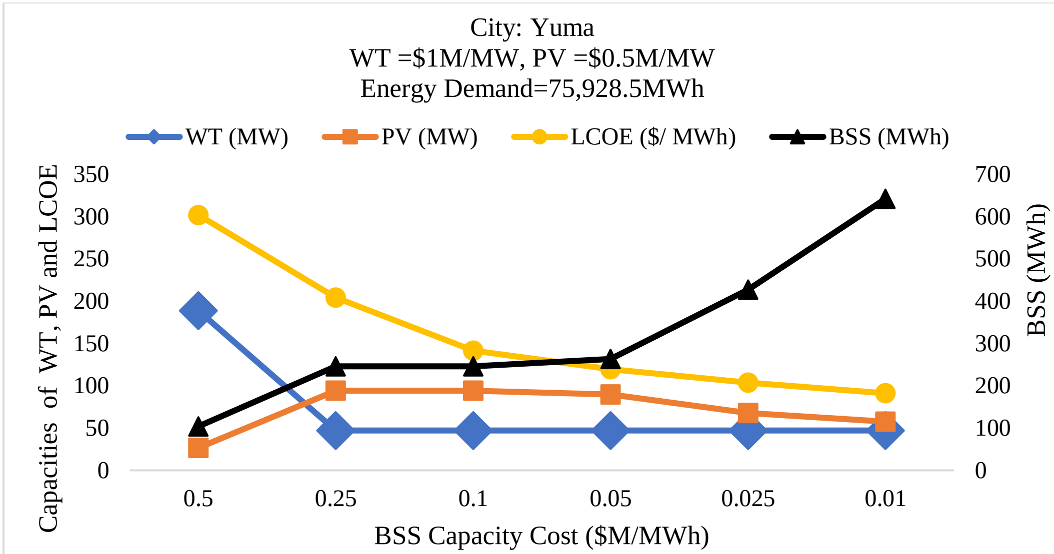

Figure 5.13: Results for the island microgrid in Yuma at WT=$1M/MW and PV=$0.5M/MW.

When we reduce the PV capacity cost to $0.5M/MW, PV power consumption is increased, and battery energy consumption is decreased at all battery capacity costs, respectively. But there is no change in WT consumption. The average LCOE is reduced to $135/MWh.

IV. San Francisco

Sensitivity Analysis is done on Problem 4.2 for the islanded microgrid system in San Francisco by taking total energy demand of benchmark case from flow shop model and final outputs are plotted in following figures.

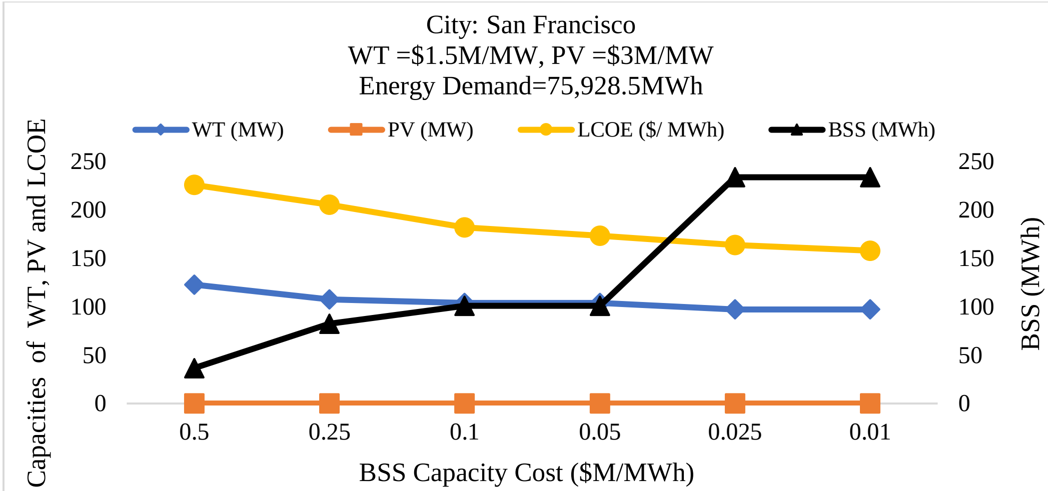

Figure 5.14: Results for the island microgrid in San Francisco at WT=$1.5M/MW and PV=$3M/MW.

Figure 5.14 show that the capacities of WT, PV and BSS and LCOE for an islanded microgrid system in San Francisco city. If we consider the capacity costs of WT and PV with $1.5M/MW and $3M/MW respectively, an average wind power of 102MW is considered and no PV power is consumed. For all battery capacity costs ranging from $0.5M-0.01M/MWh, an average battery energy of 131.52MWh is considered. The average LCOE of $177/MWh is considered in this system.

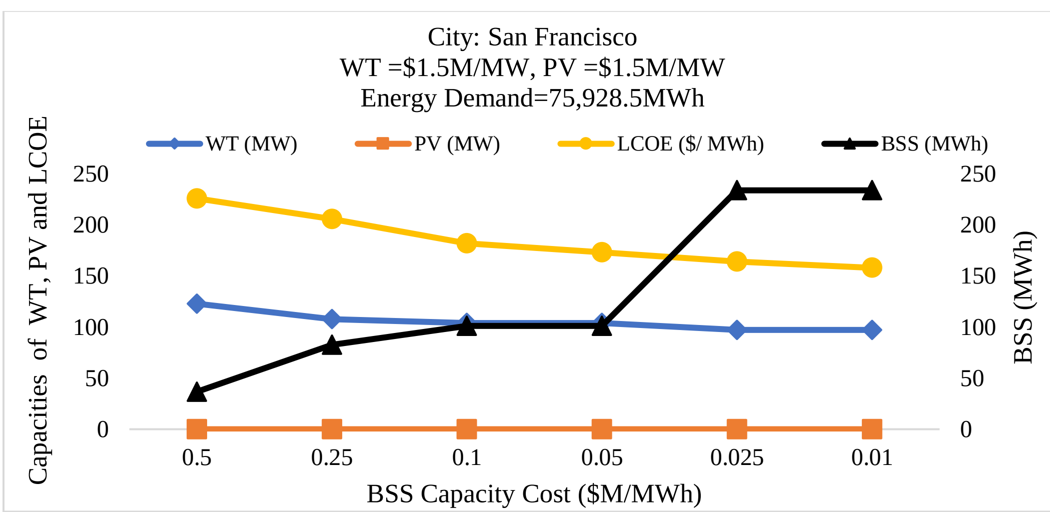

Figure 5.15: Results for the island microgrid in San Francisco at WT=$1.5M/MW and PV=$1.5M/MW.

Even though we reduce the PV capacity cost to \$1.5M/MW, there is no change in the outputs.

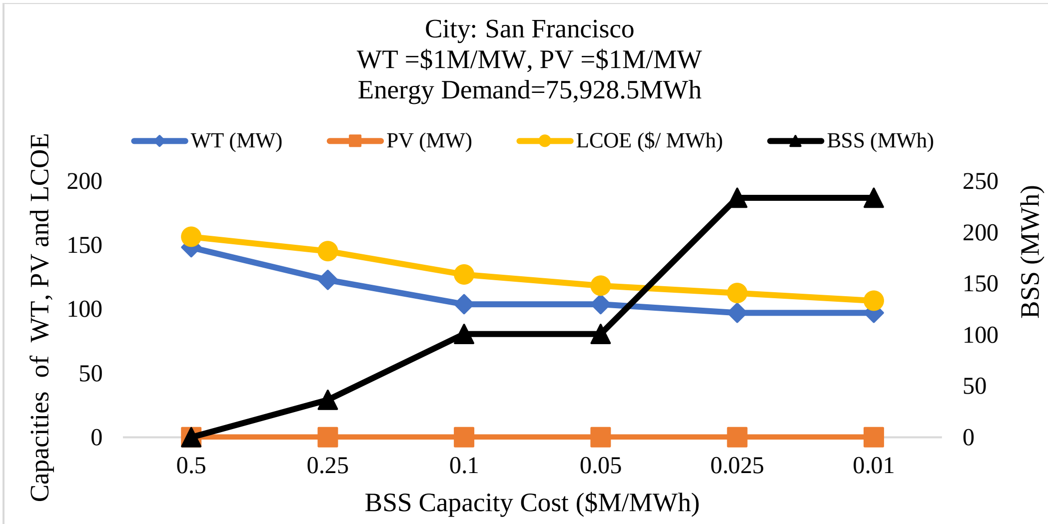

Figure 5.16: Results for the island microgrid in San Francisco at WT=\$1M/MW and PV=\$1M/MW.

If we consider the capacity costs of WT and PV with \$1M/MW each, only WT power of 148.3MW, but no battery energy and PV power is consumed at the battery capacity cost of \$0.5M/MWh. After that again an average wind power and battery energy of 102MW and 131.52MWh, respectively is considered. The average LCOE is reduced to \$122/MWh for this scenario as shown in Figure 5.16.

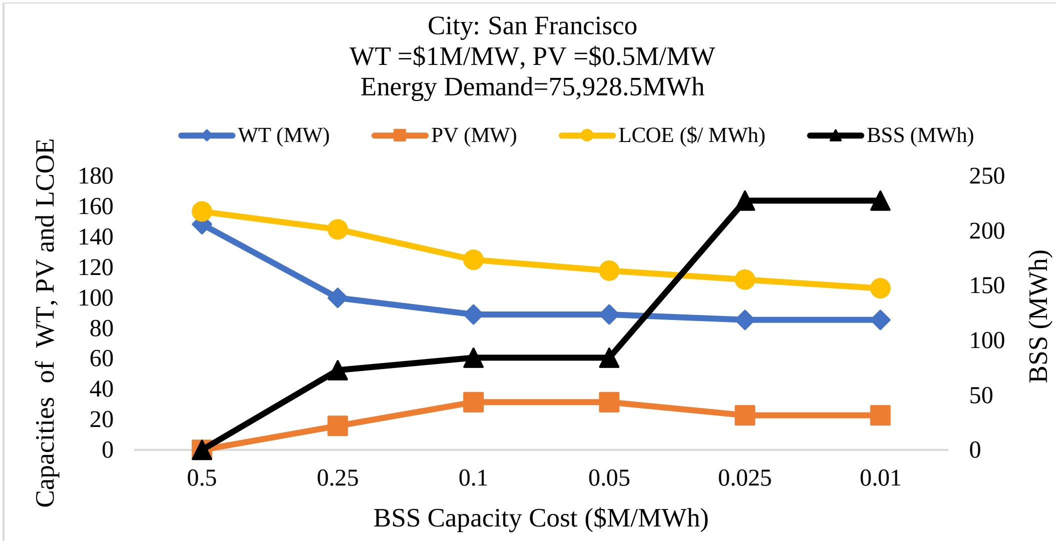

Figure 5.17: Results for the island microgrid in San Francisco at WT=$1M/MW and PV=$1M/MW.

As shown in Figure 5.17, If we reduce the PV capacity cost to $0.5M/MW, there is a PV consumption at all battery capacity costs except at $0.5M/MWh. There are minor fluctuations in the wind and battery consumptions for all battery capacity costs. The average LCOE of the system is decreased to $120/MWh.

5.2 Comparison between Island and Interconnected Microgrid Operations

For four cities, the results of island microgrid system represented in Section 5.1.3 is compared with the results of microgrid system interconnected with power grid and discussed as follows:

I. Wellington

- ❖ In Wellington, both systems choose WT power due to their windier climatic conditions and no PV power is consumed.
- ❖ When the battery capacity costs are low, both systems choose the energy from the battery system.

❖ The average value of LCOE of island microgrid system is always higher than the average LCOE of the interconnected microgrid system with main grid located in Wellington city.

II. Aswan

❖ In Aswan, even though it has sunnier climate, WT power is chosen, and no PV power is consumed for both systems at its capacity costs of $1.5M/MW and $3M/MW for WT and PV systems, respectively.

❖ When we reduce the PV capacity costs, both systems consume PV power as well as wind power. But, the consumption of PV power is less when compared to wind consumption due to its lack of availability during night times, which is not enough to meet the power demand.

❖ In island microgrid system, battery energy is consumed for all its capacity cost where as in interconnected microgrid system, battery energy is consumed only at low capacity costs.

❖ Same as Wellington, an isolated system has highest LCOE when compared to the microgrid system interconnected with main grid.

III. Yuma

❖ In Yuma city, when we consider the capacity costs of $1.5M/MW and $3M/MW for WT and PV systems respectively, both interconnected and islanded microgrid systems choose wind power even though the city has sunny weather.

- ❖ If we reduce the PV capacity cost to $1.5M/MW, both systems consider wind and PV power for all battery capacity costs. When we still reduce the PV capacity cost, the system chooses more PV power instead of wind.

- ❖ Battery energy is chosen by the islanded microgrid system for all its capacity cost whereas the interconnected microgrid system choose the energy from the battery only at its low capacity cost.

- ❖ The LCOE of the interconnected microgrid system is very less when compared to the LCOE of the islanded microgrid system.

IV. San Francisco

- ❖ If we consider the capacity costs of $1.5M/MW and $3M/MW respectively, only wind power is chosen by both interconnected and islanded microgrid systems in San Francisco city.

- ❖ Even though we reduce the PV capacity cost to $1.5M/MW, both interconnected and island microgrid system choose wind power. If we reduce the PV capacity cost to $0.5M/MW for islanded microgrid system, the system choose solar power and PV consumption is less when compared to wind, because San Francisco has high wind and also there is no PV power production during night times.

- ❖ Interconnected microgrid system choose battery energy when its capacity cost is low, whereas islanded microgrid system choose battery energy for all its capacity costs.

- ❖ Islanded microgrid system consume highest LCOE when compared to the interconnected microgrid system LCOE.

6. CONCLUSION AND FUTURE WORK

This thesis has two main objectives. In the first objective, the contribution of this work is fulfilled by optimal solutions provided by the proposed model. In this first objective, initially we make the manufacturers to behave like good prosumers even though they adopt a demand response management scheme in production planning systems. The experiments show that, when compared to the system without demand response there is nothing much difference in costs and consumption of renewable energies for a carbon-neutral production planning system with demand response. The study also reveals that PV system can only compete with WT system, when its capacity cost is reduced to $1.5M/MW. Secondly, when we add the microgrid system to the production planning, the system chooses the reasonable levelized cost of energy and both PV and battery systems can compete with the WT system when the capacity costs of PV and battery systems is reduced to $1.5M/MW and $0.1M to $0.05M/MWh, respectively.

In future work, the production planning model can be elaborated by adding different transportation modes, electric trains and inter-operation between the electric vehicles and the local microgrid systems through V2G and G2V operations in a transactive energy market mechanism. Meanwhile, further investigation of production planning is to incorporate island microgrid system.

In the second objective, the first proposed model for flow shop scheduling is solved under two different throughput rates and we obtain two different total energy demand and two different optimal power demands for each time-period. Then we have solved the second proposed model for the optimization of energy flow between the various sources and users for interconnected microgrid system with two different tariff rates like TOU and net-metering. The model is also solved for an island microgrid system considering the throughputs. The experimentation results show that, at first TOU rate is more desirable to integrate onsite wind and solar generation when compared to net-metering rate. Second, PV and battery systems can only compete with WT system when their capacity costs are reduced to $1.5M/MWh and $0.1M to $0.05M/MWh, respectively for both interconnected and island microgrid systems.

In future research, this work can be expanded by considering a multi-factory environment for the optimization of both flow shop scheduling and energy flow model. Secondly, the current research can be elaborated by considering re-entrant jobs in the production flow instead of considering the feed forward control.

The proposed model in this research can also be solved by considering the real time pricing (RTP) and critical peak pricing (CPP) tariffs. When the manufacturer considers RTP, the prices for the power taken from the grid vary hour-by-hour to match wholesale power prices. Critical peak pricing (CPP) is an electric production rate that is applied only for industrial sectors whose electric demand is high. CPP schemes only occur during peak periods like hot summer times and they have long term contracts (e.g. 12-month contract).

APPENDIX SECTION

Sample code for Problem 3.1 in Chapter 3

Appendix for first 3-month period and can easily extended to 1year period.

################################ MODEL FILE #############################

```
set Time;
set OTime11;
set OTime12;
set OTime13;
set OTime21;
set OTime22;
set OTime23;
set OTime31;
set OTime32;
set OTime33;
set MTime1;
set MTime2;
set MTime3;
set Stages;
set Machines;
set PMachines1;
set PMachines2;
set PMachines3;
set Jobs;
param PP1 {i in PMachines1, j in Jobs} >= 0;
param PP2 {i in PMachines2, j in Jobs} >= 0;
param PP3 {i in PMachines3, j in Jobs} >= 0;
param PT1 {i in PMachines1, j in Jobs} >= 0;
param PT2 {i in PMachines2, j in Jobs} >= 0;
param PT3 {i in PMachines3, j in Jobs} >= 0;
param MPT >= 0;
param BC >= 0;
param NTP1 >= 0;
param NTP2 >= 0;
param NTP3 >= 0;
param dstages >= 0;
var x_oper1 {i in PMachines1, j in Jobs, t in Time} binary;
var x_oper2 {i in PMachines2, j in Jobs, t in Time} binary;
var x_oper3 {i in PMachines3, j in Jobs, t in Time} binary;
var y_oper1 {i in PMachines1, j in Jobs, t in Time} binary;
var y_oper2 {i in PMachines2, j in Jobs, t in Time} binary;
var y_oper3 {i in PMachines3, j in Jobs, t in Time} binary;
var x_maint1 {i in PMachines1, t in Time} binary;
var x_maint2 {i in PMachines2, t in Time} binary;
var x_maint3 {i in PMachines3, t in Time} binary;
var y_maint1 {i in PMachines1, t in Time} binary;
var y_maint2 {i in PMachines2, t in Time} binary;
var y_maint3 {i in PMachines3, t in Time} binary;
var N1 {j in Jobs, t in Time} >= 0;
var N2 {j in Jobs, t in Time} >= 0;
```

```
var N3 {j in Jobs, t in Time} >= 0;
var PD {t in Time} >= 0;
f{t in Time}: PD[t] = ((sum {i in PMachines1} sum {j in Jobs} (PP1[i,j] *
x_oper1[i,j,t])) + (sum {i in PMachines2} sum {j in Jobs} (PP2[i,j] *
x_oper2[i,j,t])) + (sum {i in PMachines3} sum {j in Jobs} (PP3[i,j] *
x_oper3[i,j,t])));
subject to c1{j in Jobs, t in OTime11} : N1[j,t] = 0;
subject to c2{j in Jobs, t in OTime12} : N2[j,t] = 0;
subject to c3{j in Jobs, t in OTime13} : N3[j,t] = 0;
subject to c4{j in Jobs, t in OTime21} : N1[j,t] = (sum {i in PMachines1} sum
{k in 0..t-39} (y_oper1[i,j,k]));
subject to c5{j in Jobs, t in OTime22} : N2[j,t] = (sum {i in PMachines2} sum
{k in 0..t-59} (y_oper2[i,j,k]));
subject to c6{j in Jobs, t in OTime23} : N3[j,t] = (sum {i in PMachines3} sum
{k in 0..t-39} (y_oper3[i,j,k]));
subject to c7{j in Jobs, t in Time} : N1[j,t] >= (N2[j,t] + (sum {i in
PMachines2} (x_oper2[i,j,t])));
subject to c8{j in Jobs, t in Time} : N2[j,t] >= (N3[j,t] + (sum {i in
PMachines3} (x_oper3[i,j,t])));
subject to c9{j in Jobs, t in Time} : N1[j,t] <= (N2[j,t] + BC);
subject to c10{j in Jobs, t in Time} : N2[j,t] <= (N3[j,t] + BC);
subject to c11{j in Jobs} : N3[j,720] = NTP1;
subject to c39{j in Jobs} : N3[j,1440] = NTP2;
subject to c40{j in Jobs} : N3[j,2160] = NTP3;
subject to c12{i in PMachines1, j in Jobs, t in OTime11} : x_oper1[i,j,t] =
(sum {k in 0..t} (y_oper1[i,j,k]));
subject to c13{i in PMachines2, j in Jobs, t in OTime12} : x_oper2[i,j,t] =
(sum {k in 0..t} (y_oper2[i,j,k]));
subject to c14{i in PMachines3, j in Jobs, t in OTime13} : x_oper3[i,j,t] =
(sum {k in 0..t} (y_oper3[i,j,k]));
subject to c15{i in PMachines1, j in Jobs, t in OTime21} : x_oper1[i,j,t] =
(sum {k in t-39..t} (y_oper1[i,j,k]));
subject to c16{i in PMachines2, j in Jobs, t in OTime22} : x_oper2[i,j,t] =
(sum {k in t-59..t} (y_oper2[i,j,k]));
subject to c17{i in PMachines3, j in Jobs, t in OTime23} : x_oper3[i,j,t] =
(sum {k in t-39..t} (y_oper3[i,j,k]));
subject to c18{i in PMachines1, j in Jobs, t in OTime31} : (sum {k in t..t+39}
(x_oper1[i,j,k])) >= (y_oper1[i,j,t] * PT1[i,j]);
subject to c19{i in PMachines2, j in Jobs, t in OTime32} : (sum {k in t..t+59}
(x_oper2[i,j,k])) >= (y_oper2[i,j,t] * PT2[i,j]);
subject to c20{i in PMachines3, j in Jobs, t in OTime33} : (sum {k in t..t+39}
(x_oper3[i,j,k])) >= (y_oper3[i,j,t] * PT3[i,j]);
subject to c21{i in PMachines1, t in Time} : (sum {j in Jobs}
(x_oper1[i,j,t])) <= 1;
subject to c22{i in PMachines2, t in Time} : (sum {j in Jobs}
(x_oper2[i,j,t])) <= 1;
subject to c23{i in PMachines3, t in Time} : (sum {j in Jobs}
(x_oper3[i,j,t])) <= 1;
subject to c24{i in PMachines1, t in Time} : (sum {j in Jobs}
(y_oper1[i,j,t])) <= 1;
subject to c25{i in PMachines2, t in Time} : (sum {j in Jobs}
(y_oper2[i,j,t])) <= 1;
subject to c26{i in PMachines3, t in Time} : (sum {j in Jobs}
(y_oper3[i,j,t])) <= 1;
```

```
subject to c27{i in PMachines1, t in MTime1} : x_maint1[i,t] = (sum {k in 
0..t} (y_maint1[i,k]));
subject to c28{i in PMachines2, t in MTime1} : x_maint2[i,t] = (sum {k in 
0..t} (y_maint2[i,k]));
subject to c29{i in PMachines3, t in MTime1} : x_maint3[i,t] = (sum {k in 
0..t} (y_maint3[i,k]));
subject to c30{i in PMachines1, t in MTime2} : x_maint1[i,t] = (sum {k in t-
119..t} (y_maint1[i,k]));
subject to c31{i in PMachines2, t in MTime2} : x_maint2[i,t] = (sum {k in t-
119..t} (y_maint2[i,k]));
subject to c32{i in PMachines3, t in MTime2} : x_maint3[i,t] = (sum {k in t-
119..t} (y_maint3[i,k]));
subject to c33{i in PMachines1, j in Jobs, t in MTime3} : (sum {k in t..t+119} 
(x_maint1[i,k])) >= (y_maint1[i,t] * MPT);
subject to c34{i in PMachines2, j in Jobs, t in MTime3} : (sum {k in t..t+119} 
(x_maint2[i,k])) >= (y_maint2[i,t] * MPT);
subject to c35{i in PMachines3, j in Jobs, t in MTime3} : (sum {k in t..t+119} 
(x_maint3[i,k])) >= (y_maint3[i,t] * MPT);
subject to c36{i in PMachines1, t in Time} : (x_maint1[i,t] + (sum {j in Jobs} 
(x_oper1[i,j,t]))) <= 1;
subject to c37{i in PMachines2, t in Time} : (x_maint2[i,t] + (sum {j in Jobs} 
(x_oper2[i,j,t]))) <= 1;
subject to c38{i in PMachines3, t in Time} : (x_maint3[i,t] + (sum {j in Jobs} 
(x_oper3[i,j,t]))) <= 1;
```

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

```
set     Time := 0   1     2     3     4     5     6     7     8     9
        10    11    12    13    14    15    16    17    18    19    20
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        32    33    34    35    36    37    38    39    40    41    42
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        65    66    67    68    69    70    71    72    73    74    75
        76    77    78    79    80    81    82    83    84    85    86
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2100	2101	2102	2103	2104	2105	2106	2107	2108	2109	2110

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        2155   2156   2157   2158   2159   2160;

set     OTime11 := 0 1      2      3      4      5      6      7      8      9
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        21     22     23     24     25     26     27     28     29     30     31
        32     33     34     35     36     37     38     39;

set     OTime12 := 0 1      2      3      4      5      6      7      8      9
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        21     22     23     24     25     26     27     28     29     30     31
        32     33     34     35     36     37     38     39     40     41     42
        43     44     45     46     47     48     49     50     51     52     53
        54     55     56     57     58     59;

set     OTime13 := 0 1      2      3      4      5      6      7      8      9
        10     11     12     13     14     15     16     17     18     19     20
        21     22     23     24     25     26     27     28     29     30     31
        32     33     34     35     36     37     38     39;



set     OTime21 := 4041     42     43     44     45     46     47     48     49
        50     51     52     53     54     55     56     57     58     59     60
        61     62     63     64     65     66     67     68     69     70     71
        72     73     74     75     76     77     78     79     80     81     82
        83     84     85     86     87     88     89     90     91     92     93
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934	935	936	937	938	939	940	941	942	943	944
945	946	947	948	949	950	951	952	953	954	955
956	957	958	959	960	961	962	963	964	965	966
967	968	969	970	971	972	973	974	975	976	977
978	979	980	981	982	983	984	985	986	987	988
989	990	991	992	993	994	995	996	997	998	999
1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010
1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021
1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032
1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043
1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054
1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065
1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076
1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087
1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098

1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109
1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120
1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131
1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142
1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153
1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164
1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175
1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186
1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197
1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208
1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219
1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230
1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241
1242	1243	1244	1245	1246	1247	1248	1249	1250	1251	1252
1253	1254	1255	1256	1257	1258	1259	1260	1261	1262	1263
1264	1265	1266	1267	1268	1269	1270	1271	1272	1273	1274
1275	1276	1277	1278	1279	1280	1281	1282	1283	1284	1285
1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296
1297	1298	1299	1300	1301	1302	1303	1304	1305	1306	1307
1308	1309	1310	1311	1312	1313	1314	1315	1316	1317	1318
1319	1320	1321	1322	1323	1324	1325	1326	1327	1328	1329
1330	1331	1332	1333	1334	1335	1336	1337	1338	1339	1340
1341	1342	1343	1344	1345	1346	1347	1348	1349	1350	1351
1352	1353	1354	1355	1356	1357	1358	1359	1360	1361	1362
1363	1364	1365	1366	1367	1368	1369	1370	1371	1372	1373
1374	1375	1376	1377	1378	1379	1380	1381	1382	1383	1384
1385	1386	1387	1388	1389	1390	1391	1392	1393	1394	1395
1396	1397	1398	1399	1400	1401	1402	1403	1404	1405	1406
1407	1408	1409	1410	1411	1412	1413	1414	1415	1416	1417
1418	1419	1420	1421	1422	1423	1424	1425	1426	1427	1428
1429	1430	1431	1432	1433	1434	1435	1436	1437	1438	1439
1440	1441	1442	1443	1444	1445	1446	1447	1448	1449	1450
1451	1452	1453	1454	1455	1456	1457	1458	1459	1460	1461
1462	1463	1464	1465	1466	1467	1468	1469	1470	1471	1472
1473	1474	1475	1476	1477	1478	1479	1480	1481	1482	1483
1484	1485	1486	1487	1488	1489	1490	1491	1492	1493	1494
1495	1496	1497	1498	1499	1500	1501	1502	1503	1504	1505
1506	1507	1508	1509	1510	1511	1512	1513	1514	1515	1516
1517	1518	1519	1520	1521	1522	1523	1524	1525	1526	1527
1528	1529	1530	1531	1532	1533	1534	1535	1536	1537	1538
1539	1540	1541	1542	1543	1544	1545	1546	1547	1548	1549
1550	1551	1552	1553	1554	1555	1556	1557	1558	1559	1560
1561	1562	1563	1564	1565	1566	1567	1568	1569	1570	1571
1572	1573	1574	1575	1576	1577	1578	1579	1580	1581	1582
1583	1584	1585	1586	1587	1588	1589	1590	1591	1592	1593
1594	1595	1596	1597	1598	1599	1600	1601	1602	1603	1604
1605	1606	1607	1608	1609	1610	1611	1612	1613	1614	1615
1616	1617	1618	1619	1620	1621	1622	1623	1624	1625	1626
1627	1628	1629	1630	1631	1632	1633	1634	1635	1636	1637
1638	1639	1640	1641	1642	1643	1644	1645	1646	1647	1648
1649	1650	1651	1652	1653	1654	1655	1656	1657	1658	1659
1660	1661	1662	1663	1664	1665	1666	1667	1668	1669	1670
1671	1672	1673	1674	1675	1676	1677	1678	1679	1680	1681
1682	1683	1684	1685	1686	1687	1688	1689	1690	1691	1692
1693	1694	1695	1696	1697	1698	1699	1700	1701	1702	1703

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       1704   1705   1706   1707   1708   1709   1710   1711   1712   1713   1714
       1715   1716   1717   1718   1719   1720   1721   1722   1723   1724   1725
       1726   1727   1728   1729   1730   1731   1732   1733   1734   1735   1736
       1737   1738   1739   1740   1741   1742   1743   1744   1745   1746   1747
       1748   1749   1750   1751   1752   1753   1754   1755   1756   1757   1758
       1759   1760   1761   1762   1763   1764   1765   1766   1767   1768   1769
       1770   1771   1772   1773   1774   1775   1776   1777   1778   1779   1780
       1781   1782   1783   1784   1785   1786   1787   1788   1789   1790   1791
       1792   1793   1794   1795   1796   1797   1798   1799   1800   1801   1802
       1803   1804   1805   1806   1807   1808   1809   1810   1811   1812   1813
       1814   1815   1816   1817   1818   1819   1820   1821   1822   1823   1824
       1825   1826   1827   1828   1829   1830   1831   1832   1833   1834   1835
       1836   1837   1838   1839   1840   1841   1842   1843   1844   1845   1846
       1847   1848   1849   1850   1851   1852   1853   1854   1855   1856   1857
       1858   1859   1860   1861   1862   1863   1864   1865   1866   1867   1868
       1869   1870   1871   1872   1873   1874   1875   1876   1877   1878   1879
       1880   1881   1882   1883   1884   1885   1886   1887   1888   1889   1890
       1891   1892   1893   1894   1895   1896   1897   1898   1899   1900   1901
       1902   1903   1904   1905   1906   1907   1908   1909   1910   1911   1912
       1913   1914   1915   1916   1917   1918   1919   1920   1921   1922   1923
       1924   1925   1926   1927   1928   1929   1930   1931   1932   1933   1934
       1935   1936   1937   1938   1939   1940   1941   1942   1943   1944   1945
       1946   1947   1948   1949   1950   1951   1952   1953   1954   1955   1956
       1957   1958   1959   1960   1961   1962   1963   1964   1965   1966   1967
       1968   1969   1970   1971   1972   1973   1974   1975   1976   1977   1978
       1979   1980   1981   1982   1983   1984   1985   1986   1987   1988   1989
       1990   1991   1992   1993   1994   1995   1996   1997   1998   1999   2000
       2001   2002   2003   2004   2005   2006   2007   2008   2009   2010   2011
       2012   2013   2014   2015   2016   2017   2018   2019   2020   2021   2022
       2023   2024   2025   2026   2027   2028   2029   2030   2031   2032   2033
       2034   2035   2036   2037   2038   2039   2040   2041;
set Stages := 1 2 3;
set Machines := 1 2 3 4 5 6 7 8 9;
set PMachines1 := 1 2 3;
set PMachines2 := 4 5 6;
set PMachines3 := 7 8 9;
set Jobs := 1 2;
param PP1 :
       1      2 :=
1      3      4
2      4      3
3      4      4;
param PP2 :
       1      2 :=
4      3      4
5      3      5
6      4      4;
param PP3 :
       1      2 :=
7      3      3
8      4      4
9      3      4;
param PT1 :
       1      2 :=
1      40     40
```

```
2      40    40
3      40    40;
param PT2 :
       1      2 :=
4      60    60
5      60    60
6      60    60;
param PT3 :
       1      2 :=
7      40    40
8      40    40
9      40    40;
param MPT := 120;
param BC := 5;
param NTP1 := 8;
param NTP2 := 16;
param NTP3 := 26;
param dstages := 3;
```

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