行政院國家科學委員會專題研究計畫 成果報告

再生能源微電網之強健最佳化
研究成果報告(精簡版)

計畫類別：個別型
計畫編號：NSC 100-2221-E-009-136-
執行期間：100年08月01日至101年07月31日
執行單位：國立交通大學經營管理研究所

計畫主持人：姜真秀

報告附件：出席國際會議研究心得報告及發表論文

公開資訊：本計畫可公開查詢

中華民國 101年10月31日

中文摘要：這篇報告針對可再生的微電網提出了穩健的最佳化模型，其應用在台灣中部科學工業園區800多間主要依賴電網的公司。這份研究發展出穩健及合理的決策工具來協助微電網設計提供穩健的決策步驟及最佳解決辦法。此模型可考量多種不確定性因素，例如能源價格、規程改變、需求及突發事件的預估…等加上各取所需的利害關係人。因此，此篇報告包含了範圍廣泛的研究，例如能源政策、模型模擬、最佳化製程和情境設計。在研究的過程中，獲得了幾項成果，SSCI期刊、會議報告、學士論文以及一份進行中的論文。提出的模型導出風力對於風速很敏感而輻射僅能影響正負20%的範圍。

中文關鍵詞：可再生微電網、經濟穩健性、技術穩健性、穩健最佳化

英文摘要：This project proposed the robust optimization model for renewable microgrid applied to Taichung Industrial Park in Taiwan which has more than 800 companies, depending on the main grid exclusively. The current study has developed a sound and reasonable decision support tool for microgrid planning which provides robust solutions and decision-making procedure for a best solution. The model enables to consider various uncertainties such as energy price, regulation change, estimates of demand, emergencies, etc. with representing diverse stakeholders’ interests. Thus this project includes a broad range of studies including energy policy, modeling, optimization, and scenario planning. While pursuing the project, fruitful outcomes have obtained including a SSCI paper, a conference paper, master thesis, and a paper in preparation. The results of the proposed model found out that wind power is very sensitive to wind speed while irradiation does not make any change upto +/- 20 %.

英文關鍵詞：Renewable Microgrid, Economic Robustness, Technical Robustness, Robust Optimization

附件一

行政院國家科學委員會補助專題研究計畫

□期中進度報告
■期末報告

（再生能源微電網之強健最佳化）

計畫類別：■個別型計畫　　□整合型計畫
計畫編號：NSC 100 - 2221 - E - 009 - 136 －
執行期間：　100 年　8 月　1 日至　101 年　7 月　31 日

執行機構及系所：國立交通大學，經營管理研究所

計畫主持人：姜真秀
共同主持人：
計畫參與人員：

本計畫除繳交成果報告外，另含下列出國報告，共 _1__ 份：
□移地研究心得報告
■出席國際學術會議心得報告
□國際合作研究計畫國外研究報告

處理方式：除列管計畫及下列情形者外，得立即公開查詢
　　　　　□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

中　華　民　國　101 年　10 月　30 日

摘要：

這篇報告針對可再生的微電網提出了穩健的最佳化模型，其應用在台灣中部科學工業園區800多間主要依賴電網的公司。這份研究發展出穩健及合理的決策工具來協助微電網設計提供穩健的決策步驟及最佳解決辦法。此模型可考量多種不確定性因素，例如能源價格、規程改變、需求及突發事件的預估…等加上各取所需的利害關係人。因此，此篇報告包含了範圍廣泛的研究，例如能源政策、模型模擬、最佳化製程和情境設計。在研究的過程中，獲得了幾項成果，SSCI期刊、會議報告、學士論文以及一份進行中的論文。提出的模型導出風力對於風速很敏感而輻射僅能影響正負20%的範圍。

關鍵字：可再生微電網、經濟穩健性、技術穩健性、穩健最佳化

Abstract

This project proposed the robust optimization model for renewable microgrid applied to Taichung Industrial Park in Taiwan which has more than 800 companies, depending on the main grid exclusively. The current study has developed a sound and reasonable decision support tool for microgrid planning which provides robust solutions and decision-making procedure for a best solution. The model enables to consider various uncertainties such as energy price, regulation change, estimates of demand, emergencies, etc. with representing diverse stakeholders' interests. Thus this project includes a broad range of studies including energy policy, modeling, optimization, and scenario planning. While pursuing the project, fruitful outcomes have obtained including a SSCI paper, a conference paper, master thesis, and a paper in preparation. The results of the proposed model found out that wind power is very sensitive to wind speed while irradiation does not make any change upto +/- 20 %.

Keywords: Renewable Microgrid, Economic Robustness, Technical Robustness, Robust Optimization

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Symbols

A : a large number

Allot_{ims} : allocation of capacity of source i to the operation in month m in scenario s, kW

APV_{ims} : area of solar panels from source i in month m in scenario s, m^2

B : the number of other sources that must be operating when a source is in use

C : assumed multiplied factor of peak electricity demand over average demand

Cap_{i} : capacity of adopted DER source i, kW

CCTax_{s} : cost of carbon tax in scenario s, $

CEbuyN_{s} : cost of purchasing national grid electricity in scenario s, $

CFuel_{s} : cost of fuel consumption in scenario s, $

CInv_{s} : cost of capital investments in scenario s, $

CLoad_{mus} : average customer load in month m for end use u in scenario s, kW

COM_{s} : cost of operation and maintenance in scenario s, $

Cost_{s} : total cost of scenario s, $

CSal_{s} : revenue from sales of electricity in scenario s, $

CSS_{s} : cost of start and stop in scenario s, $

CTax_{s} : carbon tax per kg of carbon credit in scenario s, $/kg C

Cw : worst case in terms of cost, $

D : conversion factor of area of PV panels vs. 1kW electricity capacity

EbuyN_{mus} : amount of electricity bought from the national grid in month m for end use u in scenario s, kWh

ECInt : carbon intensity of electricity, kg C/kWh

EDchar_{s} : regulated demand charge rate of electricity in scenario s, $/kW

eff : efficiency of DER technology, %

Efrom_{imus} : amount of electricity produced from source i for end use u in month m in scenario s, kWh

$\mathrm{Efromstore}_{tmus}$: amount of energy output from storage type t in month m for end use u in scenario s, kWh

Eprice_{ms} : unit rate for electricity purchase from the national grid in month m in scenario s, $/kWh

ESal_{ims} : amount of electricity sold to the national grid from source i in month m in scenario s, $/kWh

ESInl_{ts} : initial energy storage level in storage type t in scenario s, kWh

ESMax_{ts} : maximum energy storage level in storage type t in scenario s, kWh

$ESMin_{ts}$: minimum energy storage level in storage type t in scenario s, kWh
$EStore_{tms}$: amount of energy stored in the battery or heat storage t in month m in scenario s, kWh
$Etostore_{itms}$: amount of excess energy sent to storage type t from source i in month m in scenario s, kWh
Expected : expected cost of scenario s, $
f : index of fuel type
$FCInt_{fs}$: carbon intensity of fuel f in scenario s, kg C/unit of fuel
$FCost_{is}$: fixed capital cost of DER technology i in scenario s, $/kW
$Fprice_{fs}$: unit fuel charge of fuel f in scenario s, $ per unit of fuel consumed
$Fuel_{fmus}$: amount of fuel consumption for fuel f in month m for end use u in scenario s, unit depends on the fuel type
G : proportion factor used to control the minimum power output of each source
i : index of power source
I : the number of DER source types
Inst : interest rate
j : alias of i
L : the weight of expected value in the dual objective function
$LTime_{is}$: prevalent life time period of technology i in scenario s, year
m : index of month in a year
$MaxEbuyN_{ms}$: peak electricity demand in month m in scenario s, kW
$MaxEqm_{is}$: maximum power capacity of DER technology i in scenario s, kW
$MinEqm_{is}$: minimum power capacity of DER technology i in scenario s, kW
N : the number of scenarios
Obj : value of objective function, $
OMf_{is} : fixed operation and maintenance cost of DER technology i in scenario s, $/kW/yr
OMv_{is} : variable operation and maintenance cost of DER technology i in scenario s, $/kWh
p_s : probability of scenario s
$prodSolar_{ims}$: possible power output from solar sources i in month m in scenario s, kWh
$prodWind_{ims}$: possible power output from wind source i in month m in scenario s, kWh
pv_i : index of solar source within i
R_{ms} : local irradiation data in month m in scenario s, kW/m^2
$RHeat_{imus}$: recovered heat from DER technology i in month m for end use u in scenario

s, kWh

s : index of scenario, 1~N

$Sprice_{is}$: selling price of electricity from source i to the national grid in scenario s, $/kWh

t : index of storage type including electricity and heat

u : index of end uses of energy including electricity, heating, and cooling

Vc_{is} : cut in wind speed of wind turbine i in scenario s, m/s

Vf_{is} : cut off wind speed of wind turbine i in scenario s, m/s

Vn_{is} : nominal wind speed of wind turbine i in scenario s, m/s

Vw_{ms} : on-site wind speed in month m in scenario s, m/s

w_i : index of wind source within i

x_{ims} : binary variable, equal to 1 when source i is operating in month m in scenario s, otherwise 0

Greek Symbols

α_i : heat recovery efficiency of source i, %

β_{fu} : heat efficiency of fuel f for end use u from direct fuel consumption, %

γ_{iu} : utilization efficiency of recovered heat from source i for end use u, %

δ_{tu} : utilization efficiency of stored energy from storage type t for end use u, %

ε_t : storage coefficient of storage type t, %

θ : minimum percentage of electricity purchase from the national grid, %

ω_i : unit start and stop cost of source i, $/time

I. Introduction

Nowadays, there is no argument that global climate change is one of most serious global issues that we face with. According to Central Weather Bureau (CWB), Taiwan has experienced a warming effect that is twice the global average, which has translated to higher temperatures, greater rainfall, and more typhoons over the past 30years - while global temperatures have risen 0.65 degrees Celsius over the past century, Taiwan has seen its temperature go up by 1.4 degrees [1]. Among many factors, the electricity sector is a major source of carbon dioxide (green house gas) emissions that contribute to climate change. Switching a substantial portion of electricity generating capacity away from fossil fuels to renewable energy technologies could have a significant effect in reducing greenhouse gases. In addition, increasing frequency of natural disasters put forward the flexibility and independence of electricity generation from the central generation. In this context, a “microgrid,” a local generation of heat and electricity, with renewable energy resources is considered as one of the most promising options to provide a more secure, clean, and efficient energy supply.

There have been many researches on a microgrid regarding autonomous operations [2],[3], control schemes [4],[5] scheduling [6], planning [7]-[12], etc. However, robust optimization of a microgrid planning has not been studied yet although a microgrid itself has lots of uncertainties concerning main grid failure, power quality issues, estimates of demand, energy price, regulation change, etc. Thus this study aims at developing robust optimization model that take the uncertainty the uncertainty into account at planning utilizing robustness measures.

There has been countless number of researches regarding robust optimization in the field of process engineering. Among them, Kang et al.[13] propose to consider robustness separately depending on the nature of a variable such as scenario independent variables, scenario-dependent technical variables (e.g., temperature, pressure, flow rate, liquid holdup, etc.), and scenario-dependent monetary or economic variables (e.g., cost, profit, production yield, etc.). The current study applies the robust optimization model proposed by Kang et al.[13], a comprehensive robust optimization model which considers both economic and technical robustness together with decision making process. The proposed model was applied to the industrial example, Taichung Industrial Park in Taiwan.

II. Research Objectives

The current study aims at developing a sound and reasonable decision support tool for microgrid planning which provides a set of robust alternatives. The model enables to consider various uncertainties such as energy price, regulation change, estimates of demand, emergencies, etc. with representing diverse stakeholders’ interest. The study, specifically, considers a Taichung industrial complex, where any environmental policy can influence the competitiveness of companies significantly. Therefore, this study aims at providing a corner stone for cleaner and emergency electricity generation in the future.

III. Literature Review

3.1 Distributed energy resources system planning approaches

According to Wikipedia, distributed energy resources (DER) systems are small-scale power generation technologies (typically in the range of 3 kW to 10,000 kW) used to provide an alternative or an enhancement of the traditional electric power system. Despite to its high cost, it has been recognized as the future model because it can enhance local reliability, reduce feeder losses, support local voltages, provide increased efficiency through using waste heat combined heat and power (CHP), voltage sag correction or provide uninterruptible power supply functions [14]-[15]. The conventional planning methods are designed based on electricity production in centralized power generation stations and delivery through passive distribution networks to end-users. In this structure, all customers, which are supplied from a distribution substation, principally allows small-scale integration of DER at distribution levels, the overall penetration level is kept low to prevent adverse impact on system operation coordination and traditional control equipment actions. Hence, DER cannot provide any type of grid support including voltage regulation, reactive power control, and power frequency stabilization.

A better way to realize the emerging potential of distributed generation and associated loads is a subsystem called microgrid. The microgrid concept assumes a cluster of loads and microsources operating as a single controllable system that provides both power and heat to its local area [14]. It includes a variety of DER units and different types of end users of electricity, heating, cooling, and/or water load. DER includes both distributed generation (DG) and distributed storage (DS) units with different capacities and characteristics. The microgrid point of common coupling (PCC) consists of the electrical connection point of microgrid to the utility system, at the low-voltage bus of the substation transformer. In addition to DG, DS, and PCC, microgrid components are loads and controllers.

The microgrid approach promotes 1) a highly efficient energy delivery and supply system based on co-locating DER and loads, 2) a secure and reliable power supply configuration with service differentiations based on customer technology preference and power quality desires, and 3) an energy delivery structure that has sufficient power generation and balancing sources to operate independent from the main grid in an autonomous manner during power outages or an energy crisis.

3.2 Robust optimization for process design under uncertainties

As any other design of engineering and industrial processes, microgrid planning often suffers from uncertainties concerning main grid failure, power quality issues, estimates of demand, energy price, regulation change, etc. It is therefore of importance to study and develop robust optimization strategies that take the uncertainty into account already at the design level.

Robustness can be inferred as the risk aversion from the economic and technical points of view. It is important to distinguish between different robustness concepts to be applied depending on the nature of the variables. It is convenient to classify the control and design variables in three groups: (i) scenario-independent variables, (ii) scenario-dependent technical variables (e.g., temperature, pressure, flow rate, liquid holdup, etc.), and (iii) scenario-dependent monetary or economic variables (e.g., cost, profit, production yield, etc.). In the case of scenario-dependent economic variables, the robustness concept should focus on the scenarios with relatively higher costs (e.g. higher costs than a target cost), in order to reduce them while keeping overall average cost as low as possible. On the other hand, the robustness measures for the scenario-dependent technical variables should be based on the requirement that the operating conditions must be insensitive to variations within certain ranges defined by the scenarios. The robustness measures for the scenario-dependent economic variables can be referred as the *economic robustness measures* and the robustness measures for the scenario-dependent technical variables, as the *technical robustness measures*.

The development of economic and technical robustness measures is a vigorous field of research. It was proven that economic robust measures should be monotonic [16]-[23]. For instance, using symmetric measure as an economic robustness measure like variance [24]-[25] yields suboptimal solutions as it is directly related to reducing the variability from the mean, which itself cannot be an objective of robust optimization. Since no single optimum solution would optimize several objectives simultaneously, Pareto optimality may be one of the important criteria to decide which robustness measure can be proper for robust economic optimization. Most studies on technical robustness have been focused on proposing robustness measures for technical variables without recognizing its difference from economic robustness measure [17]-[20], [24]-[28]. Different from economic robustness, technical robustness measures should be an even function to reduce the variation among scenarios based on the definition of technical robustness mentioned above. However, Pareto optimality, one of the important criteria for multi-objective optimization, is guaranteed only for monotonic robustness measures [20]-[21].

Kang *et al.* [13] proposed a comprehensive robust optimization model, which considers both economic robustness and technical robustness together with decision making process. The objectives consist of expected value, an economic robustness measure, and technical robustness measures. For economic robustness, worst-case is used and for technical robustness, half interval is proposed. Then, the method of global criterion [29] is applied to decide the final solution. In this study, efficient way to calculate the upper bound of Pareto set was proposed.

IV. Research Methodology

4.1 Planned layouts and settings of the microgrid

Building a microgrid or any local power supply system generally takes a significant amount of investment and a long period of time to accomplish. It is unlikely that the employer of the microgrid project can conduct a comprehensive planning or even secure a total amount of budget for the whole project at the very beginning. Thus, the proposed model in this study focuses on optimizing capacity of diverse electricity sources considering operation and uncertainties, which better fits reality. Figure 1 shows the schematic diagram of the microgrid and Figure 2 describes the proposed layout for the microgrid in Taichung Industrial Complex, respectively.

4.2. Robust Optimization Strategy

(P2) shows the robust optimization strategy in this study. There are three kinds of objectives including expected cost, worst scenario cost (economic robustness), and half interval of technical variables of interest (technical robustness).

$$\min_{\mathbf{x}, y_1, \cdots, y_N} (U_E(\mathbf{C}), U_{WC}(\mathbf{C}), U_T(\mathbf{y}))$$

subject to

$$\mathbf{x}, y_1, \cdots, y_N \in \psi$$

where

$U_E(\mathbf{C})$: Expected cost of scenario costs

$U_{WC}(\mathbf{C})$: Wost scenario cost

$U_T(\mathbf{y})$: Half internal of technical variable(s) of interest **(P2)**

In principle, it requires N+2 times of iteration to solve this multiobjective problem (P2), where N is the number of technical variables of interest. In the current study, Kang, et al. [13] is applied to solve the problem more efficiently as follows.

Case I. When the expected cost has priority

$$\begin{aligned}&\text{Solve } \min_{\mathbf{x}, y_1, \cdots, y_N} \quad U_E(\mathbf{C})\\&\text{Subject to } \mathbf{x}, y_1, \cdots, y_N \in \Psi\end{aligned}$$

Let the optimum objective value of the above problem be denoted by E^*. Then,

$$\begin{aligned}&\text{Solve } \min_{\mathbf{x}, \mathbf{y}} \quad U_{WC}(\mathbf{C})\\&\text{Subject to } U_E(\mathbf{C}) \leq E^*, \mathbf{x}, y_1, \cdots, y_N \in \Psi\end{aligned}$$

The technical robustness measure, T^1, is calculated.

Case II. When the economic robustness has priority

$$\begin{aligned}&\text{Solve } \min_{\mathbf{x}, y_1, \cdots, y_N} \quad U_{WC}(\mathbf{C})\\&\text{Subject to } \mathbf{x}, y_1, \cdots, y_N \in \Psi\end{aligned}$$

Let the optimum objective value of the above problem be denoted by W^*. Then,

$$\begin{aligned}&\text{Solve } \min_{\mathbf{x}, y_1, \cdots, y_N} \quad U_E(\mathbf{C})\\&\text{Subject to } U_{WC}(\mathbf{C}) \leq W^*, \mathbf{x}, y_1, \cdots, y_N \in \Psi\end{aligned}$$

Then, a technical robustness measure, T^2, is calculated.

The larger of the values, T^1 and T^2, is taken as the nadir objective value of the technical robustness measure because, in most cases, the value of technical robustness increases or decreases monotonically between T^1 and T^2. The nadir (i.e. largest) objective value of the economic robustness measure is decided from solving Case I, while the one for expected cost is obtained from solving Case II. In this way, one needs four single-objective optimizations to find the proposed approximate nadir vector, while the determination of the exact nadir vector requires six single-objective optimizations. If there are n technical robustness measures, then, the exact nadir vector will be achievable after 2n + 4 consecutive solutions of single objective sub-problems given in Figure 3. In contrast to it, the proposed nadir vector is obtained only after four solutions of single objective sub-problems given in Case I and Case II regardless of n. Furthermore, calculating the exact nadir vector requires of deciding the priority among several technical robustness measures, which is often tricky. This can be also avoided by using the proposed nadir vector.

4.3 Mathematical formulation of the model

Due to the increasing complexity of the microgrid composition and the interaction among various inner-grid and inter-grid components, a good mathematical model is critical to the optimization of microgrid planning and operation, in order to achieve certain set goals. In this study, a discrete time, mixed integer linear programming (MILP) model is proposed for a time horizon of one year with the scale in months.

<u>*Objective function*</u>

The objective function in this multi-objective optimization model is to minimize the weighted sum of overall expected cost of scenarios and the worst (highest) scenario cost. The expected cost is defined as in the stochastic model, but now it has to work with the influence of the other robustness component – worst-case cost. As mentioned before worst-case cost and partial mean of costs are two popular measures broadly used in robust optimization. The study of Kang et al. indicated that worst-case cost would be the better choice as the economic robustness measure because this approach avoids the problem of choosing target value in partial mean of costs and gives more allowance to for the model to consider technical robustness. In the current modeling, worst-case cost is adopted as the economic robustness measure, as well as one of the two objectives. The weights of expected cost and worst-case cost are controlled by the model users with the parameter L, as shown in (1).

$$Min\,(U_E, U_{WC}, U_T) \tag{1}$$

The expected cost of scenarios is defined as the summation of all individual scenario costs multiplied by their corresponding probabilities, as shown in (2).

$$U_E = \sum_{s}^{N} p_s Cost_s \tag{2}$$

The worst-case cost is defined as the highest scenario cost among all individual scenario costs, as shown in (3).

$$U_{WC} = \max \left\{ Cost_s \,\middle|\, s = 1, ..., N \right\} \tag{3}$$

The technical robustness is defined as the amount of carbon produced from electricity generation.

$$U_T = \frac{1}{2}(\max_s Tech_s - \min_s Tech_s) \tag{4}$$

$$Tech_s = \sum_f \left[\sum_m \sum_u Fuel_{fmus} + \sum_i \frac{\sum_m \left(\sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} \right)}{eff_{if}} \right] \cdot FCInt_{fs} \tag{5}$$

The individual scenario cost is composed of a number of cost items, including cost of annual capital investments, electricity purchase from the national grid, fuel consumption for energy generation, system operation and maintenance, and carbon tax imposed based on greenhouse gas emissions, as well as cost of starts and stops of equipment. The revenue obtained from sales of electricity to the national grid is presented as a deduction from the total cost.

$$Cost_s = CInv_s + CEbuyN_s + CFuel_s + COM_s + CCtax_s - CSal_s \tag{6}$$

The cost of annual capital investments is calculated as the present value of the amortized amount of initial invested capital, which is derived from the summation of the unit fixed capital cost multiplied by the planned capacity for each DER technology selected. The amortization of the fixed cost of each kind of DER equipment is considered over the estimated life time of each kind with respect to a given interest rate.

$$CInv_s = \sum_i Cap_i \times FCost_{is} \times \frac{Inst}{(1 - \frac{1}{(1+Inst)^{LTime_{is}}})} \tag{7}$$

The cost of buying electricity from the national grid is represented by (8). The cost structure consists of two parts, demand charge and mobile electricity charge. Demand charge is determined by the regulated demand charge rate of electricity multiplied by the peak electricity demand in one certain month, where the peak electricity demand is estimated as the average electric power provided by the national grid and for all kinds of usage (i.e. power, heating, and cooling) in one month multiplied by an assumed factor C, as shown in (9). On the other hand, mobile electricity charge is calculated as the actual amount of electricity consumed in one month multiplied by the utility electricity tariff rate.

$$CEbuyN_s = \sum_m EDchar_s \times MaxEbuyN_{ms} + \sum_m \sum_u EbuyN_{mus} \times Eprice_{ms} \tag{8}$$

$$MaxEbuyN_{ms} = \left(\frac{\sum_u EbuyN_{mus}}{720} \right) \times C \tag{9}$$

The cost of fuel consumption can be broken down into two parts as shown in (10). The first part accounts for the direct fuel consumption other than DER usage for heating and cooling purposes, and the second part accounts for the fuel consumed by different DER technologies for power generation. They are all determined by the cumulative amount of fuel usage multiplied by unit fuel charge, with respect to each kind of fuel. It should be noted that the relationship between the electricity produced (for all kinds of ultilization including meeting demands, sales to the national grid, and storage) and the fueled consumed is governed by the distinct efficiency of each kind of DER technology with respect to its corresponding fuel type.

$$CFuel_s = \sum_f \left[\sum_m \sum_u Fuel_{fmus} + \sum_i \left(\sum_m \frac{(\sum_u Efrom_{imus}) + ESal_{ims} + Etostore_{itms}}{eff_{if}} \right) \right] \times Fprice_{fs} \tag{10}$$

The cost of system operation and maintenance is constituted by the fixed cost and the variable cost of the DER equipment, as described in (11). The fixed cost of the equipment can be calculated by the summation of the unit fixed operation and maintenance cost of all DER technologies multiplied by their respective planned capacities, while the variable cost is obtained from the summation of the amount of electricity production by different DER sources multiplied by their unit variable operation and maintenance cost.

$$COM_s = \sum_i \sum_m \left[\sum_u Efrom_{imus} + ESal_{ims} + \sum_t Etostore_{itms} \right] \cdot OMv_{is} + \sum_i \left(Cap_i \cdot OMf_{is} \right) \tag{11}$$

The cost of carbon tax, which is illustrated in (12), considers the total carbon credits accumulated by direct fuel consumption for non-DER use and by distributed power generation with relation to the carbon intensity of each kind of fuel used. The carbon tax cost of purchasing electricity from the national grid, on the other hand, is calculated by the multiplication of unit carbon tax rate, carbon intensity of electricity provided by the national grid, and the cumulative amount of electricity bought from the national grid.

$$\begin{aligned} CCtax_s = {} & \sum_f \left[\sum_m \sum_u Fuel_{fmus} + \sum_i \frac{\sum_m \left(\sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} \right)}{eff_{if}} \right] \cdot CTax_s \cdot FCInt_{fs} \\ & + \sum_m \sum_u EbuyN_{mus} \times CTax_s \times ECInt \end{aligned} \tag{12}$$

When the excess electricity is sold to the national grid, the microgrid system will receive an income, which can be expressed in (12). The revenue from the sales of electricity equals to the summation of selling price of electricity (can be uniform or different among different power sources) multiplied by the amount of electricity sold.

$$CSal_s = \sum_i \sum_m ESal_{ims} \times Sprice_{is} \tag{13}$$

Major constraints

The primary constraints in this microgrid model include demand-supply relationships, energy balance, and the operation characteristics of the microgrid components, etc.

Demand-supply relationships

A fundamental principle under this model is that all forms of local energy demand (including electricity, heating, and cooling loads) must be satisfied in every time period, as illustrated in (14). The energy can be supplied from one or more of the following sources:

a. Electricity produced from one or more DER sources for different end use
b. Electricity bought from the national grid for different end use
c. Heating and cooling output transferred from direct fuel consumption via boilers and absorption chillers

d. Heating and cooling output transferred from recovered waste heat during power generation by certain CCHP DER technologies

e. Electricity, heating, and cooling output supported by energy outflow from electricity batteries and thermal storage.

It should be noted that the demand-supply relationships are presented with the amount of energy flow in kWh. The average customer load in each month, $CLoad_{mus}$ in kW, should be multiplied by the coefficient 720, which stands for the cumulative amount of electricity in kWh of one kW per month (24 hr/day x 30 day/month), in order to be converted to the amount of electricity in kWh.

$$\begin{aligned} CLoad_{mus} \times 720 \quad \leq \quad & \sum_i Efrom_{imus} + EbuyN_{mus} + \sum_f \beta_{fu} \cdot Fuel_{fmus} \\ & + \sum_i \gamma_{iu} \cdot RHeat_{imus} + \sum_t \delta_{tu} \cdot Efromstore_{tmus} \qquad \forall m,u,s \end{aligned} \tag{14}$$

Indicators of equipment operation status

By introducing the binary variables, the operation status of different microgrid components can be monitored or even controlled. The logical expression in (15) makes the binary variable x equal to 1 if electricity is produced from source i.

$$\sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} - A \cdot x_{ims} \quad \leq \quad 0 \quad \forall i,t \in \{elec\},m,s \tag{15}$$

The status of the power generation from different DER components for immediate customer use is further specified by the logical expression in (16), which makes the binary variable x equal to 1 if electricity is produced from power source i for end customer use u.

$$\sum_u Efrom_{imus} \quad \leq \quad A \cdot x_{ims} \qquad \forall i,m,s \tag{16}$$

Furthermore, the logical expression in (17) addresses the relationship between the allocation of capacity of power source i to the operation mode in each month and the binary variable x. Affected by this relationship, the status of each variable x becomes dependent on the capacity allocation mode of its corresponding power source.

$$Allot_{ims} \quad \geq \quad x_{ims} \qquad \forall i,m,s \tag{17}$$

Electricity balance and contracted agreement on electricity buy-in

For the purpose of simplifying the problem, an equation of electricity balance is specified in (18). The total sum of customer demand for electricity plus sales of electricity to the utility grid plus electricity sent to batteries should be equal to the total sum of electricity produced from all power sources plus electricity bought from the national grid plus electricity outflow from batteries. This equation exempts the possibilities that electricity can be generated by direct fuel consumption and that the heat recovered by CCHP technologies or outflowed from heat storage can be reused for electricity generation, which means that the electricity supply is purely provided by DER power generation, unless supported by power purchase from the main grid or outflow from batteries.

$$CLoad_{mus} \times 720 + \sum_{i} ESal_{ims} + \sum_{i} Etostore_{iums} = \sum_{i} Efrom_{imus} + EbuyN_{mus} + \sum_{t} Efromstore_{tmus} \quad (18)$$
$$\forall m, s \ if \ u \in \{elec\}$$

Since the selling price of electricity from different DER sources may be different from the purchasing price of electricity from the main grid. It is specified that the amount of electricity sold to the national grid, denoted as $ESal_{ims}$, must not be negative, as shown in (19).

$$ESal_{ims} \geq 0 \qquad \forall i, m, s \qquad (19)$$

The contract between the national grid and the microgrid normally includes the clause that the amount of electricity buy-in of the microgrid from the national grid must not be lower than a particular share of the total customer demand, upon the agreement between both parties. This is set forth to protect the main grid party from suffering from increased maintenance cost caused by the connection with the microgrid, when the microgrid places an unfavorable low utility rate on the main grid electricity. This condition is expressed by (20).

$$\sum_{m} \sum_{u} EuyN_{mus} \geq \theta \cdot \sum_{m} \sum_{u} \left[EbuyN_{mus} + \sum_{i} Efrom_{imus} + \delta_{tu} \cdot Efromstore_{tmus} \right] \qquad (20)$$
$$\forall s, t \in \{elec\}$$

Operation characteristics of microgrid components

General DER equipment

There is an upper limit on the total capacity of each kind of DER technology, as described in (21). These limits in most cases are present based on budgeting and power source diversity concerns, rather than on a technical concern, because the capacity mentioned here refers to the total sum of the capacities of a number of same equipment. It does not necessary refer to the maximum capacity of one single DER unit.

$$Cap_{i} \leq MaxEqm_{is} \qquad \forall i, s \qquad (21)$$

The equation and inequality stated in (22) indicate the range of the total power output of each kind of DER technology. The total sum of electricity generated from DER sources, electricity sold to the national grid, and electricity sent to storage should be positive and less or to the most equal to the allocation of the DER equipment capacity to the system operation in each period of time. This relationship also justifies that all amount of the power generated from one certain DER source should be covered by the capacity allocation of that source at any time.

$$0 \leq \sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} \leq Allot_{ims} \times 720 \qquad (22)$$
$$\forall t \in \{elec\}, i, m, s$$

When any power source is operating in any period of time, the allocation of capacity of that source to the operation must be greater or to the least equal to the minimum power capacity of that DER technology. This requirement holds true only when the power source is in operation, and is controlled by the binary variable x_{ims}, as shown in (23).

$$Allot_{ims} \geq MinEqm_{is} \quad if\ x_{ims} = 1 \qquad \forall i, m, s \qquad (23)$$

For a conditional constraint like (23), it is usually difficult to be coded in linear programming (LP). Therefore, the logical expression in (23) is reformulated as in (24) & (25) by applying the big M method.

$$Allot_{ims} \leq MinEqm_{is} + MaxEqm_{is} \cdot x_{ims} \qquad \forall i, m, s \qquad (24)$$

$$Allot_{ims} \geq MinEqm_{is} - MaxEqm_{is} \cdot (1 - x_{ims}) \qquad \forall i, m, s \qquad (25)$$

Meanwhile, the possible range of the capacity allocation for each kind of DER power source can be expressed as shown in (26). The allocation of capacity of one certain power source should be no less than zero and less than or equal to the total capacity of that power source.

$$0 \leq Allot_{ims} \leq Cap_i, \quad \forall i, m, s \qquad (26)$$

Solar energy equipment

The relation stated in (27) indicates that the electricity produced from photovoltaic (PV), for the purpose of meeting customer load, selling to the main grid, and being sent to the battery storage, cannot exceed the possible total power generation of PV technology.

$$\sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} \leq prodSolar_{ims} \qquad \forall i \in \{pv\}, t \in \{elec\}, m, s \qquad (27)$$

The possible power output from solar sources is related to the amount of local solar irradiation, as well as the the area of solar panels installed with regard to their corresponding operating efficiencies.

$$prodSolar_{ims} = APV_{ims} \times R_{ms} \times eff_{if} \times 720 \qquad \forall f \in \{solar\}, i \in \{pv\}, m, s \qquad (28)$$

It is assumed that there is a fixed linear relationship between the area of solar panels and the operating capacity of the solar panels. The allocation of capacity of the power source is in proportion to the area of solar panels installed with a constant D, which is to be specified by the model user according to the current PV technical specification.

$$Allot_{ims} = APV_{ims} / D \qquad \forall i \in \{pv\}, m, s \tag{29}$$

Wind power equipment

Similar to the case in PV generation, the electricity produced from wind farms, for the purpose of meeting customer demand, selling to the national grid, and being sent to the batteries, cannot exceed the possible total power generation of wind power technology.

$$\sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} \le prodWind_{ims} \qquad \forall i \in \{wind\}, t \in \{elec\}, m, s \tag{30}$$

The electricity generated from wind turbines heavily depends on local wind velocity and equipment performance characterisics, as illustrated in (31) - (33). In the case that the local wind speed is greater than or equal to the minimum cut-in wind speed requirement of the wind turbines but less than or equal to the nominal wind speed of the wind turbines, the possible power output of the wind power system should be determined by the proportion of the on-site wind speed to the nominal wind speed of the equipment. In the case that the local wind speed is greater than the nominal wind speed but still less than the cut off wind speed of the equipment, the wind turbines perform in their full capacities. However, in the case that the local wind speed is too low to activate the wind turbines or that the wind speed is too high and exceeds the cut off wind speed of the wind turbines, the equipment does not operate and thus deliver no power output.

$$prodWind_{ims} = Allot_{ims} \times \frac{Vw_{ms} - Vc_{is}}{Vn_{is} - Vc_{is}} \times 720 \qquad \forall i \in \{wind\},\ Vc_{is} \le Vw_{ms} \le Vn_{is} \tag{31}$$

$$prodWind_{ims} = Allot_{ims} \times 720 \qquad \forall i \in \{wind\},\ Vn_{is} \le Vw_{ms} \le Vf_{is} \tag{32}$$

$$prodWind_{ims} = 0 \qquad \forall i \in \{wind\},\ Vw_{ms} < Vc_{is}\ \cup\ Vw_{ms} > Vf_{is} \tag{33}$$

Heat recovery by CCHP technology

Heat recovered from the waste heat associated with power generation is considered an important source of heating and cooling supplies in this model. Nonetheless, the performance of heat recovery highly correlates to the heat conversion efficiency of each DER technology, as can be seen in (34). For each type of equipment, there is a limit on its heat/electricity ratio, which determines the maximum heat that can be recovered for customers' immediate usage or sent to storage.

$$\sum_{u} RHeat_{imus} + Etostore_{itms} \leq \alpha_i \cdot \sum_{u} Efrom_{imus} \qquad \forall i, t \in \{heat\}, m, s \tag{34}$$

Energy storage constraints

The initial volume of energy stored, in the form of electricity or heat, must be input as a parameter in accordance with the ending volume of energy storage in the previous time period before running the model. Equation (35) serves as a typical example (i.e. in months and starting from January). In other words, the data in the starting point of any time period should conform to that in the ending point of perious period. This rule of continuity ensures the possibility of analyzing a long time span that can be longer than one year or even as long as several years.

$$EStore_{tms} = ESInl_{ts} \qquad \forall t, m \in \{Jan\}, s \tag{35}$$

The main constraint of energy balance for electricity and heat storage is stated in (36) with time consideration. It is assured that the total amount of energy in storage at the beginning of any time period be equal to the residual amount of energy at the beginning of the previous time period after considering the natural loss by time, plus the net energy flow during that time interval (i.e. energy inflow for storage minus energy outflow to meet customer demand).

$$EStore_{t,m+1,s} = \varepsilon_t \cdot EStore_{tms} + \sum_{i} Etostore_{itms} - \sum_{u} Efromstore_{tmus} \qquad \forall t, m, s \tag{36}$$

In addition, the constraint in (37) states that the amount of energy stored in the battery or heat storage must always be greater the minimum amount reserved for emergency and less than the maximum energy storage capacity in any period of time.

$$ESMin_{ts} \leq EStore_{tms} \leq ESMax_{ts} \qquad \forall t, m, s \tag{37}$$

Diversity constraints for DER generation

Diversity constraints plan an important role in ensuring a microgrid scheduling with diverse DER power generation. The objective of enabling diverse DER operation normally conflicts with the objective of economic optimization, as the function of cost minimization in most cases would prefer a power generation scheme with running only one or a few highly centralized power sources, through the realization of economy of scale. However, this kind of economic concern simply highlights the differences between microgrids and the macrogrid. Cost minimization should not be the only concern from the microgrid planners' point of view. Diverse operation of the microgrid components is beneficial based on the concerns of energy-saving and risk management. When certain local electricity demand is satisfied by a DER unit nearby, the energy loss due to distant transmission can be significantly reduced. In addition, diverse DER operation can reduce the risk of local blackouts caused by the failure of the centralized power supply system (i.e. sudden power shortage caused by malfunction of one or a few DER generation units can be quickly supported by the additional allocation of capacities of other generation units), which may increase the stability and independence of the local power supply.

In this model, a set of linear diversity constraints is constructed as shown in (38) & (39), with the focuses on "on and off" status and the proportion of power supply of each power source, respectively. The equation in (38) ensures that power and heat supplies are diverse, while the equation in (39) ensure that power supplied from each source is of reasonable proportion of the customer demand. The degree of diversity is controlled by B, the number of other sources that must be operating when one source is in use, and the minimum proportion of power supply supported by each DER sources is further controlled by G, a proportion factor specified by the microgrid planner.

$$B \cdot x_{ims} \leq \sum_{j=1, i \neq j}^{Q} x_{jms} \qquad \forall i, m, s \tag{38}$$

$$Efrom_{imus} \geq \frac{CLoad_{mus}}{B + G} \cdot x_{ims} \qquad \forall i, m, u, s \tag{39}$$

Decision variables

The decision variables in this microgrid model include integer variables and continuous variables. The integer variables are basically binary variables indicating the on/off status of each kind of DER equipment, as well as the time points when the equipment is started up or shut down.

The continuous variables include positive technical variables and economic variables. Positive technical variables typically referring to the amount of fuel consumption, capacities and allocation of capacities of different DER technologies, energy inflow and outflow rate, as well as the amount of energy storage, etc. Economic variables are evaluated in monetary units and normally dependent on the system layout planning and the variation of technical variables, through the optimization procedure.

The total capacity of each DER technology, which is a continuous positive variable, is regarded as the main decision variable to be determined as part of the output of this model so as to serving as the baseline of future detailed planning. The number of individual DER equipment units, however, is not within the scope of the current model, as the detailed technical specifications of the equipment normally are not readily available during the preliminary design stage.

According to the list of hypothesized demand schemes in Table 1, the load-time curve of each scenario can be drawn as illustrated in Figure 4. It is expected that the diversity and variation among scenarios and within scenarios should be able to account for the possible uncertainties facing the microgrid model.

V. Results, Discussion, and Outcomes

5.1 Results & Discussion

The resulting model has 540 of binary variables and 7,375 of continuous variables. Figure 5 shows the set of robust alternatives with applying the microgrid model to Taichung Industrial Park in Taiwan attained from the robust optimization model proposed. Pareto curves show trade-off relationship between expected cost and worst scenario cost (economic robustness) and expected cost and environmental regulation (technical robustness).

Figure 6 shows the capacity of DER equipment when the expected cost has minimized and the worst-case cost has minimized, respectively. When the worst case cost is minimized, the electricity generation tends to concentrate on DER equipment where the amount of carbon generation is relatively less than others. The following figure (Figure 7) shows the power generation of each scenario. In addition, Figure 8 and 9 describe the power generation when wind speed has reduced by 10% or increase by 10%, respectively. In contrast, the optimization is insensitive to changes in irradiation.

This project, in general, has been a challenging but also fruitful task. The biggest challenge was to work with an MBA student who did not have any background on operations management. Thus, the project leader had to teach him from optimization to mathematical modeling. Also, obtaining data has been a time-consuming work. It required layers of administrative process. In this process, it was surprising to find that Taichung industrial complex exclusively depends on main grid and there is no policy for renewable energies. While renewable energies are often inefficient and expensive, these definitely affect on the quality of our environment. As this environmental policy affects on the competitiveness of the complex significantly, more field-based studies are required to prepare for the future when the complex is ready to change to cleaner sources of electricity.

5.2 Outcomes

1. John Edward Burns and **Jin-Su Kang* (2012),** Comparative economic analysis of supporting policies for residential solar PV in the United States: Solar Renewable Energy Credit (SREC) potential, Energy Policy, 44:217–225

2. **Jin-Su Kang***, Chung-Chuan Chang, Dong-Yup Lee, Tai-yong Lee (2012) Robust Optimization of Microgrids – An Application to Taichung Industrial Park, Proceedings of the 11th International Symposium on Process Systems Engineering, 15-19 July 2012, Singapore. Oral Presentation

3. Chung-Chuan Chang (with Advisor: **Jin-Su Kang**) (2012) A Decision Support Model for Microgrids – An Application to Taichung Industrial Park, A Thesis Submitted to Global MBA Program, College of Management, National Chiao Tung University

4. Robust Economic Optimization of Microgrid in preparation with Chung-Chuan Chang

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An Application to Taichung Industrial Park, A Thesis Submitted to Global MBA Program, College of Management, National Chiao Tung University

Table 1. Model Parameters – Hypothesized Demand Schemes of Taichung Industrial Park

Month				Jan			Feb			Mar		
Item		Unit	Capacity	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Scenario 1	Avg Customer Load	kW	146,800	82,208	54,805	27,403	88,080	58,720	29,360	93,952	62,635	31,317
	Percentage		100%	56%			60%			64%		
Scenario 2	Avg Customer Load	kW	146,800	68,996	45,997	22,999	80,740	53,827	26,913	99,824	66,549	33,275
	Percentage		100%	47%			55%			68%		
Scenario 3	Avg Customer Load	kW	146,800	74,868	49,912	24,956	82,208	54,805	27,403	91,016	60,677	30,339
	Percentage		100%	51%			56%			62%		
Scenario 4	Avg Customer Load	kW	146,800	64,592	43,061	21,531	67,528	45,019	22,509	70,464	46,976	23,488
	Percentage		100%	44%			46%			48%		
Scenario 5	Avg Customer Load	kW	146,800	58,720	39,147	19,573	73,400	48,933	24,467	85,144	56,763	28,381
	Percentage		100%	40%			50%			58%		

Month				Apr			May			Jun		
Item		Unit	Capacity	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Scenario 1	Avg Customer Load	kW	146,800	101,292	50,646	50,646	108,632	54,316	54,316	115,972	38,657	77,315
	Percentage		100%	69%			74%			79%		
Scenario 2	Avg Customer Load	kW	146,800	114,504	57,252	57,252	127,716	63,858	63,858	142,396	47,465	94,931
	Percentage		100%	78%			87%			97%		
Scenario 3	Avg Customer Load	kW	146,800	101,292	50,646	50,646	115,972	57,986	57,986	121,844	40,615	81,229
	Percentage		100%	69%			79%			83%		
Scenario 4	Avg Customer Load	kW	146,800	91,016	45,508	45,508	102,760	51,380	51,380	121,844	40,615	81,229
	Percentage		100%	62%			70%			83%		
Scenario 5	Avg Customer Load	kW	146,800	102,760	51,380	51,380	117,440	58,720	58,720	129,184	43,061	86,123
	Percentage		100%	70%			80%			88%		

Month				Jul			Aug			Sep		
Item		Unit	Capacity	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Scenario 1	Avg Customer Load	kW	146,800	124,780	41,593	83,187	117,440	39,147	78,293	111,568	37,189	74,379
	Percentage		100%	85%			80%			76%		
Scenario 2	Avg Customer Load	kW	146,800	137,992	45,997	91,995	126,248	42,083	84,165	108,632	36,211	72,421
	Percentage		100%	94%			86%			74%		
Scenario 3	Avg Customer Load	kW	146,800	136,524	45,508	91,016	123,312	41,104	82,208	110,100	36,700	73,400
	Percentage		100%	93%			84%			75%		
Scenario 4	Avg Customer Load	kW	146,800	136,524	45,508	91,016	143,864	47,955	95,909	127,716	42,572	85,144
	Percentage		100%	93%			98%			87%		
Scenario 5	Avg Customer Load	kW	146,800	146,800	48,933	97,867	132,120	44,040	88,080	123,312	41,104	82,208
	Percentage		100%	100%			90%			84%		

Month				Oct			Nov			Dec		
Item		Unit	Capacity	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Scenario 1	Avg Customer Load	kW	146,800	104,228	52,114	52,114	96,888	48,444	48,444	89,548	59,699	29,849
	Percentage		100%	71%			66%			61%		
Scenario 2	Avg Customer Load	kW	146,800	93,952	46,976	46,976	73,400	36,700	36,700	60,188	40,125	20,063
	Percentage		100%	64%			50%			41%		
Scenario 3	Avg Customer Load	kW	146,800	101,292	50,646	50,646	91,016	45,508	45,508	85,144	56,763	28,381
	Percentage		100%	69%			62%			58%		
Scenario 4	Avg Customer Load	kW	146,800	118,908	59,454	59,454	105,696	52,848	52,848	83,676	55,784	27,892
	Percentage		100%	81%			72%			57%		
Scenario 5	Avg Customer Load	kW	146,800	105,696	52,848	52,848	89,548	44,774	44,774	70,464	46,976	23,488
	Percentage		100%	72%			61%			48%		

Source: The demand scheme was developed based on the data of current Taipower supply capacity and the total demand of Taichung Industrial Park as of March, 2012 excerpted from Chang [31].

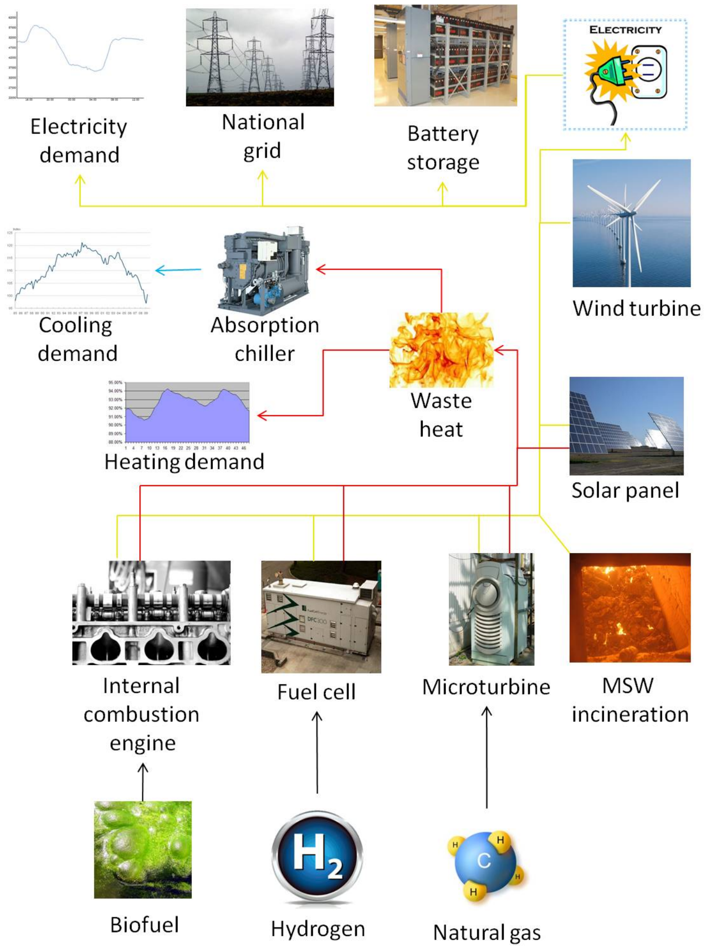


Figure 1. Schematic Diagram of the Microgrid (Source: Kang, et al.[30])

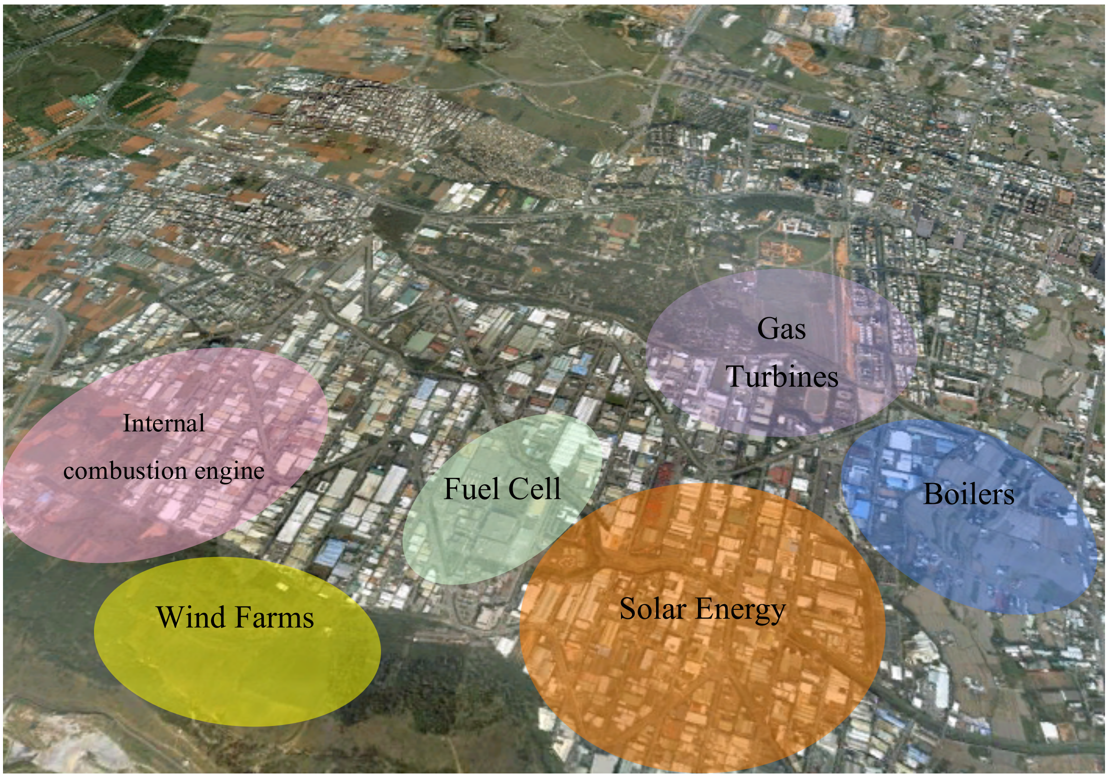


Figure 2. Proposed Layout of Microgrid for Taichung Industrial Park

Source: Kang et al. [30]

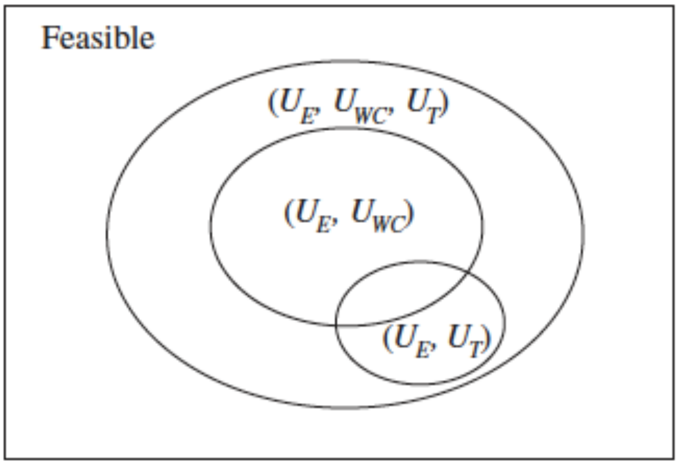


Figure 3. Feasible regions of robust solutions using robustness measures.

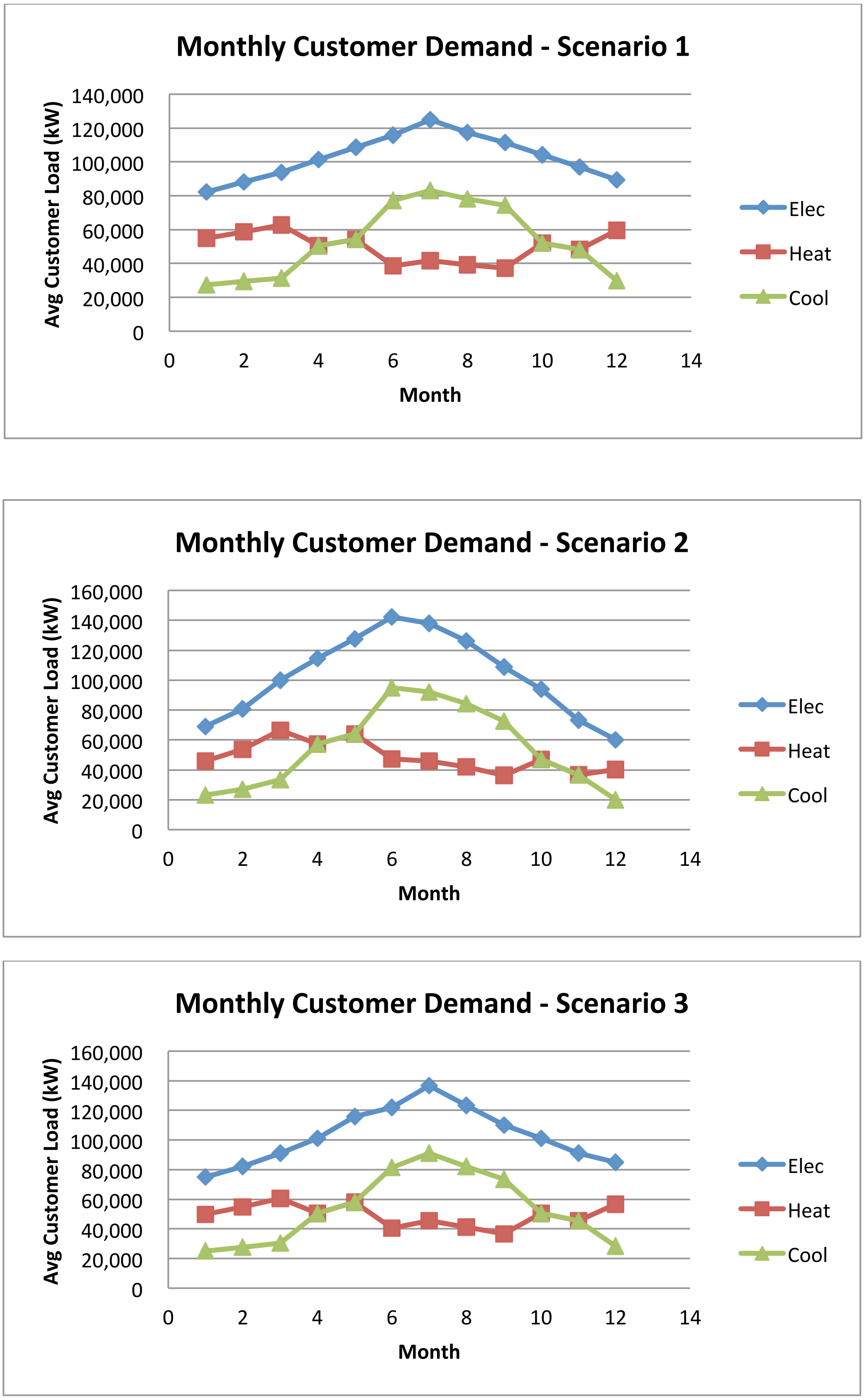
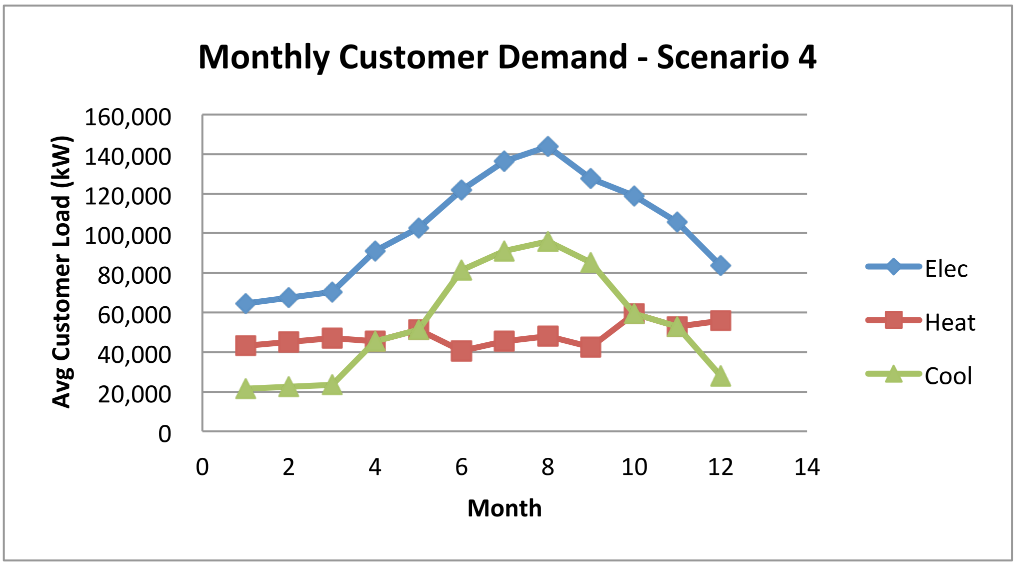


Figure 4. Monthly customer demand curves of Taichung Industrial Park for five scenarios



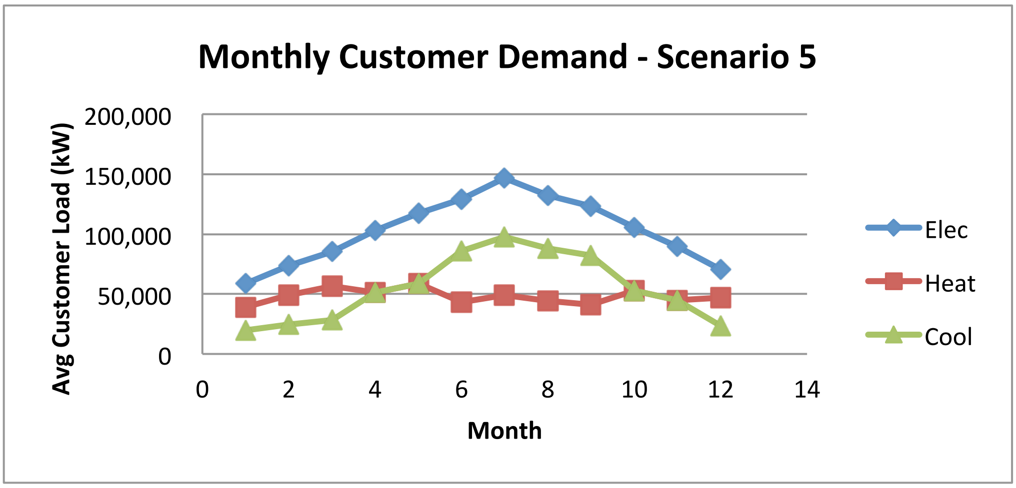


Figure 4(continued). Monthly customer demand curves of Taichung Industrial Park for five scenarios

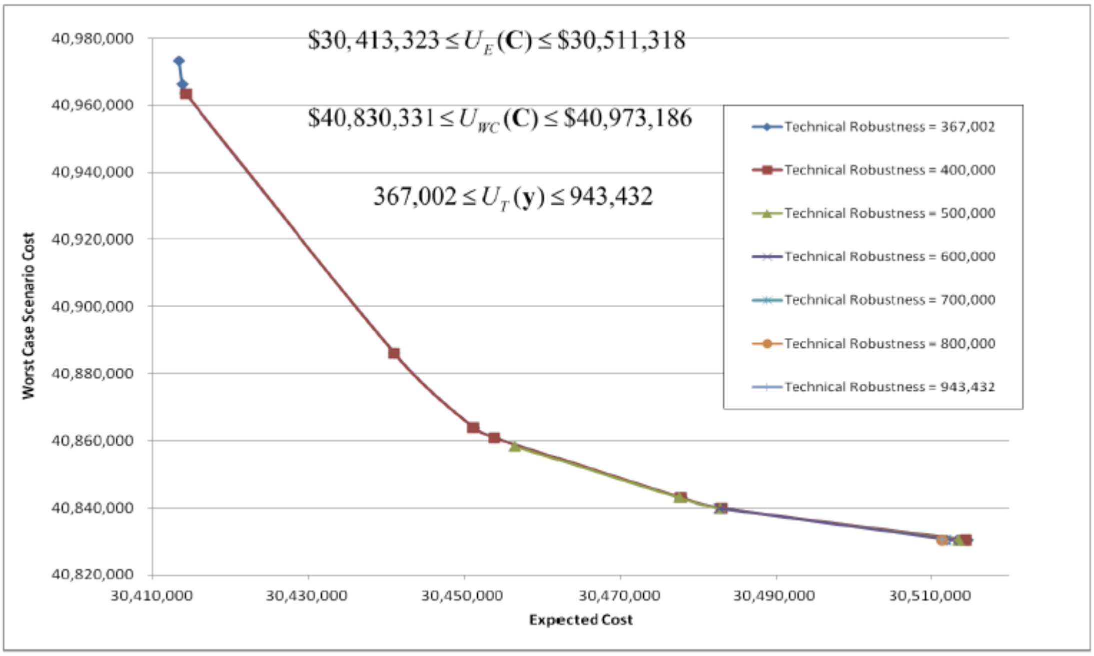


Figure 5. Set of Robust Alternatives

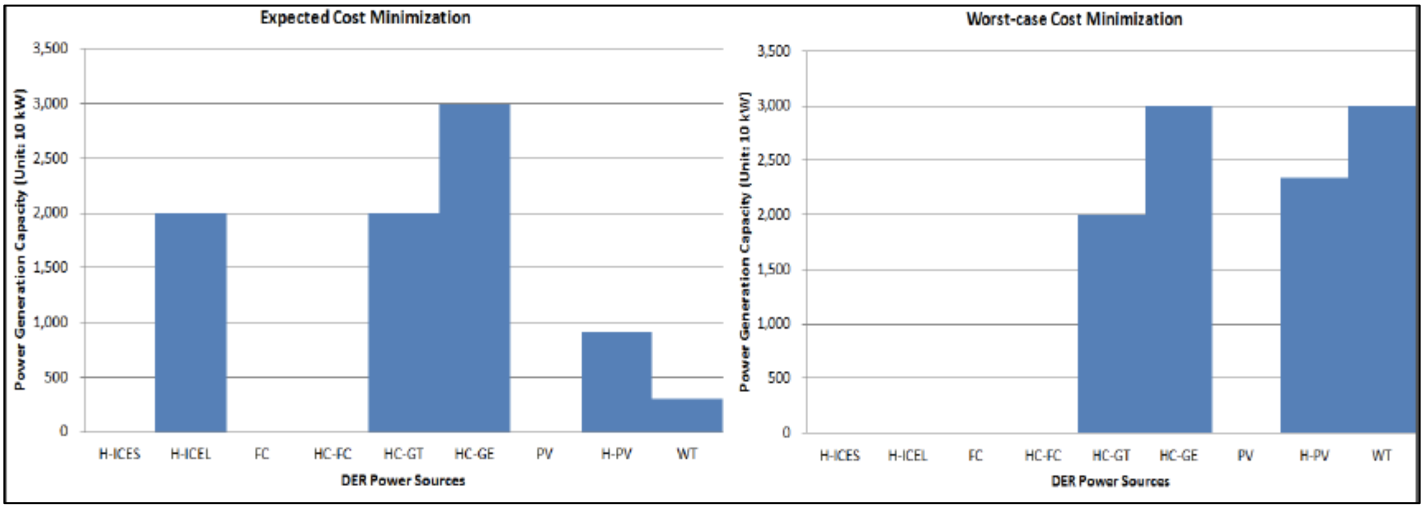


Figure 6. Capacity of DER

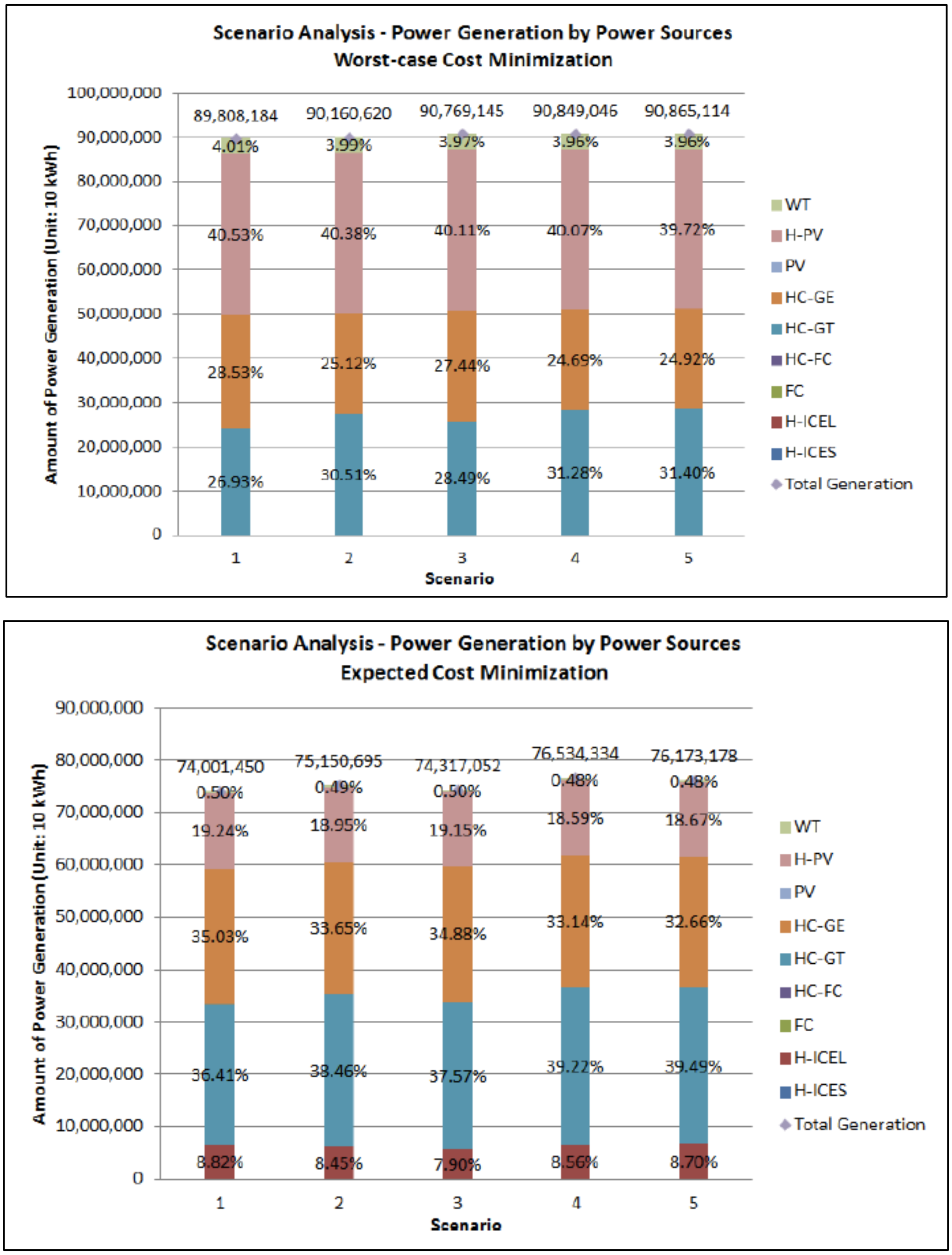


Figure 7. Scenario Analysis

Figure 8. Increase of Wind Speed by 10%

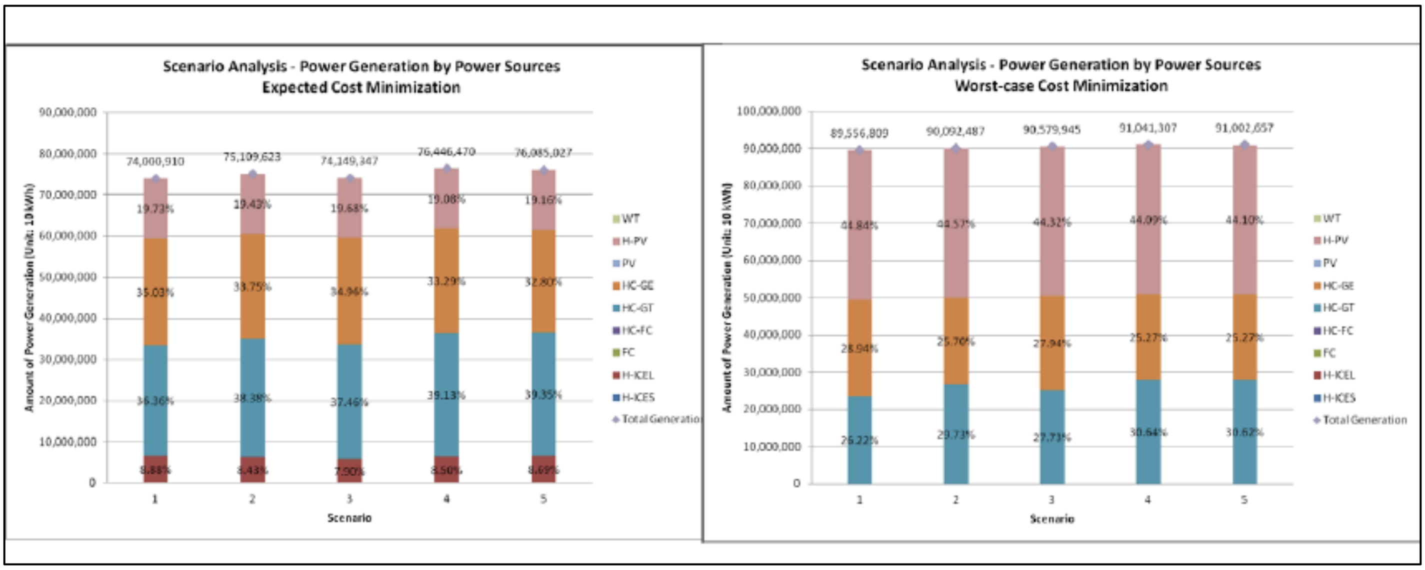


Figure 9. Reduction of Wind Speed by 10%

附件二

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□　未達成目標（請說明，以 100 字為限）

　　□　實驗失敗

　　□　因故實驗中斷

　　□　其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■ 已發表 □ 未發表之文稿 ■ 撰寫中 □ 無

專利：□ 已獲得 □ 申請中 □ 無

技轉：□ 已技轉 □ 洽談中 □ 無

其他：（以 100 字為限）

Outcome of the projects

1. John Edward Burns and **Jin-Su Kang* (2012),** Comparative economic analysis of supporting policies for residential solar PV in the United States: Solar Renewable Energy Credit (SREC) potential, Energy Policy, 44:217–225
2. **Jin-Su Kang***, Chung-Chuan Chang, Dong-Yup Lee, Tai-yong Lee (2012) Robust Optimization of Microgrids – An Application to Taichung Industrial Park, Proceedings of the 11th International Symposium on Process Systems Engineering, 15-19 July 2012, Singapore. Oral Presentation
3. Chung-Chuan Chang (with Advisor: **Jin-Su Kang**) (2012) A Decision Support Model for Microgrids –An Application to Taichung Industrial Park, A Thesis Submitted to Global MBA Program, College of Management, National Chiao Tung University
4. 4. Robust Economic Optimization of Microgrid in preparation with Chung-Chuan Chang

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以500字為限）

The current project successfully proposed robust optimization model for renewable microgrid design, specifically applied to Taichung Industrial Park, one of major industrial complex in Taiwan. To reflect the reality, the study tried to incorporate the field data into the model to construct scenarios as well as considering different portion of electricity produced from microgrid. The results of the model show that under the microgrid proposed, reducing technical variability (i.e., reducing the difference in the amount of carbon generated) among scenarios appears requiring more increment in expected cost than reducing economic variability (i.e., reducing worst-case scenario cost). This means that it is more expensive to keep the consistent level of carbon generated under price uncertainty. Thus, it calls for careful consideration when to design microgrid for the place like Taichung industrial complex where the cost is one of main competitiveness of companies. In conclusion, this project results in one SSCI paper, one conference oral presentation, one Master thesis and a paper in preparation.

附件四

國科會補助專題研究計畫項下出席國際學術會議心得報告

日期：101 年 7 月 24 日

計畫編號	NSC 100－2221－E－009－136－		
計畫名稱	再生能源微電網之強建化		
出國人員姓名	姜真秀	服務機構及職稱	助理教授及傳案教學人員, 經營管理研究所, 國立交通大學.
會議時間	101 年 7 月 15 至 101 年 7 月 19 日	會議地點	Singapore
會議名稱	(中文) (英文)11th International Symposium on Process Systems Engineering		
發表論文題目	(中文) (英文) Robust optimization of microgrids – An application to Taichung Industrial Park		

一、參加會議經過

The International Symposia on Process Systems Engineering (PSE) have been a triennial tradition since 1982 organized by several disciplines of world class universities. It has proved to be an attractive global platform for the PSE academics, researchers, and practitioners from all corners of the world for sharing advances in PSE education, research, and application.

This time, there were about 350 participants in this conference across various fields including modeling and optimization, product and process design, operations and control, biological and biomedical systems, business decision support, information processing & cyber infrastructure, energy and sustainability, and PSE education. There were 7 plenary speeches, 7 keynote speeches, 176 oral presentations, and 145 poster presentation.

I arrived there in the evening of July, 14th. After the registration on July, 15th, the schedule was very tight starting at 8:30am and finishing at 6pm. Everyday, I was busy with attending the presentation or discussing with other scholars about state-of-art research topics in the fields. For instance, Dr. Brenda L. Dietrich from IBM research gave an excellent presentation regarding how PSE research can be applied to real practices under the title “Optimizing the End-to-End Value Chain through Demand Shaping and

Advanced Customer Analytics.” On the other hands, Professor Wolfgang Marquardt from RWTH showed the future opportunity for PSE in Bio-industry, together with the presentation from Merck&Co., Inc. about the application of PSE in medicine and vaccine manufacturing. This time, the general trend of plenary lectures focused on bio-industry, energy, and water treatment.

My oral presentation was 19th of July (Thursday) at the end of morning session. Although this was right before lunch break, many people still stayed because my topic “microgrid” is one of hottest topics in the field of energy. The terminology “microgrid” started to appear on academic papers since 2002 in IEEE journals. In the beginning, mostly electrical engineering showed a great interest focusing on control and autonomous operation, however, more and more researcher from various fields started to give an attention on it. In PSE, this is still new and especially there are little research using real industrial complex. Since our paper utilized local data from Taichung industrial park regarding power demand, weather conditions, fuel prices, etc., audiences showed a great interest on this promising field in the future. Right after the presentation, Professor Lee, In-Beom from POSTECH, one of prestigious schools for science and technology in South Korea, came to me and wanted to discuss about future collaboration.

The last session in this conference was technical tour, which I chose to visit the water-treatment facility, PUB Newater, run by Singaporean government. More and more, the water becomes scarce and important natural resource that we need to fight for. Specifically, Singapore used to purchase water from Malaysia. After they have been looking for ways to secure water supply for three decades, the government started water-treatment facility to utilize used water in 2000 when the necessary technology had matured and driven productions costs down. Currently there are 4 NEWater plants in Singapore meeting 30% of Singapore’s total water demand. By 2060, NEWater is projected to meet 50% of Singapore’s future water demand.

二、與會心得

PSE society has been moving fast away from its process design and control to bioscience and energy. Many scholars have focused on liquefaction of LNG or scheduling, monitoring, and fault diagnosis of gas and oil related processes. Or pharmaceutical process and medicine manufacturing have become one of main applications. This shows the importance of interdisciplinary research. Nevertheless, many researchers appear not to be aware of development of other topics well. Specifically, young PhD or MS students often had little knowledge about operations research, which reminds university faculties of the importance of university education.

There was also a division of research topics depending on areas. European scholars have more attention on concurrent engineering emphasizing conceptual design of operations while American scholars focused on industrial application. Asian scholars showed the strong tendency on theoretical perspectives. Since each area has it own characteristic, international collaboration can definitely benefit researchers for more broad and comprehensive research.

In addition, NEWater was very impressive because I am sure that Singapore will be one of leaders to secure water in the future with their early development and advanced technology. Taiwan, so far, tend to rely on rain and dams for water supply but, we need to care for our nature by utilizing used water for clean sustainability.

三、考察參觀活動(無是項活動者略)

Technical tour to PUB NEWater run by Singaporean government to treat used water, which is explained as a part of the itinerary above. The link is as follows.

http://www.pub.gov.sg/about/historyfuture/Pages/NEWater.aspx

NEWater Visitor Centre

The NEWater Visitor Centre is the focal point of PUB's public education on NEWater. First opened in 2003, the Centre highlights the importance of water and how Singapore leverages on advances in technology to reclaim water. Visitors are able to view firsthand the operation of the advanced dual-membrane and ultraviolet technologies used to produce NEWater. Admission to the centre is free.

NEWater Visitor Centre's popularity has won it the Best Sightseeing/Leisure/Educational Programme at the 20th Tourism Awards 2005 and the IWA Marketing & Communication Award 2006.

You will also get to see a NEWater factory that is incorporated in the NEWater Visitor Centre. You will be able to witness at first hand the operation of advanced membrane and ultraviolet technologies in the production of NEWater.

Tours for the Visitor Centre can now be booked through an online system found at this website or via telephone at 6546 7874 / 6593 1533.

四、建議

It was impressive how Singapore attracts international conference and organizes every activity. Despite expensive prices, participants really enjoyed this conference with pleasure. Specifically, they utilized this opportunity to advertise their advanced technologies including water treatment and research institute as well as enjoy tourists' purse. A lot of Europeans enjoyed every detail of Singapore. This is one thing that we can learn from Singapore.

五、攜回資料名稱及內容

E-copy of 11th International Symposium on Process Systems Engineering – PSE2012 (978-0-444-59505-8). Since this proceeding has more than 1,000 pages, this is not included in this document.

六、其他

國科會補助計畫衍生研發成果推廣資料表

日期:2012/10/31

國科會補助計畫	計畫名稱: 再生能源微電網之強健最佳化
	計畫主持人: 姜真秀
	計畫編號: 100-2221-E-009-136- 學門領域: 能源科技

無研發成果推廣資料

100 年度專題研究計畫研究成果彙整表

計畫主持人：姜真秀 **計畫編號：**100-2221-E-009-136-

計畫名稱：再生能源微電網之強健最佳化

成果項目			量化			單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
			實際已達成數（被接受或已發表）	預期總達成數(含實際已達成數)	本計畫實際貢獻百分比		
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	0	100%		
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
國外	論文著作	期刊論文	1	3	33%	篇	One SSCI paper published (another SSCI paper in preparation)
		研究報告/技術報告	0	0	100%		
		研討會論文	1	1	100%		Oral presentation
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（外國籍）	碩士生	4	2	200%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	In addition to one SSCI paper and international conference (oral presentation), a master thesis has resulted too.

🟥	**成果項目**	**量化**	**名稱或內容性質簡述**
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標
□未達成目標（請說明，以 100 字為限）
　　□實驗失敗
　　□因故實驗中斷
　　□其他原因
說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■已發表 □未發表之文稿 □撰寫中 □無
專利：□已獲得 □申請中 ■無
技轉：□已技轉 □洽談中 ■無
其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

According to Central Weather Bureau (2011), Taiwan has experienced a warming effect that is twice the global average, which has translated to higher temperatures, greater rainfall, and more typhoons over the past 30 years - while global temperatures have risen 0.65 degrees celsius over the past century, while Taiwan has seen its temperature go up by 1.4 degrees. Thus, a 'microgrid,' a local generation of heat and electricity with renewable energy resources, is considered a some of the most promising options to provide a more secure, clean, and efficient energy supply. This project has proposed the robust optimization model of microgrid applied to Taichung industrial complex. While this complex exclusively depends on main grid for its electricity at this moment, it will be necessary to switch, at least, part of its electricity supply from the cleaner energy sources. The results of the model imply the significant economic impact on the competitiveness of products produced in the complex once CO2 reduction policy implemented. Also, this research found out that wind turbine is very sensitive to wind speed while photovoltaic (PV) panels are less sensitive to irradiation. Thus, more emphasis on PV than wind turbine will contribute on efficient generation of electricity.