National Chiao Tung University

Global MBA Program

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Master of Business Administration Degree Thesis

微電網之決策支援模型 – 以應用於台中工業區為例

A Decision Support Model for Microgrids –

An Application to Taichung Industrial Park

Student: Chung-Chuan Chang
Advisor: Prof. Jin-Su Kang

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Chinese Abstract

微電網之決策支援模型 – 以應用於台中工業區為例

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摘　　要

近年來，由於社會大眾對環境保護及永續的關注及對更穩定的能源供應系統的需求，結合了分佈式能源及再生能源之應用的微電網概念逐漸獲得重視。然而，截至目前為止，微電網所具有的潛在優勢卻尚未能在實際生活中展現出來，這與該系統本身的複雜性及不確定因素造成的進入門檻頗有關連。在過去，有許多種微電網模型陸續被提出以支援微電網規劃工作的最佳化；然而，強健最佳化理論及方法卻至今尚未被應用在微電網的模型建立上以因應消費者能源需求、燃料價格、電價及碳稅稅率等方面的不確定性。本研究提出一個混合型線性整數規劃(MILP)模型，並採用最壞情況下的成本(經濟性強健化方法之一)作為本模型多目標函數的最佳化目標之一，以便及早在微電網的早期規劃設計階段就導入強健最佳化的分析。本模型被設計為可同時進行微電網系統的成本期望值最小化及最壞情況成本的最小化，而最壞情況成本的最小化即是用來因應系統運作的各種不同情況之間的差異性。本模型藉由一套完整的數學公式模擬系統運作，從兼顧經濟、節能及環境保護等觀點為基礎，致力於為一規劃中的微電網系統提供可行的容量設計建議。此模擬的輸出結果尚包含產生一條描述成本期望值及最壞情況成本之間關係的帕累托曲線(Pareto curve)，該曲線可協助本模型的使用者判斷他們在微電網設計上的風險控管程度。在本研究中，此一模型被應用於台灣的台中工業區以驗證其作為微電網決策支援工具的適用性。

English Abstract

A Decision Support Model for Microgrids – An Application to Taichung Industrial Park

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ABSTRACT

The microgrid concept, which encompasses the application of distributed energy resources and renewable energy, has gained arousing interest in recent years due to the increasing concern on environmental sustainability and demand for a more reliable power supply system from the civil society. So far, the pontential benefits of microgrids have not yet been exploited because of the entry barrier caused by the complexity and uncertainty within the microgrid system. A variety of microgrid models have been presented before to optimize the planning of microgrids; however, robust optimization has not been applied to the modeling of microgrids to deal with uncertainties in customer loads, fuel prices, electricity tariff rate, and carbon tax rate, etc. In this study, a mixed-integer linear programming (MILP) model is proposed to adopt an economic robust measure, worst-case cost, as one of the components in the multi-objective function to allow robust optimization of a planned microgrid as early as in the design stage. The model is designed to simultaneously address the issue of expected cost minimization and worst-case cost minimization, which helps in handling the variation among different scenarios of the system operation. With comprehensive mathematical formulation, the model aims at rendering capacity design recommendations for a microgrid from economic, energy-saving, and environmental perspectives. The results of the simulation include the formation of a Pareto curve between the expected cost and worst-case cost of the project, which enables the model users to judge the degree of their risk-taking on microgrid design. The application of the proposed model to Taichung Industrial Park in Taiwan demonstrates the applicability of the model as a decision support tool for microgrid planning.

Acknowledgement

The author of this Master thesis sincerely thanks his advisor, Professor Jin-Su Kang, for her guidance through this research. She carefully understood the author's education background and work experience at the beginning and advised the author a possible direction of his research. The modeling of a typical microgrid in this research not only requires basic knowledge in distributed generation and microgrid-related technologies, but also incorporates the application of economic robust measures in multi-objective optimization. Prof. Kang is a specialist in robust optimization and has long been studying various economic and technical robust measures. She conducted tutorial sessions and explained the principles of robust optimization to the author. She also recommended related papers and helped the author obtain prerequisite knowledge step by step.

During this research, Prof. Kang always knew how to test the author's microgrid models and was capable of quickly identifying the possible problems within these models. She taught the author how to diagnose the root causes of some problems when difficulties were encountered. She often gave the author valuable suggestions regarding how to improve the modeling and facilitate the problem solving. Without her advice, the research would not have been carried out smoothly and presented with a logical manner.

The author also appreciates the support from Taichung Industrial Park Service Center during his research. The staff of the service center kindly provided relevant data, such as their catalog illustrating the history and current status of Taichung Industrial Park and the latest contracted power capacity (i.e. estimated power demand) of the companies in the park, which were of great importance in this study. Thanks to the assistance of the service center, the simulation of the hypothesized microgrid for Taichung Industrial Park was able to be performed based on realistic on-site conditions.

The work of this study is also partly supported by Central Weather Bureau, Taiwan R.O.C. as it provided detailed local weather data of the Taichung area in the year of 2011. The proposed microgrid model involves the presence of solar energy systems and wind turbines, whose performance deeply depends on local weather conditions. The reference to the real data of the past year enhances the accuracy of the predicted power output from these renewable sources.

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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

$Efromstore_{tmus}$: 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

$EqStart_{ims}$: binary variable, equal to 1 when source i starts up in month m in scenario s,

	otherwise 0
$EqStop_{ims}$	: binary variable, equal to 1 when source i stops in month m in scenario s, otherwise 0
$ESal_{ims}$	: 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, %

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

I. Introduction

1.1 Background

For several decades, humans have been facing the threats of natural resources depletion and global climate change to the Earth. Nevertheless, energy consumption contributes to a large portion of these problems. Huge amounts of fossil fuels are used and converted into different energy types such as electricity and heat to meet domestic and industrial demands. On the other hand, energy generation in most cases comes with undesired byproducts, such as carbon dioxide and solid particles, among others, which have been proved to be some of the major causes of greenhouse effect and air pollution. However, continuous technology advancement in electrical appliances and economic growth of human society are often driving forces that place even higher pressure on energy demands. As a result, seeking alternative power sources, which may share the loading on the centralized power supply system while mitigating environmental impacts, has been receiving more attention than ever before.

1.2 An introduction to microgrids and the related technology

In recent years, renewable energy that is naturally replenished, such as sunlight, wind, rain, etc., has gained renewed interests due to the fact that the technology advancement in efficiency improvement and cost down has gradually made it commercially feasible. Some other power soures such as biomass, hydrogen, and natural gas, etc., though not completely renewable, are also deemed green because they are applicable substitutes for the traditional fossil fuels like oil and coal. Meanwhile, distributed generation (DG) or distributed energy resources (DER), which generates electricity from dispersed small on-site power sources as the supplement to or replacement for the traditional electricity supply system, is another concept that is gaining increasing popularity because of its capability of exploiting local resources, reducing long-distance power transmission loss, and ensuring power generation diversity. A DER system often incorporates a variety of power generation technologies such as fuel cells, wind turbines, and photovoltaic system (PV), as well as trigeneration, also called combined cooling, heat and power (CCHP), which recovers waste heat from electricity generation for the usage of heating and cooling. As a complement of DG, distributed energy storage (DS) enables excess energy generated, in the form of electricity or heat, to be saved near the power sources and local demands for future usage.

The term microgrid refers to a cluster of customer loads, microsources (DER), and energy storage (DS) operating as a single controllable system, which provides both power and heat to its local area[1]. One of the features of a microgrid is that it normally connects to a traditional centralized grid, which is also called a macrogrid or national grid. A single point of common coupling (PCC) controls the connection or disconnection of a microgrid to the centralized grid, such that the microgrid may operate autonomously when PCC is disconnected. The point of control gives the grid operator flexibility in maximizing the energy ultilization efficiency, as the operator can decide to purchase electricity from the national grid when internal power generation is in shortage, to sell electricity to the national grid when internal generation is in excess, or to disconnect the microgrid from the national grid when malfunction of the centralized power supply system occurs. Figure 1 presents an example of microgrid configuration[2]. A microgrid typically comprises the aforementioned components including DG, DS, CCHP, PCC, and different types of end users demanding electricity, heating, and/or cooling with the application of various renewable and green energy sources.

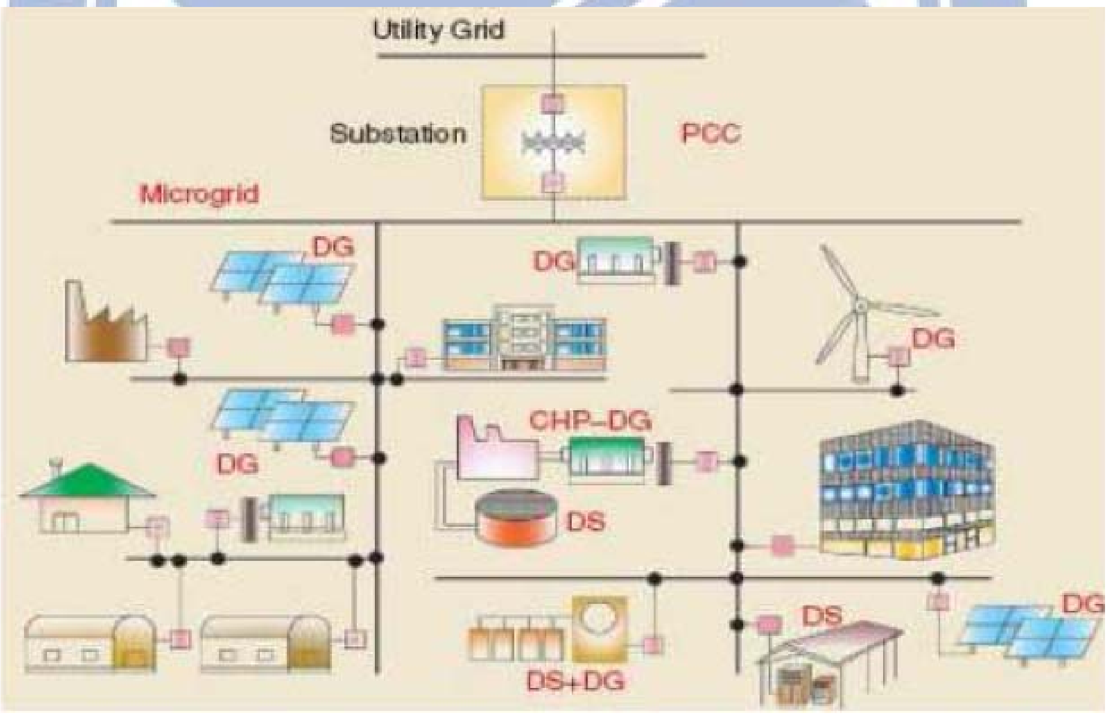


Figure 1: A typical microgrid schematic diagram

Source: Jeon et al. 2010[2]

Power generation and customer loads in a microgrid are often interconnected at low voltage, and this can be assured by the low-voltage bus of the substation transformer.

1.3 The advantages and potential of microgrids

1.3.1 Advantages of the microgrid system

Over the past decade, there have been emerging interests worldwide in the development of the microgrid system in that microgrids have the following advantages:

1. Unlike current centralized power supply grid or huge power plants, they require much smaller financial commitments in each project, although the unit cost of the electricity generated may be higher. This is a tradeoff between economy of scale and flexibility, and when considered with other factors, microgrids may gradually increase their competitive advantages. For example, lower budget thresholds may encourge central govenments to empower local goverments or even communities to build their own power systems.
2. By utilizing more renewable resources, microgrids can be more environmentally friendly with less carbon footprints.
3. With the application of advanced technology, microgrids demand fewer technical skills to operate and rely more on automation.
4. The microgrid system can be adopted by an isolated area, such as an industrial park or an island, and therefore protecting the area free from grid disturbance or power outage caused by unexpected national grid failure.
5. The multiple diverse generation sources would provide highly reliable electric power to the local area in the way that when one source fails, the other sources may run in higher allocation of capacities to cover the shortage. Moreover, when there is a need from the national grid or other local areas, the excess energy generated by one microgrid can be transmitted to the national grid to release the other loading.
6. Microgrids enable the autonomy of local energy supply and therefore take the individual customers out of the grip of large power corporations or central power suppliers.

1.3.2 History and future potential of microgrid development

Due to their many advantages over the traditional centralized grids, microgrids have gained popularity among countries and become hot topics of national projects and academic research in the past few years. As of 2006, researches and experiments related to microgrids were conducted in four countries or regions including EU, US, Japan, and

Canada[3]. For example, 11 EU countries and 22 partners are currently involved in the "MICROGRIDS" project, which is part of the"Intergration of RES+DG" projects in Europe and aims to increase the penetration of micro-generation in the general power networks. In the United States, various organizations including Consortium for Electric Reliaility Technology Solutions (CERTS), Power Systems Engineering Research Center (PSERC), and Lawrence Berkeley National Laboratory (LBNL) have participated in the research of microgrids, and several test fields have been built in different states. In Japan, several projects with field tests on local power system are currently executed by New Energy and Industrial Technology Development Organization (NEDO)[4]. There are also projects led by CanMET energy technology center in Canada.

Seeing the potential of microgrids as a promising alternative of traditonal power supply system, governments of Singapore, Korea, and Taiwan began to invest in the research of microgrids recently, following the advanced countries (region) mentioned above. The Institute of Nuclear Energy Research (INER) in Taiwan started to develop power control and energy management technology for microgrids in 2009. Although there has been limit research on the topic of microgrids in Taiwan so far, it can be expected that an increasing number of research projects will be launched in the years to come.

1.4 Objective of the current research

1.4.1 Development of a decision support model for microgrids

Due to the lack of empirical data and the complex compostion of microgrids, it is often quite annoying for government agencies or the designers they hire to perform initial analyses, such as power source selection, capacity design, budgeting, and risk evaluation, etc., especially when the specific data of equipment models and manufacturers are not readily available. The designers would need a handy tool to capture the big picture of a proposed project and make a prelimernary planning that takes into account the actual local data, such as customer loads and weather statistics, etc.

The objective of the current study is to develop a decision support model, which provides a set of optimization solutions and can be used for microgrid planning in the design stage. The modle should be capable of performing multiobjective optimization, while considering possible uncertainties to certain degree at the early stage. Although the output data of this kind of model can be rough, their influence may be critical to the whole project because they often serve as a reference point which indicates whether to proceed with the project or not at the first place.

1.4.2 Scope and position of the current study

There have been numerous researches with different focuses in the field of microgrids. Existent studies include control schemes, scheduling, single-objective optimization, and multi-objective optimization without considering uncertainties, etc. Nevertheless, renewable energies are always full of uncertainties. For instance, the amount of sunlight in an area is deeply depended on the local weather condition, which may change every day. Similarly, the wind power in most cases is unstable because the velocity and direction of wind may change in every minute. Customer demands and fuel prices are also unstable factors, which varies from time to time. Therefore, one of the goals of the study is to use robust optimization to deal with uncertainties in a microgrid system.

In addition, a power generation project always involves the participation of diverse stakeholders, including power system developers, government agencies, law makers, and civil society. From the viewpoints of different parties, some objectives are conflicting by nature. For example, capacity maximization enlarges economy of scale but places lower flexibility; cost minimization may cause larger adverse environmental impacts; minimizing expected cost of a project may increase the variation among different scenario costs. This study proposes a model that would take multiple objectives into consideration and help decision makers seek compromising solutions among all stakeholders.

To summarize, this study aims at developing a decision support tool for microgrid planning, which provides robust solutions on the basis of multiobjective optimization. The model established will later be applied to Taichung Industrial Park as an example of microgrid planning.

1.5 Framework of the current research

The current study starts with a brief introduction to the key items, such as DER and microgrids, the advantages and potential of microgrids, and then a statement of the research objective. Chapter 1 ends with the framework of the current research. A comprehensive literature review is conducted in Chapter 2, which is categorized into four parts: DER system planning approaches, multi-objective optimization on DER, uncertainties in DER and robust optimization on process design, and others. The significance of the current study is then mentioned, compared to the prior researches.

Chapter 3 states the motivating problem that drives the development of the proposed model. The generic and localized (customized) applications of the model are initially discussed. Chapter 4 presents the methodology of the current research, including the position of this model in the entire microgrid design process and rigorous mathematical formulation of the model.

In Chapter 5, the proposed model is applied to plan a microgrid system to be used in Taichung Industrial Park, which is located in central Taiwan. An overview of the industrial park and the hypothesized layouts and settings of the microgrid are presented, followed by a series of parameter assignments as the model input. The output of the modeling and the analysis of the output data are shown in Chapter 6. Scenario analysis, sensitivity analysis, and case analysis are performed repectively in this study. The performance of the model can be observed through various analyses.

Chapter 7 contains the discussion of the applicability and limitation of the model, as well as the suggestions for future research. A Pareto curve between expected cost and worst-case cost is present in this chapter as one of the important outputs of this model, which may facilitate the evaluation of the model users on the microgrid configuration and budgeting. The conclusion of the entire study is presented in Chapter 8. Figure 2 shows the main structure of the current study.

The reference part and appendix, which contain the bibliography and the programming codes, repectively, are listed after the main text.

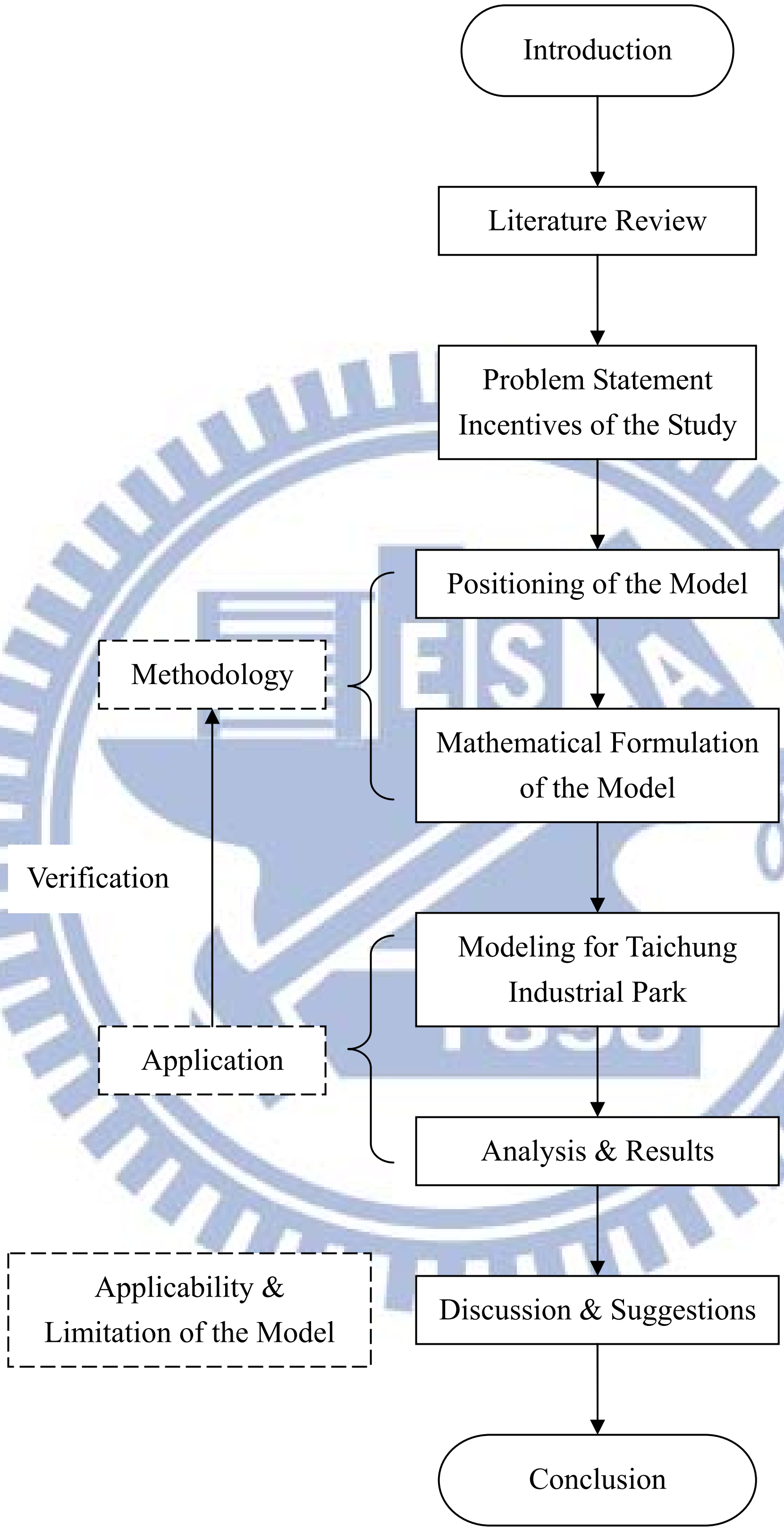


Figure 2: Framework of this study

II. Literature Review

Despite the late introduction of the microgrid concept, there have been many researches in different espects of this field of study. With regard to the objective and scope of the current study, the related prior researches can be categorized into the following sections.

2.1 DER system planning approaches

The planning of DER system or microgrids is a job with broad scope, covering tasks from the initial proposal of an investment plan, through the process of preliminary evaluation, budgeting, and basic design, all the way to the detailed design and the operation plan. Due to the complexity of the real projects, modeling has always been a popular way in simplifying and simulating the actual system, for facilitating the design process and decision making. With the distinct purpose and scope of each stage described above, sometimes it is necessary for a planner to adopt different plan and evaluation models in different stages of the planning process.

In general, models used in early stages of a project should aid in the synthesis evaluation of the project, while those used in the later stages should assist in detailed operation planning. A hierachical relationship among tasks of different levels in the planning of a DER system is shown in Figure 3 (Ren & Gao, 2010)[5]. It can be seen that a complete optimization process consists of several levels with different scopes and concerns.

In the synthesis optimization level, the designated area is evaluated with a macro analysis, in terms of natural conditions (e.g. geography and climate), technology (e.g. local supply chains), and social-economic characteristics. The objectives of this level are to select DER technology candidates for further evaluation and to consider the system connection. When it comes to the design optimization level, the estimate of capital cost (i.e. budgeting) and the target efficiency of the proposed system should be taken into account. In this stage, different candidates of pre-selected DER components should be put into analysis for an optimized planning of system layouts. It is very important to identify the technical characteristics of all components and observe the properties of the substances entering and exiting each component at the nominal load of the system. Finally in the operation optimization level, factors to be considered include energy prices (e.g. fuel price and electricity purchase price, etc.) and environmental constraints, such as carbon tax rate and government regulations. The goal of this stage is to obtain a detailed operating schedule of each selected components for the optimum overall system performance, given the system planning derived from the design stage.

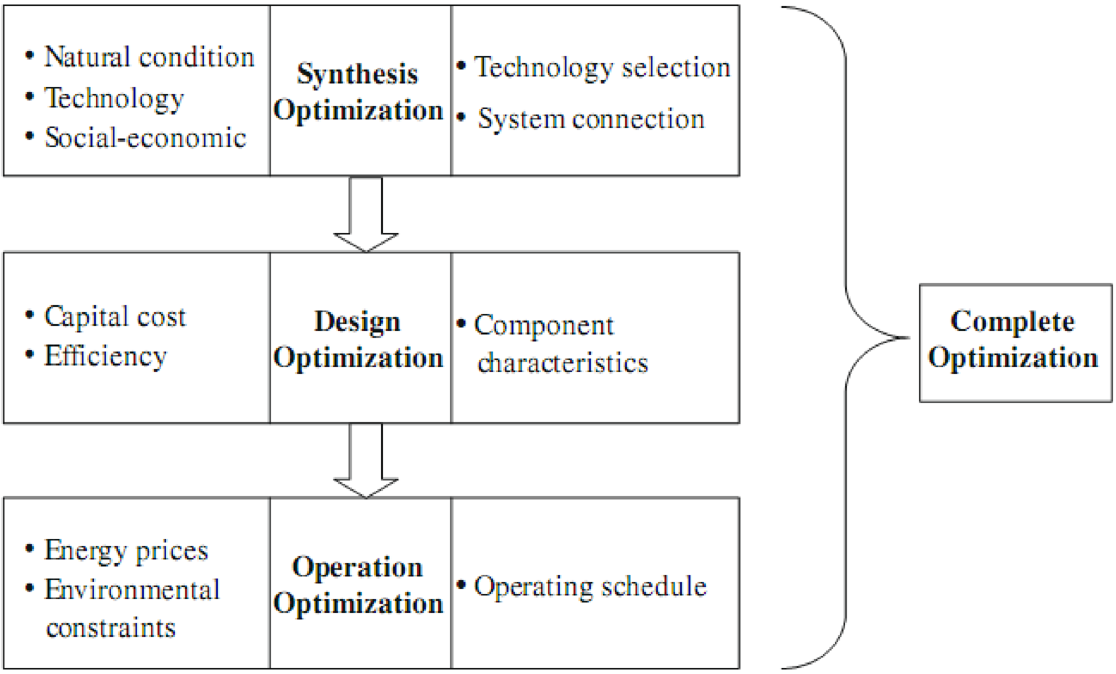


Figure 3: Structure of the levels of DER system optimization

Source: Ren and Gao 2010[5]

Based on different backgrounds and designed for different purposes, many models with specific focuses and capacities have been proposed in prior literature. Hiremath et al. have reviewed a variety of plan and evaluation models for DER system, in terms of the modeling approaches and application[6].

In this paper, various models are further divided into some sub-scetions according to their characteristics and the planning stages they belong to.

2.1.1 System planning and design

Modeling for strategic design of microgrids normally goes ahead of those for detailed design and operation plans, and appears in the early stage of the planning. Driesen and Katiraeri reviewed different trends in planning methods for distribution system from the past to the future and compared the planning approaches of conventional centralized system, decentralized energy system, and microgrids[7]. Hawkes and Leach presented an economic optimization model for high level system design and unit commitment of a microgrid[8]. Li et al. developed a thermo-economic optimization model of a DER system in Beijing[9]. Chinese and Meneghetti constructed a mixed-integer linear programming (MILP) model for utility profit maximization and a linear programming (LP) model for adverse emissions minimization for a biomass-based industrial district-heating area in Italy[10]. Medrano et al. developed a simulation model and researched the economic, energetic, and environmental impacts of integrating microgrids into generic types of commercial buildings in California[11]. Maribu et al. presented a market diffusion model for analyzing DER adoption in US commercial buildings[12]. Zhou et al. applied a simulation model to anayzing the optimal DER adoption of five prototype commercial buildings in the Japanese context, with US cases for comparison[13].

Ren and Gao proposed a synthesis concept for designing the layouts of DER system, considering the integration among DER technologies and customer services[5]. They also proposed a MILP model for integrated plan and evaluation of DER system, aiming at integrating synthesis, design, and operation optimization in one single model. Since its goal was to generate a detailed plan of the equipment deployment, this model was developed based on an "equipment concern", which means that detailed design, such as the number and capacity of the machines in each type of DER equipment selected, can be achieved by setting the number of equipment as integer variables in the model.

2.1.2 Operation plan and scheduling

After the basic design is completed, normally the selected types of DER technologies, the total capacity of each type, and even the number of equipment are also determined. These data then serve as input parameters in the operation plan and detailed scheduling of the DER system or microgrid. Numerous researches have been reported in this field of study. Morais et al. developed a MILP model for optimal scheduling of a renewable microgrid in an isolated load area[14]. Kalantar and Mousavi proposed a model simulating the dynamic behavior of an isolated microgrid, which consisted of wind turbine, solar array, microturbine, and battery storage[15]. Logenthiran et al. presented an agent-based system for energy resource scheduling of integrated microgrids[16]. Ruan et al. analyzed four types of DER technologies for the optimal operation modes of four commercial buildings[17].

Naraharisetti et al. constructed a sophisticated MILP model for scheduling in microgrids with a linear diversity constraint, which provides an efficient way to ensure the diverse operation of various DER technologies[18]. This was a detailed scheduling plan with source type and capacities given as parameters. Soderman and Pettersson proposed a structural and operational optimization model with MILP for a DER system with the involvement of district heating[19].

2.2 Multi-objective optimization on DER

Microgrids and DER system have long been ideal targets of optimization modeling, as they generally involve a complicated network of multiple energy suppliers (e.g., power generation sources, energy storage, and the national grid) and energy consumers. There are so many possible arrangements of the energy transmission between senders and receivers that a single best solution is not readily available or solvable. Depending on the intended objective of the designers and the complexity of the modeling, single or multi-objective functions may be constructed for optimization.

For a single-objective function, normally the one optimal solution can be found if the model is solvable. As for a multi-objective function, in most cases there should be a set of compromise solutions between different or even conflicting objectives, instead of one best solution. This problem can be mathematically formulated as (P1)[20]:

$$\min F(\mathbf{x}) = \min\,(f_1(\mathbf{x}),\ f_2(\mathbf{x}), \ldots,\ f_n(\mathbf{x})) \qquad \text{(P1)}$$

$$s.t.\quad \mathbf{x} \in \Omega$$

$$\mathbf{G(x)} = \mathbf{0}$$

$$\mathbf{H(x)} \le \mathbf{0}$$

where f_i is the i^{th} objective function; n is the number of objectives; $\mathbf{x}$ is the decision vector (variable); Ω is the decision domain that defines the possible outcomes of $\mathbf{x}$; $\mathbf{G(x)}$ represents the set of equality constraints and $\mathbf{H(x)}$ represents the set of inequality constraints. In this kind of problem, various objectives are conflicting that there is no single solution but a set of optimal solution, called Pareto set. A solution belongs to the Pareto set if no improvement is possible in one objective without losing in any other objective. Figure 4 illustrates the possible outcomes of a two-objective problem as an example. It can be seen from the chart that for a certain two-objective problem, the set of optimal solution lies along a Pareto curve. A solution "a" is stated to dominate a solution "b" if "a" is not worse than "b" in all objectives and "a" is better than "b" in at least one objective.

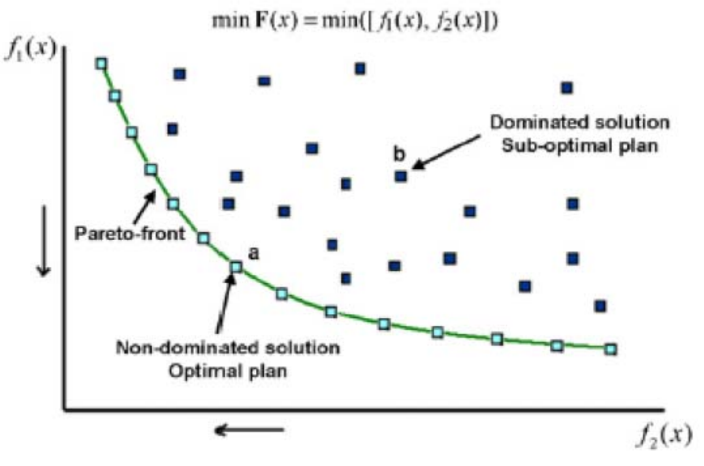


Figure 4: A Pareto front for a two-objective problem
Source: Alarcon-Rodriguez et al. 2010[20]

Multi-objective optimization is of great importance to solving the inherent dilemmas within the design of a microgrid or DER system. In most cases, diverse parties of stakeholders, such as microgrid developers, utility operators, end-users of energy, government agencies, and the civil society, etc., are involved in the same project with different concern of interests[21]. The objectives of these parties can be mutually conflicting because each of them evaluates from different point of view. For instance, microgrid developers may prefer cost minimization, while the society may have more concern on low greenhouse gas emissions; utility operators may encourage a higher utilization rate of the centralized power supply, while the local communities hope to depend more on distributed power sources. In addition, the goal of minimizing expected cost of a power supply system conflicts with that of minimizing the variation among different scenario costs. The multi-objective optimization can be useful in seeking compromising solutions, which benefit all parties of stakeholders[22].

2.2.1 Development of multi-objective optimization and decision making

The development of multi-objective optimization includes how to systematically obtain the diverse solutions of the Pareto front and how to find a compromising final solution after a considerable number of Pareto solutions are generated. Zangeneh and Jadid used single-objective minimization to obtain diverse solutions of the Pareto front for planning distributed generation systems[23].The normal boundary intersection method was used to generate evenly distributed solutions in the Pareto set. Tang and Tang presented a weighted sum method in the multi-objective planning for choosing the locations and sizes of distributed generation units[24]. The authors discussed the issue of how to assign proper weights to the objectives depending on the planner's preference. Barin et al. addressed the problem of choosing the best solution from an existent list of feasible planning options for distributed generation systems[25].

2.2.2 Application of multi-objective optimization

Multi-objective optimization was widely used in prior research of microgrids and DER system. Celli et al. worked for minimizing different costs with multi-objective modeling for the optimal sizing and siting of distributed generation[26]. Ren et al. considered both economic and environmental aspects while constructing a multi-objective linear programming (MOLP) model for analyzing the operation of distributed energy systems in a local area of Japan[27]. Kavvadias and Maroulis applied multi-objective optimization to the design of a trigeneration plant with economic, energy-saving, and environmental concerns[28]. This is a detailed small scale optimization model focusing on a single plant. Becerra-Lopez and Golding presented a multi-objective optimization model for the capacity expansion of regional power generation systems[29]. Haesen et al. incorporated multiple objectives into the model for long-term planning of DER deployment and sizing[30].

2.3 Uncertainties in DER and robust optimization on process design

Uncertainties exist in almost every design of engineering and industrial processes. There is no exception to the planning of DER systems and microgrids. A microgrid design, for instance, may encounter a variety of uncertainties, such as fluctuation of energy and fuel prices, variation of customer demands, changes in local weather, changes in regulations, unstable power supply quality, and possible outcome of main grid failure, etc. Robust optimization, which minimizes the risk of uncertainties, can be a solution to this kind of problems. There have been a number of researches in prior literature regarding uncertainties in distributed generation systems. However, the research on the application of robust optimaiztion is limited.

2.3.1 Prior research regarding uncertainties in DER design

Consideration to various uncertainties in the design of DER systems can be found in some of the literature before. Handschin et al. used mathematical programming in achieving better economic efficiency of distributed generation system under uncertainty [31]. Fleten et al. considered price uncertainty while constructing a mathematical model to obtain optimal investment strategies in distributed renewable power resources[32]. Afzal et al. studied investiments in the DER system with a microgrid model under uncertainty[33]. Mavrotas et al. developed an integrated model with a mathematical programming framework for planning the CHP system in buildings of the services' sector, while considering the uncertainties in customer demand[34]. Houwing et al. also used modeling to systematically analyze uncertainties in the design and operation of DER systems[35].

2.3.2 Robust optimization on process design under uncertainties

In the design of engineering process, one of the critical issues is to deal with different kinds of uncertainties, which may adversely increase variations in the performance of the designed system. For instance, in the process design of a microgrid or DER system, uncertainties come along with the estimated customer demand, fuel prices for power generation, and local weather conditions, such as the amount of sunlight and wind, etc.

Multiple scenarios are typically used to express possible uncertainties in a model that copes with uncertainty. Different scenarios usually have different objectives (e.g. cost minimization for different scenarios). When a number of scenrios are evaluated together, optimizing various objectives simultaneously results in a multi-objective problem. The prevailing way to deal with this problem is to use the stochastic model (Dempster, 1980) [36], which optimizes the expected value of all objectives with a cost vector. This approach can be expressed as follows:

$$\min_{\mathbf{x}, y_1, \ldots, y_N} \; Expected \qquad \text{(P2)}$$

$$s.t. \quad Expected = \sum_s p_s \times Cost_s$$

$$Cost_s = f(\mathbf{x}, y_s)$$

$$\mathbf{x}, y_1, \ldots, y_N \in \Psi$$

where *Expected* is the expected cost of scenarios; p_s is the probability of scenario s; C_s is the cost of scenario s constituded by a certain function $f(\mathbf{x}, y_s)$; Ψ is the set of viable vectors. In practice, the set of viable vectors is usually restricted to the Pareto optimal set, Ψ^*. Each scenario s is formed with a different set of design and control variables, denoted as $\mathbf{x} \in R^{n_0}$ and $y_s \in R^{n_1}$ respectively, which corresponds to a certain practical realization of the operation process. The stochastic model is established based on the assumption that the decision maker is risk-neutral, such that the optimal decision only depends on the expected cost. Handschin et al. used a stochastic model to deal with uncertainties when optimizing the operation of a distributed generation system[31].

Although the stochastic model ensures that the probability-weighted average of the scenario costs is minimized, it is not guaranteed that the process of this approach can perform to a certain level over all of the uncertain parameters[37]. In addition, the accurate assessment of the probability of each scenario cannot easily be achieved in most cases. Hence it is necessary to use some additional robustness approaches to cope with the process variability among scenarios.

Robustness can be inferred as risk aversion from the economic and technical points of view (Kang et al., 2011)[37]. Due to the fact that the nature of each variable is different, Kang et al. proposed that the design and control variables can be classified into three groups: (1) scenario-independent variables, (2) scenario-dependent economic or monetary variables (e.g., cost and profit), and (3) scenario-dependent technical variables (e.g. temperature, pressure, and efficiency, etc.). For the scenario-dependent economic variables, the robustness mechanism should work in the way to reduce relatively higher scenario costs, while keeping the overall average cost as low as possible. As for the scenario-dependent technical variables, the robustness measures should be acting to make the operation conditions insensitive to variations within certain ranges as defined by the scenarios.The robustness measures for scenario-dependent economic variables can also be referred to as the “economic robustness measures”, while the robustness measures for scenario-dependent technical variables being referred to as the “technical robustness measures” [37].

Considerable research has been done in the development of economic and technical robustness measures. It has been verified that economic robust measures should be monotonic, and that using symmetric measures (e.g., variance) as economic robustness measures generates suboptimal solutions, because symmetric measures act for reducing the variability from the mean, a mechanism which itself cannot be an objective of robust optimization[37]. In addition, in a multi-objective problem, no single optimal solution can optimize several objectives at the same time. Pareto optimality has been shown to be one of the effective criteria in deciding which robustness measures are suitable for robust economic optimization. It should be noted that Pareto optimality is guaranteed only for monotonic robustness measures. Kang et al. introduced the application of robust economic optimization for process design under uncertainties in 2004[38]. On the other hand, study has shown that unlike economic robustness measures, technical robustness measures should be even functions to reduce variations among scenarios[37]. Although a number of robustness measures have been developed for technical variables, the differences between economic and technical variables and between their respective robustness measures have seldom been studied.

Regarding economic variables, various kinds of economic robustness measures have been available so far for variability control. Suh and Lee presented the Pareto-optimal subset condition, in which worst-case cost and partial mean of costs were recommended for robust economic optimization[39]. It was proven that these two approaches guaranteed the Pareto optimality of multi-scenario problems. The definitions of worst-case cost and partial mean of costs are listed and given by (P3) and (P4):

Worst-case cost: $$C_w = \max \{ Cost_s | s = 1, \ldots, N \} \qquad \text{(P3)}$$

Partial mean of costs: $$U_{PM}(C,t) = \sum_{s=1}^{N} p_s \times \max\{ Cost_s - t, 0 \} \qquad \text{(P4)}$$

where t is a target value defining the criterion for penalizing exceedingly high scenario costs. Both measures have been proven to be effective in robust economic optimization. Kang et al. presented an integrated robust optimization model, which incorporates both economic and technical robustness measures, along with a decision making procedure[37]. The objectives include expected value, an economic robustness measure, and technical robustness measures. In this study, an innovative formulation for robust economic optimization was proposed for suggesting the proper range of target values in a robust partial mean model. In addition, worst-case cost is recommended to be the economic robustness measure and half interval is proposed as the technical robustness measure.

This study also applies the global criterion (Miettinen, 1999)[40] to help determine the compromising final solution of the multi-objective model.

2.4 Other researches related to DER and microgrids

2.4.1 Applicability and classification of microgrids

Defined as a localized grouping of distributed electricity generation, energy storage, and customer loads that is normally able to operate independently with optional connection to a traditional centralized grid, a microgrid system can be applied to many kinds of local regions (e.g. an industrial park or a remote island)[7].

Table 1: List of microgrid architectures

		Utility Microgrids		Industrial/Commercial Microgrids		Remote Microgrids
		Urban	Rural	Multifacility	Single Facility	
Application		Downtown areas	Planned islanding	Industrial parks, university campus, and shopping centers	A commercial or residential building	Remote communities and geographical island
Main Drivers		Outage management, RES integration		Power quality enhancement, reliability and energy efficiency		Electrification of remote areas and reduction in fuel consumption
Benefits		GHG[1] reduction Supply mix Congestion management Upgrade deferral Ancillary services		Premium power quality Service differentiation (reliability levels) CHP integration DRM[2]		Supply availability RES integration GHG reduction DRM
Operating modes		GD[3], GI[4], IG[5]		GD, GI, IG		IG
Transition to GI and IG mode	Accidental	Faults (on adjacent feeders or substation)		Main grid failure, power quality issues		
	Pre-scheduled	Maintenance		Energy price (peak time), utility maintenance		

1: greenhouse gases; 2: demand resource management; 3: grid dependent;
4: grid independent and autonomous operation; 5: isolated grid
Source: Driesen and Katiraeri, 2008[7]

A number of possible microgrid types have been presented in prior literature (Driesen and Katiraeri, 2008)[7]. Table 1 shows a general classification of applicable microgrid architectures and their characteristics, based on a comparison of their applications, drive forces, and benefits, etc. It can be seen from the list that industrial parks and islands are two of the best targets for microgrid adoption.

2.4.2 General studies on renewable energy and DER technologies

Numerous studies have been carried out on the topics of renewable energy and DER technologies. Chicco et al.[41] and Hiremath et al.[6] conducted comprehensive reviews on distributed generation, discussing emerging green energy such as biomass, fuel cells, solar energy, and wind power, etc. Alanne et al. analyzed the advantages of distributed energy generation and identified it as a favorable option for low carbon emissions and sustainable development of human society[42]. Huang et al. reviewed the current operation and market penetration of DER and microgrids[43].

2.4.3 Miscellaneous in literature review

Katiraei et al.[44] and Lopes et al.[45] studied the autonomous operations of microgrids. Barsali et al.[46], Piagi and Lasseter[47], and Yuan et al.[48] focused on control schemes of microgrids. Jiang-Jiang W et al.[49] and Cho et al.[50] placed particular concerns on combined cooling, heating, and power systems (CCHP), which is one of the major forms of DER technologies. Mohamed and Koivo used Mesh Adaptive Direct Search algorithm to solve a nonlinear model of microgrids[51]. Chen et al. analyzed the influence of introducing a DER system for redevelopment of a densely built-up area in Tokyo[52].

2.5 Significance of the current study

Compared to the existing literature mentioned above, the current study features in the following espects:

2.5.1 Application of robust optimization to microgrid design

It can be found from the literature review that most studies regarding microgrids have focused on system analysis and evaluation, scheduling, control schemes, planning with single-objective optimization, and planning with multi-objective optimization without considering uncertainties. However, uncertainties constitute one of the most annoying problems in microgrid design and thus cannot be ignored. There has been rigorous research in the field of robust optimization, but the application of robustness measures in microgrid modeling has not been explored yet. Hence this study proposes a decision support model with multi-objective optimization, which takes an economic robustness measure as one of the components of the dual objective function. The optimization approach aims at lowering the impacts of comparably higher scenario costs, while minimizing the overall expected cost of the system. This model may be used in practice for microgrid planning, taking uncertainties into account already in the design level.

2.5.2 MILP modeling with capacity concern

Modeling has been widely used in previous research to simulate the operation of various microgrids. Some models are designed for primary analysis of a project, while others are specified to do detailed planning on microgrid operation. Linear programming (LP), mixed integer linear programming (MILP), and nonlinear programming are typical appoaches to be applied in modeling. Although models with nonlinear programming sometimes can better simulate the real situation, they are generally much more difficult to be solved practically. On the other hand, models with integer or binary variables usually place substantial computing load in the solving process. In this study, a MILP model is developed to facilitate the planning of a microgrid project, by simulating the possible operation of the proposed microgrid in response to given conditions.

Unlike some other models, which were designed to generate the detailed plans of equipment types and numbers for a certain microgrid (e.g., Ren and Gao, 2010), the model presented in this study is designed based on a "capacity concern" and can be used even for the preliminary analysis of a proposed project with unknown or insufficient equipment data. In other words, the current model aims at capacity sizing for different power source candidates, such as fuel cells, photovoltaic panels, and wind farms, etc., rather than suggesting in detail which types of power generators and the number of each type to be installed. In addition, this model adopts several piece-wise linear relationships between cost and capacity to approximate the effect of economy of scale.

2.5.3 Application of the model to an industrial park

The model proposed in this study is applied to design a mirogrid for Taichung Industrial Park, which is one of the most important industrial clusters in Taiwan. A strategic layout of different DER technologies is also proposed for the park. The trial of modeling a microgrid for Taichung Industrial Park helps in verifying the applicability of this model as a decision support tool and indicates the potential of applying it elsewhere.

III. Problem Statement

For a few years, the microgrid concept, which encompasses renewable energy and distributed energy resources, has been attracting increased attention from the academia, governments, and industry in many countries. Owing to the facts that renewable energy can assist in releasing humans' dependence on fossil fuels and reducing greenhouse gas emissions, and that the DER system can enhance the flexibility and independence of local energy supply, the demand for microgrid development can only be stronger in the foreseen future because of the arousing global concerns on long-term sustainability.

With the above-mentioned incentives and other advantages brought by renewable energy and DER technologies, the microgrid topic has drawn a wide range of research from all over the world and has been studied from economic, energy-saving, and environmental points of view. Some studies reviewed the history and current status of microgrid and DER development, while others analyzed the performance of microgrid systems with respect to various factors, and still some others proposed mathematical models for microgrid planning. Aside from the other research in the literature, the problem to be solved in this study is addressed as follows.

3.1 Motivation of the current modeling

Taiwan is still in the early stage of introducing DER and microgrid concepts to the academia and industry, falling behind EU, US, Japan, and Canada. There is lack of green energy information, such as the accurate trade price of biomass or hydrogen, not to mention detailed DER equipment information, such as the fixed cost and operation cost of each equipment type, or the technical characteristics (e.g. efficiencies) of each type. This information gap between planners (e.g. government agencies) and equipment suppliers (e.g. domestic or oversea manufacturers) usually causes difficulties in the preparatory work of an intended project under assessment. Hence there is a need for an applicable model that would only require generic parameters and can be used as early as in the budgeting or design stage of a project before the planners would bother to obtain comprehensive equipment specifications from various manufacturers.

The proposed modeling in this study enables a quick evaluation of building a microgrid in a newly developed local area or an existent district supplied by traditional centralized power system. This approach may ease the pressure of data collection with limited time and resources in the preliminary planning stages when there is inadequate equipment information. Furthermore, under the situations that customer demand and local weather data are variable and that detailed equipment and fuel price information are not easily available, uncertainties play a critical role in determining the feasibility of a microgrid proposal and the tolerance of budgeting, and therefore need to be considered in advance. It is thus necessary that the robustness measures be included in the initial planning for risk control. The current modeling attempts to handle uncertainties with the initiative of robust optimization, while still keeping other economic and environmental objectives as primary concern.

3.2 Description of the model structure

In order to simulate the real operation of a microgrid, the proposed model consists of a variety of power generation sources, namely the different DER technologies, energy storage such as batteries and heat storage, and different kinds of customer loads, including electricity, heating, and cooling demands, as well as the external connection with the national grid. The individual elements are interconnected with others to form a circulated system, such that the energy flows therein to feed demand with supply. The schematic structure of the energy supply networks is shown in Figure 5. The power generators produce electricity with different types of fuels. For example, fuel cells use hydrogen to generate electricity, internal combustion engines transform biomass or natural gas into electricity, and wind turbines convert wind power into electricity, etc. The electricity produced normally should be sent to the end-users directly for their immediate use. When the power supply is in excess of the customer demand, the extra electricity can either be sent to the storage for future usage, or be sold to the national grid to support other areas in need.

As for the heating demand of customers, it can be satisfied either with the heat generated from the CCHP technology (i.e., recovered from the waste heat of power generation), or with heat generation from direct combustion of fuels such as biomass and natural gas, through the use of traditional boilers. Similar to the case of electricity, excessive heat may be saved in the thermal storage for future arrangement. However, there is currently no such mechanism that energy can flow out of the microgrid in the form of heat.

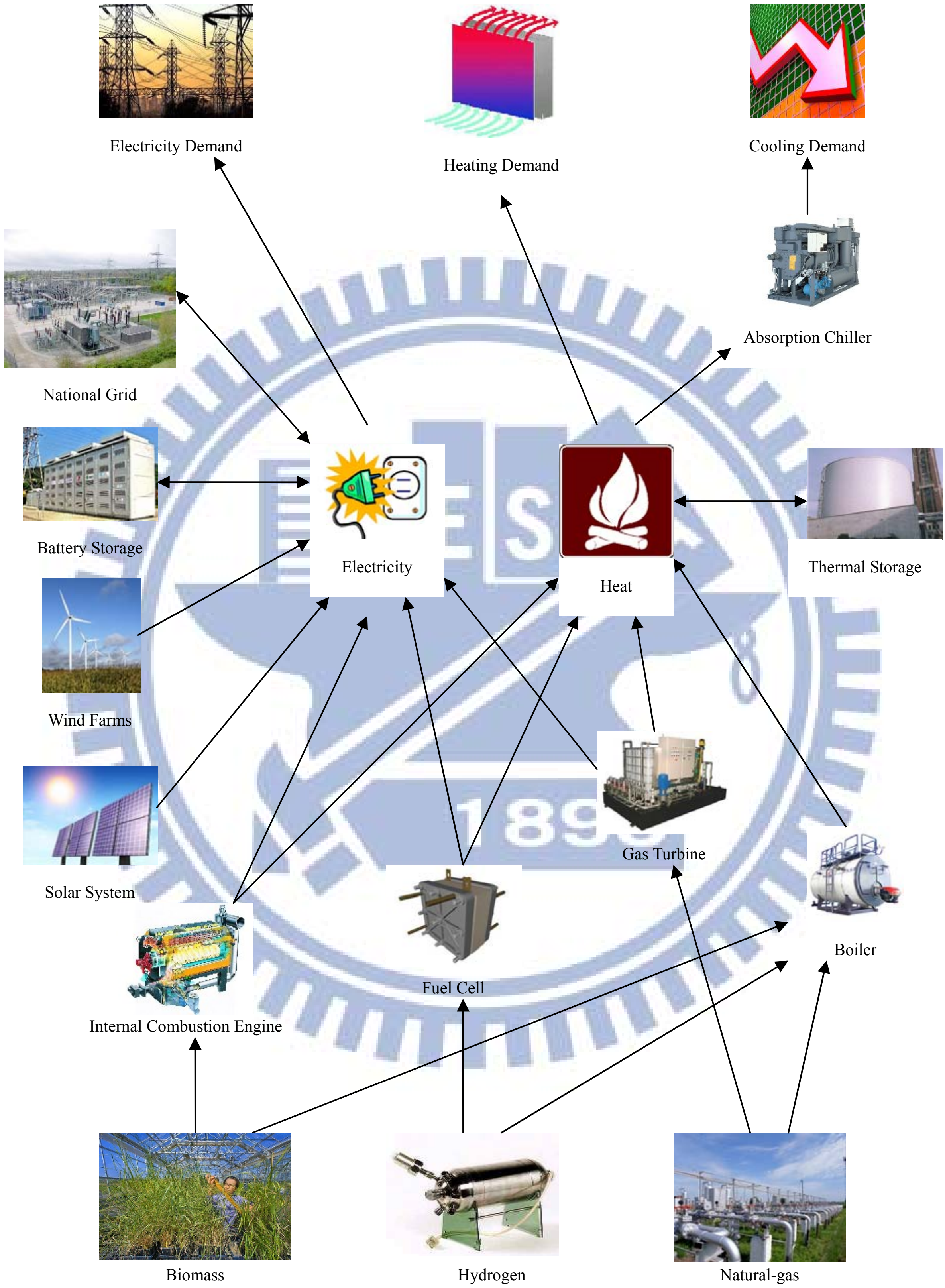


Figure 5: Conceptual networks of a typical microgrid

On the other hand, heat can also be transferred to meet local cooling demand, generally through the application of absorption chillers. In this model, the chilling process is not independently presented, but combined with the operation of some particular kinds of DER technologies, including fuel cells with heat recovery for heating and absorption cooling (HC-FC), small size gas turbines with heat recovery for heating and absorption cooling (HC-GT), and large size gas engine with heat recovery for heating and absorption cooling (HC-GE), each with the prefix HC-.

Finally, the interaction between the microgrid and the national grid is configured in the way that the microgrid operator can choose either to connect or to disconnect with the national grid. When the PCC is disconnected, the microgrid operates independently and all customer loads should be met with internal power supply. In the case that the microgrid is connected to the national grid, the deal with the centralized power supplier should be subject to some contracted conditions. The macrogrid operator may request to set up a threshold, such that a minimum percentage of the total power supply within the microgrid should be purchased from the main grid. This kind of request is generally deemed reasonable because the flexible connection option between the microgrid and the national grid inevitably lifts up the maintenance cost of the national grid, reduces power supply quality, and increases the possibility of system malfunction. When the PCC is connected, the microgrid is allowed to purchase electricity from the national grid or to sell its electricity to the national grid.

3.3 Pre-settings of the optimization model

The problem stated in this chapter is addressed and analyzed with a multi-objective optimization model, which is aiming at generating a feasible plan of the microgrid design. The model is formulated mathematically in the next chapter with different sets of parameters, variables, and equations. Before the modeling process is systematically presented, some pre-conditions regarding the model should be put forward here.

3.3.1 Basic assumptions of the model

The model is constructed based on the following basic assumptions:

1. All arrangements of the DER system and their corresponding performances in the model are evaluated from purely the economic point of view. Although the criteria

for decision making involve economic, environmental, and risk concerns, they are all reconciled to allow comparison on the same monetary scale. For instance, the environmental competitiveness of each DER technology can be assassed on the same basis of imposed carbon tax, which can be calculated from unit carbon tax rate multiplied by the carbon credit produced.

2. Uncertainties within the DER system are dealt with multiple scenarios. By assigning distinct parameters to different scenarios with probabilities based on empirical data, the model attempts to simulate the variation of parameters in the real world with the set of scenarios.
3. It is assumed that the DER units are interconnected within the microgrid and that the microgrid is connected to the national grid, such that any temporary localized shortage of power supply can be supported by energy flow from the vicinity or by purchase of electricity from the national grid.
4. The efficiency of each DER technology is assumed to be uniform, regardless of the rate of throughput and the duration of operation. The rate of recovered heat from power generation is assumed to be fixed.
5. The differentiated relationships between fixed cost and total capacity and between variable cost and power generation for each DER source are simplified as linear.

3.3.2 Possible applications of the model

The model is designed as a generic tool, which is able to be used widely in different cases and to fit in various situations with different requirements. The equations and functions in this model are universal and flexiable, such that data with different scales and magnitudes can still be input as parameters to represent different cases for analysis. In other words, the model can be applied to a variety of microgrids in different locations with different customer demands and different local climates. Moreover, a number of settings in the model, such as the number of power source options or the number of fuel types, can be adjusted as per users' needs according to the real conditions.

3.3.3 Summary of the model composition

Parameters that should be given by the planner according to realistic data:

1. Probability of different scenarios, which constitute the set of possible occurrences
2. Predicted customer demand for electricity, heating, and cooling

3. The purchasing/selling price of electricity from/to the national grid
4. Limits on the percentage of electricity purchase in total power supply from the national grid, based on the contract
5. The purchasing prices of different energy carriers, including biomass, hydrogen, and natural gas, etc.
6. The operation efficiencies and life spans of different kinds of DER technologies
7. The fixed and variable unit cost of each kind of DER equipment, with the effect of economy of scale modeled by piece-wise linear rates
8. The upper and lower limits on the total capacity of each kind of DER technology, usually based on budgeting and power source diversity concerns
9. Local weather data that would directly influence the performance of solar generation system and wind power system
10. Upper and lower limits on the total capacity of energy storage, including battery storage and thermal storage, possible transmission loss of power and heat, as well as natural loss of energy in storage
11. Carbon intensity per unit of fuel, which is related to the environmental impact of each kind of fuel for power or heat generation
12. Carbon intensity per unit of electricity purchased from the national grid

Technical variables that would be determined by the optimization:

1. Power generated from different power generation sources
2. Amount of electricity that would be purchased from or sold to the national grid
3. Amount of different fuels consumed to produce electricity and heat
4. The status of energy storage and flow
5. The optimal capacity and operation mode of each DER technology

Economic variables that would be determined by the optimization:

1. Cost of individual scenarios, given the input parameters
2. The optimum expected cost of various scenario costs with regard to probability
3. The optimum worst cost of various scenario costs

The objective of the optimization is to minimize the overall expected cost of all scenarios, while minimizing the possible worst-case (i.e., highest) cost among scenarios.

IV. Methodology

4.1 Positioning of the model

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. In most countries and regions, the development of a microgrid project is broken down into different segments, from initial design to construction. And even for design, the process can be divided into several stages with different missions and scopes. It is thus reasonable that different types of models and optimizations with different objectives should be applied to different stages of the planning process.

Ren and Gao attempted to achieve the complete optimization of a DER system from synthesis optimization to operation optimization with one single model, as mentioned in 2.1[5]. However, developing a model that can be used throughout all the stages of microgrid planning is not the goal of the current study. The position of the proposed model in this study is mainly a design optimization model between the synthesis optimization level and the operation optimization level, with partial coverage on the operation optimization. The reason of narrowing the scope of the model is to better fit in the situation that a planner may face in reality. In addition, separating the model from synthesis analysis may help avoid a great deal of uncertainties caused by the complexity of technology selection and focus on enhancing the model performance in robust optimization with controllable factors.

Despite of the exemption of synthesis optimization, the current model integrates part of the operation optimization, because sometimes the operation strategy may influence the allocation of capacities for different DER technologies. However, the objective of the downward integration is not to obtain a detailed scheduling plan of the microgrid, but to assist in making better arrangement in system design. As a result, the scale of the time horizon is chosen to be in months or in days. It is not recommended to adopt hours as the time scale in optimizing the model, as this may significantly increase the computing load of the solving process.

4.2 Mathematical formulation of the model

Due to the increasing complxity 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.

4.2.1 Nomenclature by categories

Set (Index) – expressed as subscripts

i — index of power source, 1~Q

j — alias of i

pv_i — index of solar source within i

w_i — index of wind source within i

m — index of month in a year

f — index of fuel type

t — index of storage type, including electricity and heat

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

s — index of scenario, 1~N

Parameters

p_s — probability of scenario s

Inst — interest rate

$EDchar_s$ — regulated demand charge rate of electricity in scenario s, $/kW

ECInt — carbon intensity of electricity in kg C per kWh

$CTax_s$ — carbon tax per kg of carbon credit in scenario s, $/kg C

A — a large number

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

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

G — proportion factor that is used to control the minimum power output of each source

L — the weight of expected value in the dual objective function

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

$Fprice_{fs}$ — unit fuel charge of fuel f in scenario s, $ per unit of fuel consumed

eff_{if} — efficiency of DER technology i with respect to fuel type f, %

$FCost_{is}$ — fixed capital cost of DER technology i in scenario s, $/kW

$LTime_{is}$ — prevalent life time period of technology i in scenario s, year

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

$MaxEqm_{is}$ — maximum power capacity of DER technology i in scenario s, kW

$MinEqm_{is}$ — minimum power capacity of DER technology i in scenario s, kW

$ESMax_{ts}$ — 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

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

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

$FCInt_{fs}$ — carbon intensity of fuel f in scenario s, kg C/unit of fuel

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

R_{ms} — local irradiation data in month m in scenario s, kW/m^2

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

Vc_{is} — cut in 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

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

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

Variables

$Efrom_{imus}$ — amount of electricity produced from source i for end use u 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

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

$MaxEbuyN_{ms}$ — peak electricity demand in month m in scenario s, kW

$Fuel_{fmus}$ — amount of fuel consumption for fuel f in month m for end use u in scenario s, unit depends on the fuel type

$RHeat_{imus}$ — recovered heat from DER technology i in month m for end use u in scenario s, kWh

$prodSolar_{ims}$ — 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

$EStore_{tms}$ — 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

$Efromstore_{tmus}$ — amount of energy output from storage type t in month m for end use u in scenario s, kWh

Cap_i — capacity of adopted DER source i, kW

$Allot_{ims}$ — 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

$Cost_s$ — total cost of scenario s, \$

$CInv_s$ — cost of capital investments in scenario s, \$

$CEbuyN_s$ — cost of purchasing national grid electricity in scenario s, \$

$CFuel_s$ — cost of fuel consumption in scenario s, \$

COM_s — cost of operation and maintenance in scenario s, \$

$CCtax_s$ — cost of carbon tax in scenario s, \$

CSS_s — cost of start and stop of equipment in scenario s, \$

$CSal_s$ — revenue from sales of electricity in scenario s, \$

Cw — worst case in terms of cost, \$

Expected — expected cost of scenario s, \$

Obj — value of objective function, $

Binary Variables

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

$EqStart_{ims}$ — equal to 1 when source i starts up in month m in scenario s, otherwise 0

$EqStop_{ims}$ — equal to 1 when source i stops in month m in scenario s, otherwise 0

4.2.2 Objective function

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).

$$Min\ \{Obj = L \times Expected + (1-L) \times Cw\} \tag{1}$$

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

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

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

$$Cw = \max\ \{Cost_s \mid s = 1, ..., N\} \tag{3}$$

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.

$$Cost_s = CInv_s + CEbuyN_s + CFuel_s + COM_s + CCtax_s + CSS_s - CSal_s \tag{4}$$

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. The calculation can be expressed in (5).

$$CInv_s = \sum_i Cap_i \times FCost_{is} \times \frac{Inst}{(1 - \frac{1}{(1+Inst)^{LTime_{is}}})} \tag{5}$$

The cost of buying electricity from the national grid is represented by (6). 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 (7). 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.

$$CEbuyN_s = \sum_m EDchar_s \times MaxEbuyN_{ms} + \sum_m \sum_u EbuyN_{mus} \times Eprice_{ms} \tag{6}$$

$$MaxEbuyN_{ms} = \left(\frac{\sum_u EbuyN_{mus}}{720} \right) \times C \tag{7}$$

The cost of fuel consumption can be broken down into two parts as shown in (8). 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.

$$CFuel_s = \sum_f \left[\sum_m \sum_u Fuel_{fmus} + \sum_i \left(\sum_m \frac{(\sum_u Efrom_{imus}) + ESal_{ims} + Etostore_{itms}}{eff_{if}} \right) \right] \times Fprice_{fs} \quad (8)$$

$$t \in \{elec\}$$

The cost of system operation and maintenance is constituted by the fixed cost and the variable cost of the DER equipment, as described in (9). 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.

$$COM_s = \sum_i \sum_m \left[\sum_u Efrom_{imus} + ESal_{ims} + \sum_t Etostore_{itms} \right] \cdot OMv_{is} + \sum_i \left(Cap_i \cdot OMf_{is} \right) \quad (9)$$

The cost of carbon tax, which is illustrated in (10), 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.

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

$$+ \sum_m \sum_u EbuyN_{mus} \times CTax_s \times ECInt \quad (10)$$

$$t \in \{elec\}$$

As the operation planning of microgrids is included in this model, the cost of starts and stops of different DER equipments should be taken into account. It is well known that frequent starts and stops may cause damage to equipment and increase of cost of maintenance. With only a few expections, most of the DER technologies may incur additional cost when they start up or shut down. The following equation (11) addresses this issue by assuming a linear relationship between the cost of start and stop and the frequency of start and stop for each DER technology, with a fixed unit start and stop cost given as a parameter.

$$CSS_s = \sum_i \sum_m \left[EqStart_{ims} + EqStop_{ims} \right] \times \omega_i \tag{11}$$

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.

$$CSal_s = \sum_i \sum_m ESal_{ims} \times Sprice_{is} \tag{12}$$

4.2.3 Major constraints

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

1. 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 (13). 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.

$$CLoad_{mus} \times 720 \quad \leq \quad \sum_{i} Efrom_{imus} + EbuyN_{mus} + \sum_{f} \beta_{fu} \cdot Fuel_{fmus}$$

$$+ \sum_{i} \gamma_{iu} \cdot RHeat_{imus} + \sum_{t} \delta_{tu} \cdot Efromstore_{tmus} \qquad \forall m,u,s \tag{13}$$

2. 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 (14) makes the binary variable x equal to 1 if electricity is produced from source i.

$$\sum_{u} Efrom_{imus} + ESal_{ims} + Etostore_{itms} - A \cdot x_{ims} \quad \leq \quad 0 \qquad \forall i,t \in \{elec\},m,s \tag{14}$$

The status of the power generation from different DER components for immediate customer use is further specified by the logical expression in (15), which makes the binary variable x equal to 1 if electricity is produced from power source i for end customer use u.

$$\sum_{u} Efrom_{imus} \quad \leq \quad A \cdot x_{ims} \qquad \forall i,m,s \tag{15}$$

Furthermore, the logical expression in (16) 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.

$$Allot_{ims} \quad \geq \quad x_{ims} \qquad \forall i,m,s \tag{16}$$

As mentioned before, frequent start and stop of equipment is undesired because it may shorten the life spans of most kinds of machines. Since the operation of the microgrid system is incorporated in this model, this problem can be monitored and handled by the two indicators, EqStart and EqStop. A set of logical equations regarding the start-up and shut-down status of each DER technology has been formulated as expressed in (17) ~ (20). The logical expressions in (17) and (18) link up the relationship between EqStart and binary variable x, while the equations in (19) and (20) define the action mode of EqStop.

$$x_{ims} - 0 = EqStart_{ims} \qquad \forall i, m \in \{Jan\}, s \tag{17}$$

$$x_{ims} - x_{i,m-1,s} = EqStart_{ims} \qquad \forall i, m \in \{Feb, Mar, ..., Dec\}, s \tag{18}$$

$$EqStop_{ims} = 0 \qquad \forall i, m \in \{Jan\}, s \tag{19}$$

$$x_{ims} - x_{i,m-1,s} = EqStart_{ims} - EqStop_{ims} \qquad \forall i, m \in \{Feb, Mar, ..., Dec\}, s \tag{20}$$

3. Electricity balance and contracted agreement on electricity buy-in

For the purpose of simplifying the problem, an equation of electricity balance is specified in (21). 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.

$$CLoad_{mus} \times 720 + \sum_i ESal_{ims} + \sum_i Etostore_{iums} = \sum_i Efrom_{imus} + EbuyN_{mus} + \sum_t Efromstore_{tmus}$$

$$\forall m, s \;\; if \;\; u \in \{elec\} \tag{21}$$

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 (22).

$$ESal_{ims} \;\; \geq \;\; 0 \qquad \forall i, m, s \tag{22}$$

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 (23).

$$\sum_{m}\sum_{u} EuyN_{mus} \quad \geq \quad \theta \cdot \sum_{m}\sum_{u}\left[EbuyN_{mus} + \sum_{i} Efrom_{imus} + \delta_{tu} \cdot Efromstore_{tmus} \right] \qquad (23)$$

$$\forall s, t \in \{elec\}$$

4. Operation characteristics of microgrid components
    a. General DER equipment

There is an upper limit on the total capacity of each kind of DER technology, as described in (24). 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.

$$Cap_i \quad \leq \quad MaxEqm_{is} \qquad \forall i, s \qquad (24)$$

The equation and inequality stated in (25) 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.

$$0 \quad \leq \quad \sum_{u} Efrom_{imus} + ESal_{ims} + Etostore_{itms} \quad \leq \quad Allot_{ims} \times 720 \qquad (25)$$

$$\forall t \in \{elec\}, i, m, s$$

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 (26).

$$Allot_{ims} \geq MinEqm_{is} \quad if \ x_{ims} = 1 \qquad \forall i, m, s \tag{26}$$

For a conditional constraint like (26), it is usually difficult to be coded in linear programming (LP). Therefore, the logical expression in (26) is reformulated as in (27) & (28) by applying the bigM method.

$$Allot_{ims} \leq MinEqm_{is} + MaxEqm_{is} \cdot x_{ims} \qquad \forall i, m, s \tag{27}$$

$$Allot_{ims} \geq MinEqm_{is} - MaxEqm_{is} \cdot (1 - x_{ims}) \qquad \forall i, m, s \tag{28}$$

Meanwhile, the possible range of the capacity allocation for each kind of DER power source can be expressed as shown in (29). 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.

$$0 \leq Allot_{ims} \leq Cap_i \qquad \forall i, m, s \tag{29}$$

b. Solar energy equipment

The relation stated in (30) 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.

$$\sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} \leq prodSolar_{ims} \tag{30}$$

$$\forall i \in \{pv\}, t \in \{elec\}, m, s$$

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, as illustrated in (31).

$$prodSolar_{ims} = APV_{ims} \times R_{ms} \times eff_{if} \times 720 \tag{31}$$

$$\forall f \in \{solar\}, i \in \{pv\}, m, s$$

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.

$$Allot_{ims} = APV_{ims} / D \qquad \forall i \in \{pv\}, m, s \tag{32}$$

c. 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, as indicated by (33).

$$\sum_u Efrom_{imus} + ESal_{ims} + Etostore_{itms} \leq prodWind_{ims} \quad \forall i \in \{wind\}, t \in \{elec\}, m, s \tag{33}$$

The electricity generated from wind turbines heavily depends on local wind velocity and equipment performance characterisics, as illustrated in (34) ~ (36). 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.

$$prodWind_{ims} = Allot_{ims} \times \frac{Vw_{ms} - Vc_{is}}{Vn_{is} - Vc_{is}} \times 720 \quad \forall i \in \{wind\}, Vc_{is} \leq Vw_{ms} \leq Vn_{is} \tag{34}$$

$$prodWind_{ims} = Allot_{ims} \times 720 \tag{35}$$

$$\forall i \in \{wind\}, Vn_{is} \le Vw_{ms} \le Vf_{is}$$

$$prodWind_{ims} = 0 \qquad \forall i \in \{wind\}, Vw_{ms} < Vc_{is} \cup Vw_{ms} > Vf_{is} \tag{36}$$

d. 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 coversion efficiency of each DER technology, as can be seen in (37). 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.

$$\sum_u RHeat_{imus} + Etostore_{itms} \le \alpha_i \cdot \sum_u Efrom_{imus} \qquad \forall i,t \in \{heat\}, m, s \tag{37}$$

e. 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 (38) 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.

$$EStore_{tms} = ESInl_{ts} \qquad \forall t, m \in \{Jan\}, s \tag{38}$$

The main constraint of energy balance for electricity and heat storage is stated in (39) 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).

$$EStore_{t,m+1,s} = \varepsilon_t \cdot EStore_{tms} + \sum_i Etostore_{itms} - \sum_u Efromstore_{tmus} \tag{39}$$

$\forall t, m, s$

In addition, the constraint in (40) 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.

$$ESMin_{ts} \quad \leq \quad EStore_{tms} \quad \leq \quad ESMax_{ts} \qquad (40)$$

$\forall t, m, s$

5. 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 (41) & (42), with the focuses on "on and off" status and the proportion of power supply of each power source, respectively. The equation in (41) ensure that power and heat supplies are diverse, while the equation in (42) 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.

$$B \cdot x_{ims} \leq \sum_{j=1, i \neq j}^{Q} x_{jms} \qquad \forall i, m, s \tag{41}$$

$$Efrom_{imus} \geq \frac{CLoad_{mus}}{B+G} \cdot x_{ims} \qquad \forall i, m, u, s \tag{42}$$

4.2.4 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.

V. Modeling for Taichung Industrial Park

With the goal of achieving maximum applicability, the model proposed in this study has been designed with the attempt to fit in a variety of regional environments. With the mathematical formulation presented in the previous chapter, the model should be applied to a real area for the verification of its workability.

Taiwan is an island where natural resources, especially mines and energy carriers, are scarce. Fuels for power generation in Taiwan are mostly imported from overseas. With the arousing public voice in finding cleaner alternatives in place of fossil fuels and gradually approaching the goal of non-nuclear power generation, Taiwan has become one of the suitable regions to be introduced to the microgrid concept.

In the leading stages of microgrid development, enclosed districts such as industrial parks in Taichung or Kaohsiung and isolated islands such as Penghu, where sunlight and wind resources are abundant, can be considered ideal target places to be receiving investment in microgrid projects. In an industrial district, there is continuous demand for stable electricity supply, associated with high demand for heating and cooling, which may be together resolved by diverse power generation and CCHP technology of a microgrid system. In addition, industrial clusters are always deemed pollution makers as most manufacturing activities and traditional power generation involve a great deal of toxic and greenhouse gas emissions. Adoption of microgrids can help move a substantial portion of power generation away from fossil fuels and thus reduce the pollutants.

On the contrary, in an offshore island where the majority of power demand comes from residential and tourist sectors, the high cost of distant power transmission from the main grid and the plentiful renewable energy resources (e.g. tidal and wind power) on-site contribute to the most attractive incentives for microgrid development.

In this study, the proposed model of robust optimization is applied to Taichung Industrial Park for a number of reasons. As one of the largest industrial areas in Taiwan, Taichung Industrial Park has long placed heavy energy demand on the national grid. The various types of tenants not only demand for substantial electricity, heating, and cooling services, but also produce a great amount of greenhouse gases. On the other hand, the ample sunlight irradiation and wind power in Taichung area indicate valuable resources that can be utilized in energy supply by various DER technologies. All the above are emerging incentives for the park to invest in building a microgrid system, in great efforts to ease its deep dependence on the centralized power supply system, to develop a more energy efficient industry, and to achieve a cleaner environment.

5.1 Overview of Taichung Industrial Park

Taichung Industrial Park is located in the foothills of Tatu Mountain at the cental section of Taichung City, a city which is located in west-central Taiwan. The park is bounded in the north by Taijunggang Road and bounded in the south by Nantuen Road, and is positioned to the west of National Freeway No. 1 and to the east of National Freeway No. 2, with 9 km distant from Taichung train station, 15 km from Taichung port, and 1 km from the interchange of National Freeway No.1 in Taijunggang Road or Nantuen Road. Located in the heart of Taiwan with sound infrastructure, the industrial park provides the companies therein with convenient transportation and communications to support their manufacturing and trading activities. The geographic location and traffic condition are illustrated in Figure 6.

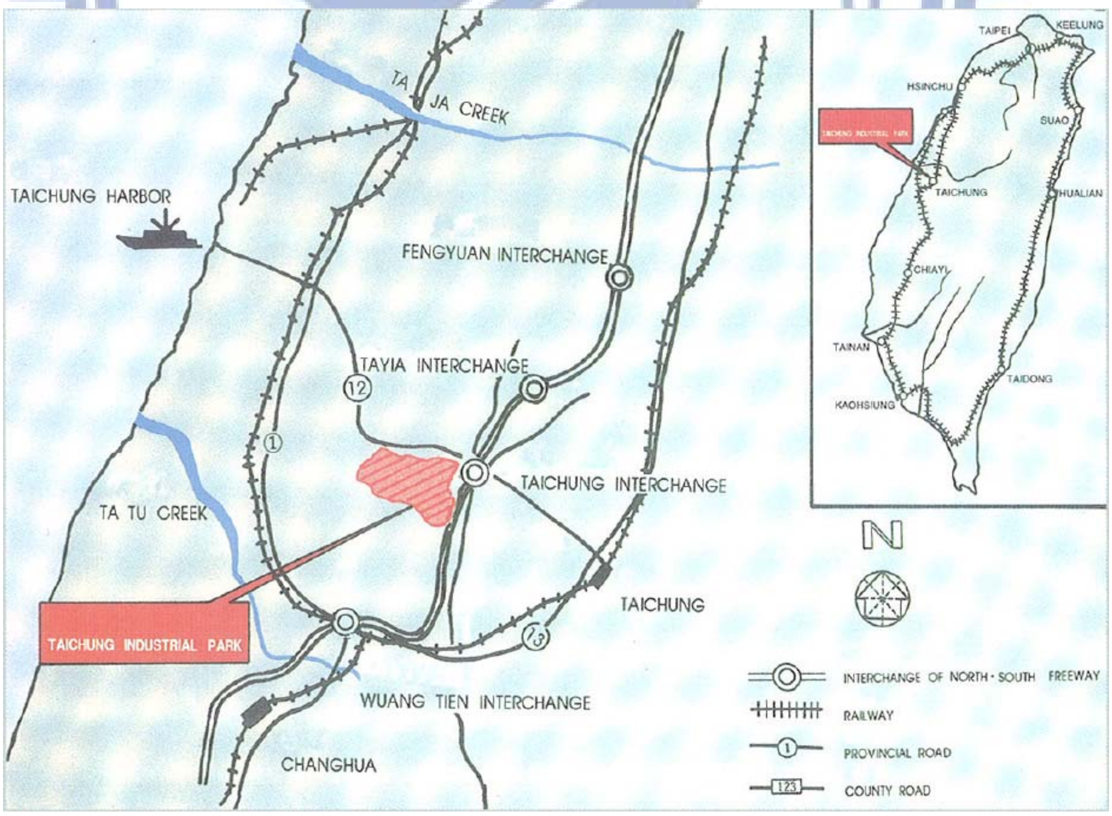


Figure 6: Geographic location of Taichung Industrial Park

Source: Taichung Industrial Park Service Center, obtained 2012[53]

For promoting the regional development of central Taiwan, the government started building Taichung Industrial Park in 1970's. The development took three stages to complete, with 168 hectares developed from 1973 to 1977, 232 hectares developed from 1977 to 1981, and 180 hectares developed from 1983 to 1987. Taichung Industrial Park is a comprehensive industrial zone with a total area of 580 hactares, which can be classified into three parts: 68 ha. for residential use, 140 ha. for public facilities, and 372 ha. for industrial use. Currently there are altogether 887 factories in operation in the industrial park, with the most (184) of them engaged in machinery, second most (99) in transportation related work, and third most in manufacturing metallic products. The statistics of distribution in lines of business can be found in Figure 7.

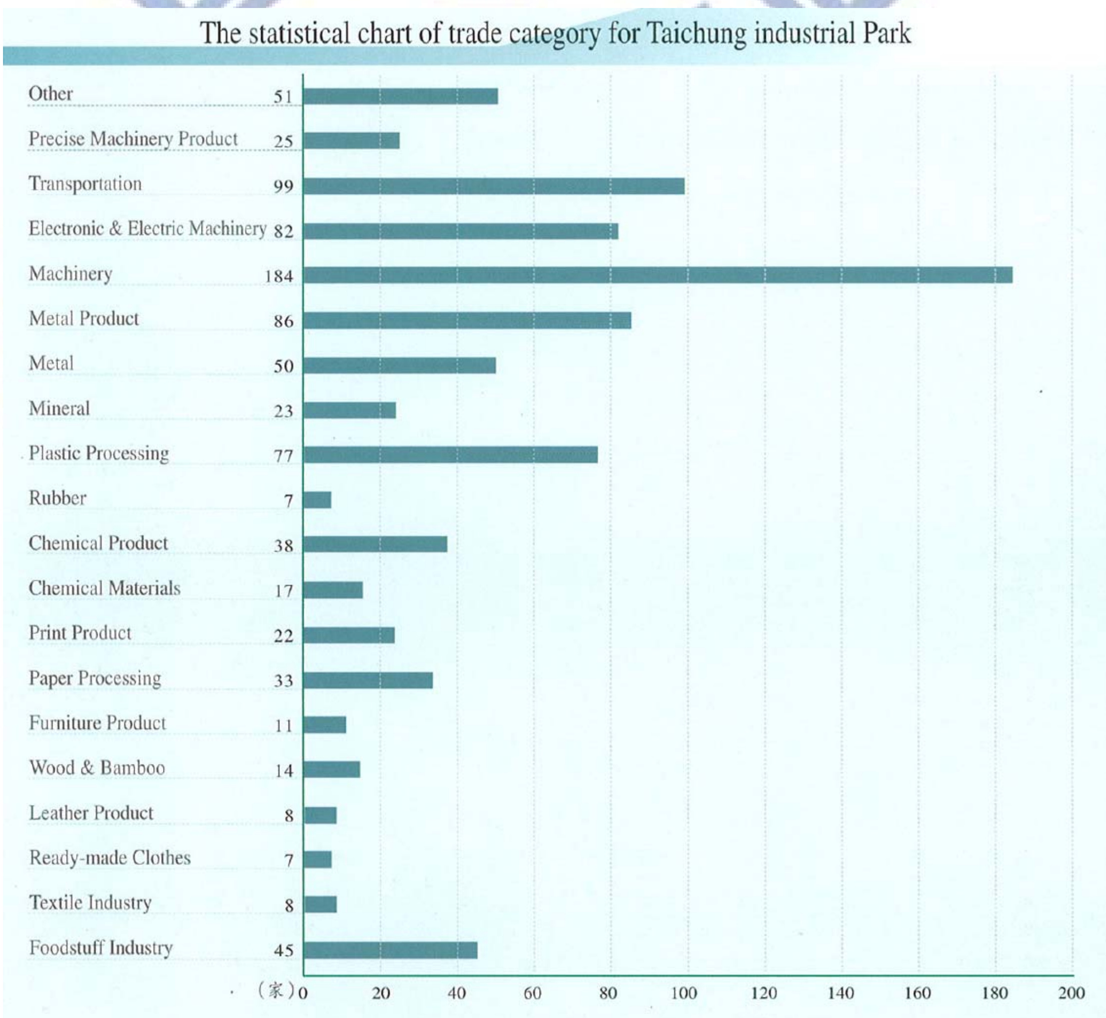


Figure 7: Statistics of lines of business in Taichung Industrial Park
Source: Taichung Industrial Park Service Center, obtained 2012[53]

As for the public facility system within the park, there are currently four sets of transformer stations, owned by Taiwan Power Company and located in four separate places, transmitting electricity from the national grid to meet the demand of all companies and the residential district inside the park. Other major infrastructure includes inner-park road networks, drainage system, water supply, and sewerage, as well as telecommunications including phone lines, broadband pipelines, and optic fiber networks, etc. So far, approximately 40,000 employees are stationed in the industrial park, and the total annual production value is estimated to be NT$ 329.9 billion.

With its broad land and existent facilities, Taichung Industrial Park has attracted a great number of companies to move in. All developmental land in the park is currently occupied. In addition to the existing conventional industries, most new companies joining the park in recent years belong to high-tech industries. It can be seen that Taichung Industrial Park is in the transition from a hub for traditional industries to a mix of diversified industries.

5.2 Planned layouts and settings of the microgrid

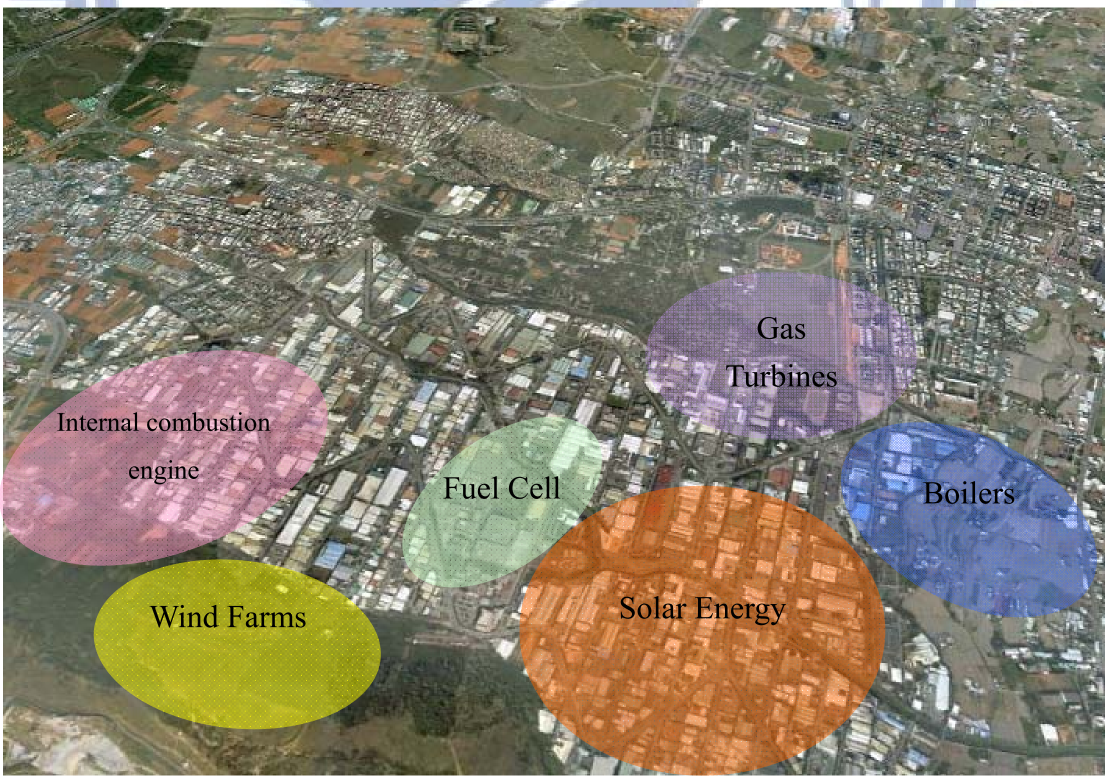


Figure 8: Proposed Layout of Microgrid for Taichung Industrial Park

Source: Kang et al. 2012[54]

Before a series of analyses can be carried out through the optimization process of the model, a hypothesized microgrid layout has been proposed for Taichung Industrial Park, along with some preliminary settings. The planning should be conducted with proper reasoning, based on the data of on-site situation. Figure 8 shows the planned layouts and settings of the microgrid in the industrial park, which was developed by Kang et al.[54]

The wind turbines are recommended to be located in the open area in the south-west of the industrial park in order to capture the wind blowing from Taiwan Strait and not to be blocked by any buildings. The photovoltaics panels are designed to be clustered in the south-east region of the park, spreading over the roofs of most buildings in this area with high density. According to the empirical local weather data, there is typically plentiful sunlight during daytime from central Taiwan to southern Taiwan. The microgrid in Taichung should be able to exploit the solar energy available.

Regarding to other green power sources, biomass-fueled internal combustion engines are proposed to be located in the western edge of the industrial park as they produce comparatively more carbon credit per unit of fuel than the other DER power sources do, and thus should be positioned farther from most of other buildings. Similarly, traditional boilers that burn biofuel, hydrogen, or natural gas to generate heat generally emit more greenhouse gases than most other equipment do, and therefore are suggested to be placed in the eastern suburbs of the park.

Fuel cells, which make use of hydrogen to produce electricity, and gas turbines/engines, which consume natural gas for power generation, basically produce less carbon credit than those fueled by biomass or fossil fuels. However, these power sources require frequent supply of the fuels and therefore need to be located in places with convenient access to external transport. It is recommended that fuel cells be placed in the central area of the industrial park and gas turbines/engines be placed in the north-eastern area, with both zones near the gate of the industrial park.

5.3 Scenario construction for robust optimization

It has been mentioned in the methodology of this study that scenarios are typically used in the model to deal with uncertainties. For modeling the microgrid designed for Taichung Industrial Park, five scenarios are constructed to account for possible variation and uncertainties of various parameters that would impact the performance of microgrid operation. In this section, all the indices and parameters needed as inputs in the optimization model will be assigned based on the real empirical data or reasonable assessment of in-situ conditions of the industrial park.

5.3.1 Model index assignment

Table 2 lists all the possible elements and arrangments that would appear as assignments of all the model indices, including DER power source types, each unit of time interval, fuel types, energy storage types, and possible end use of energy supplied, as well as the number of scenarios (five as mentioned). Altogether nine types of DER technologies are suggested to be considered in the model. Some of them can be used for electricity generation only; some others can also be used for heating (with the prefix H-), while the others can simultaneously be used for heating and cooling (with the prefix HC-), both with heat recovery through CHP or CCHP technology. Since the microgrid model of this study is proposed for use in the design stage, a thorough evaluation regarding which types of DER technologies should be included as candidates for selection (e.g. 9 types in this case) should be carried out via a synthesis analysis before using the current model.

On the other hand, while obtaining a detailed operation or scheduling plan is not among the primary goals of this optimization, "month" has been chosen as the unit of time interval. In addition, five fuel types including biomass, hydrogen, natural gas, solar energy, and wind power are included in this model for analysis. Although there is almost zero cost for solar and wind energy, they are virtually concerned as two fuel types to fit in the mathematical formulation for simulation. Besides, two kinds of energy storage, electricity and heat, are considered to be installed in the microgrid for more efficient use of excess energy. Nevertheless, energy in the form of heat can be transferred to meet the cooling demand via the operation of absorption chillers. Therefore, three kinds of customer loads including electricity, heating, and cooling can be put into consideration in this model.

Table 2: Model Indices for Taichung Industrial Park

Symbol	Assignments	Description
i	H-ICES	Small size internal combustion engines with heat recovery for heating
	H-ICEL	Large size internal combustion engines with heat recovery for heating
	FC	Fuel cells for electricity generation only
	HC-FC	Fuel cells with heat recovery for heating and absorption cooling
	HC-GT	Small size gas turbines with heat recovery for heating and absorption cooling
	HC-GE	Large size gas engine with heat recovery for heating and absorption cooling
	PV	Photovoltaics equipment (solar panels) for electricity generation only
	H-PV	Photovoltaics equipment (solar panels) with heat recovery for heating
	WT	Wind turbines for electricity generation only
pv_i	PV, H-PV	Specific index of solar sources within i
w_i	WT	Specific index of wind power source within i
m	Jan ~ Dec	Index of month in a year under the discrete time horizon of this model
f	Biomass	Consumed by H-ICES and H-ICEL
	Hydrogen	Consumed by FC and HC-FC
	Natural-gas	Consumed by HC-GT and HC-GE
	Solar	Solar energy that is used by PV and H-PV
	Wind	Wind energy that is used by WT
t	elec	Electricity storage including cells and battery
	heat	Thermal energy storage applying hot water, molten salt, ice, etc.
u	elec	Energy used in the form of electricity
	heat	Energy used for heating, such as space heating or process water heating, etc.
	cool	Energy used for cooling, such as air conditioning or water chilling, etc.

s	1 ~ 5	Five scenarios were included for model optimization analysis

5.3.2 Model parameter assignment

After all the model indices are given, the model can be further specified with the assignment of all parameters, which conforms to the real situation of the area analyzed. A comprehensive list of assigments for most parameters in the Taichung Industrial Park model is shown in Appendix 1. In this case, multiple common or different parameters are assigned to the five scenarios.

Banking interest rate (i.e. Inst) is set up based on the value typically used in the examples of most financial textbooks. The regulated demand charge rate of electricity (i.e. $EDchar_s$) is assigned with the value in scenario 1 approximity equal to the price that is currently charged by Taipower Company in Taiwan, and the values in scenario 2 to 5 kept increasing until the value equal to twice the current price. The assumption is that it is unlikely that the electricity price can remain in the current level in the long run, as well as increase to twice the current amount in the near future. It is more likely that the price of electricity will increase to a certain level but not too much based on inflation. The same reasoning applies to the unit tariff rate for electricity purchase from the national grid (i.e. $Eprice_{ms}$), with one difference that Taipower Company currently adopts a different tariff rate level for summer usage, with the electricity charge rate in summer (i.e. June to September) significantly higher than that in other months. This is due to the fact that there is typically much higher power demand in Taiwan during the summer in relation to the high utility rate of air conditioners, which in turn places additional burden to the centralized power supply system. By contrast, the selling price of electricity from various power sources to the national grid (i.e. $Sprice_{is}$), can be subject to different kinds of condition (e.g. with a uniform price regardless DER source types or different unit prices depending on government policies).

The carbon tax per unit weight of carbon credit (i.e. $CTax_s$) is set up such that the value in scenario 1 is in accordance with the rate that is currently charged, while it is expected that the rate will be gradually increased in the future (i.e. scenario 2 to 5) with humans' increasing concern on environmental sustainability. The carbon intensity of electricity supplied by the national grid is referred to an average value represented by coal firing power generation, which currently accounts for the largest portion of world power generation. By comparison, the carbon intensities of different fuel types are referred to the generic data that can be found in previous research.

Some of the capital letters are designated for use in some logical formula in this model (e.g. A), while others are designed to be used by the model users for controlling the microgrid operating conditions and performance (e.g. B, C, G). The conversion factor of area of PV panels vs. 1kW electricity capacity, D, is assigned based on the calculation from some real PV panel products. Additionally, the weight of expected cost in the dual objective function, L, which also determines the weight of worst-case cost as (1-L), should be given based on the analysts' judgement and risk consideration.

Due to the lack of trading data with regard to bulk sales of energy-carrying fuels (i.e. $Fprice_{fs}$), such as biomass and hydrogen, in Taiwan, unit fuel prices of differet fuel types are given by citing the generic data from other research. Regarding detailed equipment characteristics of all DER power sources, they are assigned to the model with referece to Table 3 (Ren and Gao, 2010)[5]. Related characteristics of different DER technologies include: average efficiency of each DER technology (i.e. eff_{if}), unit fixed capital cost of each DER technology per kW (i.e. $FCost_{is}$), prevalent or average life time period of each technology in years (i.e. $LTime_{is}$), fixed operation and maintenance unit cost of each DER technology per kW per year (i.e. OMf_{is}), and variable operation and maintenance unit cost of DER technology per kWh (i.e. OMv_{is}). The representative values assigned to these DER characteristics have been chosen with careful assessment by evaluating the relative relationships among properties of various equipment types/models. It should be noted that the DER technology information listed in Table 3 is reported based on "equipment concern", which means that different models or levels of the same kind of DER technology will have different characteristics, depending on the capacities and characteristics of different machine.

By contrast, in the model of this study, DER technologies are evaluated based on "capacity concern", which means that within the same kind of DER technology, the equipment characteristics are assumed to vary along a linear relationship in proportion to the capacity of the equipment. This measure helps reduce the problem of selecting particular machine, which must be solved with complicated integer variables, to the problem of determining the total capacity of each DER technology to be installed, which can significantly enhance the efficiency of problem solving in practice. The output of this model will render reasonable recommendation for total capacity allocation, regardless the specific machine types and the number of machine for each type. There can be a number of possible permutations and combinations for a certain amount of total capacity, the planners can further decide these specific arrangements in the next stage of detailed design, taking into account how many manufacturers they would like to invite for tendering and which kinds/ models of certain DER equipment should be considered, as well as how many sets of each kind of equipment should be installed.

However, in order to prevent the current model from oversimplified, a piece-wise linear relationship is adopted to simulate the effect of economy of scale. It is usually the case that when the capacity of certain equipment increases, the cost of the machine increases along a quadratical or non-linear curve. In this model, different sections of cost-capacity relationships are defined, each section with a linear relationship of a differet slope, to approximate the non-linear cost-capacity relationship.

Although the piece-wise linear relationships can be used to allocate the total capacity of each DER technology through optimization, there should be an upper limit of total power capacity for each DER technology in reality, depending on the budgeting or power generation diversity concern of the planners or government policies. This issue is addressed in this model with the parameter – maximum power capacity of each DER technology (i.e. $MaxEqm_{is}$). There is also a lower limit of total power capacity for each DER technology (i.e. $MinEqm_{is}$), because for any certain technology there should be an equipment model/type with minimum possible power capacity in practice.

For the same reason as above, the maximum energy storage level (i.e. $ESMax_{ts}$), as well as the minimum energy storage level (i.e. $ESMin_{ts}$), should be assigned to the model as parameters for each type of storage (i.e. electricity and heat). In the meantime, the initial energy storage level in the beginning (first) time period should also be given according to the residual level of energy storage in the pervious time period or the last time period of previous time span (e.g. December of previous year if the current analysis starts from January this year). By doing so recursively, the model can be capable of planning for a time span of several years.

Furthermore, the values of cut in wind speed of wind turbines (i.e. Vc_{is}), nominal wind speed of wind turbines (i.e. Vn_{is}), and cut off wind speed of wind turbines (i.e. Vf_{is}) are specifically assigned to the wind power sources (i.e. w_i) as part of equipment properties.

Table 3: DER equipment information

Type	Capacity (kW)	Lifetime (year)	Capital cost ($/kW)	O&Mfix ($/kW/year)	O&Mvar ($/kW h)	Efficiency (%)	Heat/electricity ratio
FC	200	10	5243	0.00	0.03	36.0	0.00
H-FC	200	10	5448	0.00	0.03	36.0	1.25
HC-FC	200	10	5622	10.15	0.03	36.0	1.25
GT	1000	20	1470	0.00	0.01	21.9	0.00
H-GT	1000	20	2001	0.00	0.01	21.9	2.45
HC-GT	1000	20	2238	10.86	0.01	21.9	2.45
MT	100	10	1651	0.00	0.02	26.0	0.00
H-MT	100	10	1853	0.00	0.02	26.0	1.71
HC-MT	100	10	2111	14.95	0.02	26.0	1.71
GE	75	20	1020	0.00	0.02	29.1	0.00
	100	20	984	0.00	0.02	30.0	0.00
	300	20	828	0.00	0.01	31.0	0.00
	1000	20	754	0.00	0.01	34.0	0.00
	3000	20	744	0.00	0.01	35.0	0.00
	5000	20	728	0.00	0.01	37.0	0.00
H-GE	100	20	1319	0.00	0.01	33.3	2.05
	300	20	1215	0.00	0.01	31.0	1.85
	610	15	1745	0.00	0.01	40.8	0.84
	815	15	1571	0.00	0.01	40.8	0.81
	1000	20	990	0.00	0.01	34.0	1.36
	2383	15	1135	0.00	0.01	41.1	0.81
	3000	20	980	0.00	0.01	35.0	1.20
	5000	20	932	0.00	0.01	37.0	1.22
HC-GE	1000	20	1170	7.30	0.01	34.0	1.36
	3000	20	1087	4.58	0.01	35.0	1.20
	5000	20	1013	3.61	0.01	37.0	1.22
B-H-GE	300	20	1458	0.00	0.01	31.0	1.85
	1000	20	1187	0.00	0.01	34.0	1.35
	5000	20	1118	0.00	0.01	37.0	1.22
PV	-	30	5714	9.52	0.00	12.0	0.00

Source: Ren and Gao, 2010[5]

Some parameters regarding mechanical efficiencies of different DER technologies, as well as operation efficiencies of equipment for direct fuel consumption and energy storage, are represented by Greek letters. Appendix 2 describes the value assignments of these characters, which include: heat recovery efficiency of each DER source (i.e. α_i), Energy conversion efficiency of each fuel type for different end uses through direct fuel consumption of boilers (i.e. β_{fu}), utilization efficiency of recovered heat from each power source (i.e. γ_{iu}), utilization efficiency of stored energy from each type of storage (i.e. δ_{tu}), storage coefficient of each storage type (i.e. ε_t), and the minimum percentage of electricity purchase from the national grid (i.e. θ), as well as the unit start and stop cost of each DER source in $/time.

The efficiency in terms of heat vs electricity ratio of each DER technology (i.e. α_i) is determined by referring to the technical data listed in Table 3. The efficiency for each fuel type to be converted into the heat form to support end use in heating and cooling (i.e. β_{fu}) is derived as explained in the note of Appendix 2. It should be noted that unlike the conversion factors of fuels for DER power generation which are separated from fixed cost of equipment, the conversion factors of fuels for direct consumption have been estimated by incorporating all the fixed and variable costs associated with the process. The other data entered as assigned values are obtained with reference to other research.

Since the power sources of renewable energy, such as PV panels and wind turbines, play a significant role in the microgrid layout and their operation and performance are often subject to uncertainties of weather conditions, it is strongly recommended that the local weather data of Taichung Industrial Park be included in this model for predicting the output of power generation from the sources of solar and wind energy. It is well understood that energy from sunlight and wind changes from place to place and from time to time. In order to make a reasonable prediction on the weather conditions to be input the model, a set of one-year local weather data for Taichung area in 2011 was obtained from Central Weather Bureau of Taiwan, as shown in Appendix 3.

Local irradiation data in different months (i.e. R_{ms}) within a year, together with the energy transforming efficiencies of the solar panels, are of great importance to the prediction of PV generation output. Although the local irradiation data of previous year may not be the same as those of the current year, they can serve as valuable reference points as to making predictions for the near future. Likewise, on-site wind speeds in different months (i.e. Vw_{ms}) have direct impact on the power output of wind turbines. Obtaining the wind speed data of 2011 for Taichung may contribute to a more accurate estimate on future wind speed. With these empirical data serving as benchmark, a reasonable prediction of future weather condition can be made in the following chapter to allow evaluation of the impact of changes in weather on the model performance.

Variations in customer demand is one of the most critical factors that constitute the uncertainties faced by a microgrid. To construct the scenarios with realistic customer loads is especially important as to enhancing the accuracy of the modeling, and this is normally achieved by referring to the historical data of electricity bills of the studied area. However, real electricity load data of all tenants in Taichung Industrial Park are extremely difficult to obtain, because neither Taichung Industrial Park Service Center nor Taipower Company have the statistics regarding the total sum of monthly electricity bills of all individual organizations in the park, not to mention other detailed data of customer loads in heating and cooling services.

Nevertheless, a reasonable prediction of different kinds of customer loads in Taichung Industrial Park can still be made via a reverse way (i.e. based on the capacity of supply). It is well known that the four existing transformer stations of Taipower Company are currently supplying power with a total capacity of 146.8MW to the park. A report of factories data obtained from Taichung Industrial Park Service Center indicates that as of March 2012, the total contracted power capacity (i.e. estimated power demand) of all companies in the park amounts to 128.2MW. Together with other generic information such as the nationwide average reserve capacity rate of 20.6% as of August 18, 2011, and that in general the electricity demand in summer is roughly twice that in winter, a set of hypothesized demand schemes of Taichung Industrial Park for five scenarios can be constructed as shown in Table 4.

The five scenarios of monthly average customer loads have been arranged in the logic that scenarios with extremely large or small variations in customer demand should have lower probability of occurrence than those with moderate variations do. Scenarios with the largest demand in July would be likely to have relatively higher probability of occurrence than those with the largest demand in June or August, based on the fact that the highest average air temperature normally occurs in July. However, these principles do not necessarily apply because sometimes their influences can be mixed with those of other factors. Therefore, the overall probability of each scenario should be evaluated with careful consideration.

Regarding the heating and cooling demand of Taichung Industrial Park, it is assumed that the heating demand in winter should be higher than that in summer, while the cooling demand in summer should be higher than that in winter. Although this principle holds true for all five scenarios, the degree of variations in monthly heating and cooling demands is different for each scenario.

Table 4: 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%		

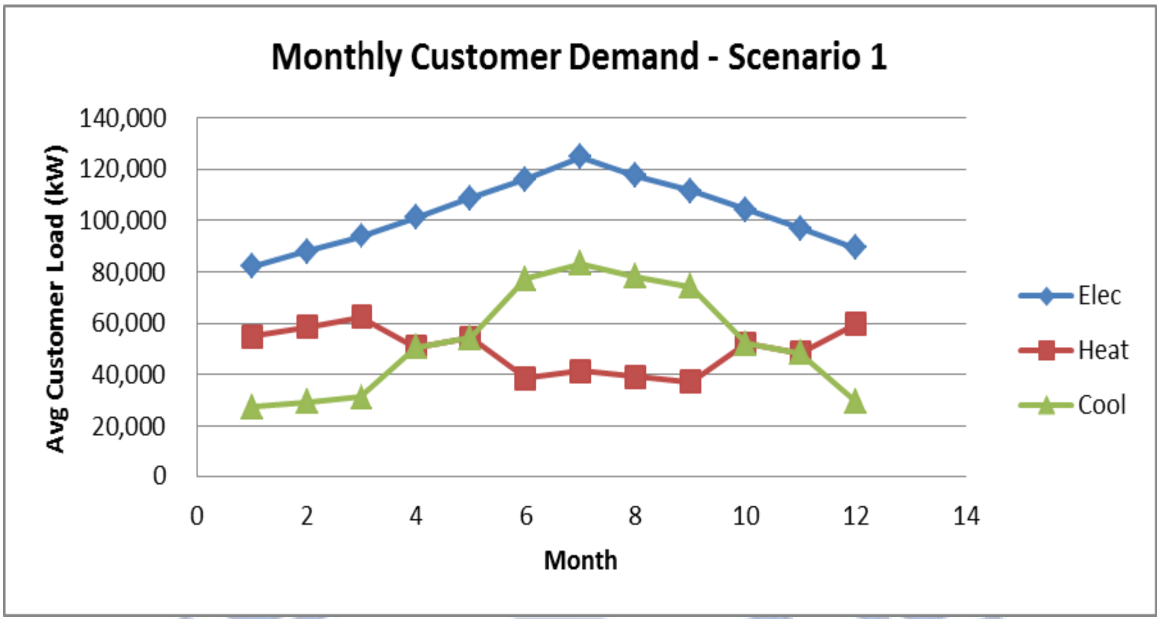
Month				Apr			May			Jun		
Item		Unit	Capacity	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Scenario 1	Avg Customer Load	kW	146,800	101,292	50,646	50,646	108,632	54,316	54,316	115,972	38,657	77,315
	Percentage		100%	69%			74%			79%		
Scenario 2	Avg Customer Load	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%		

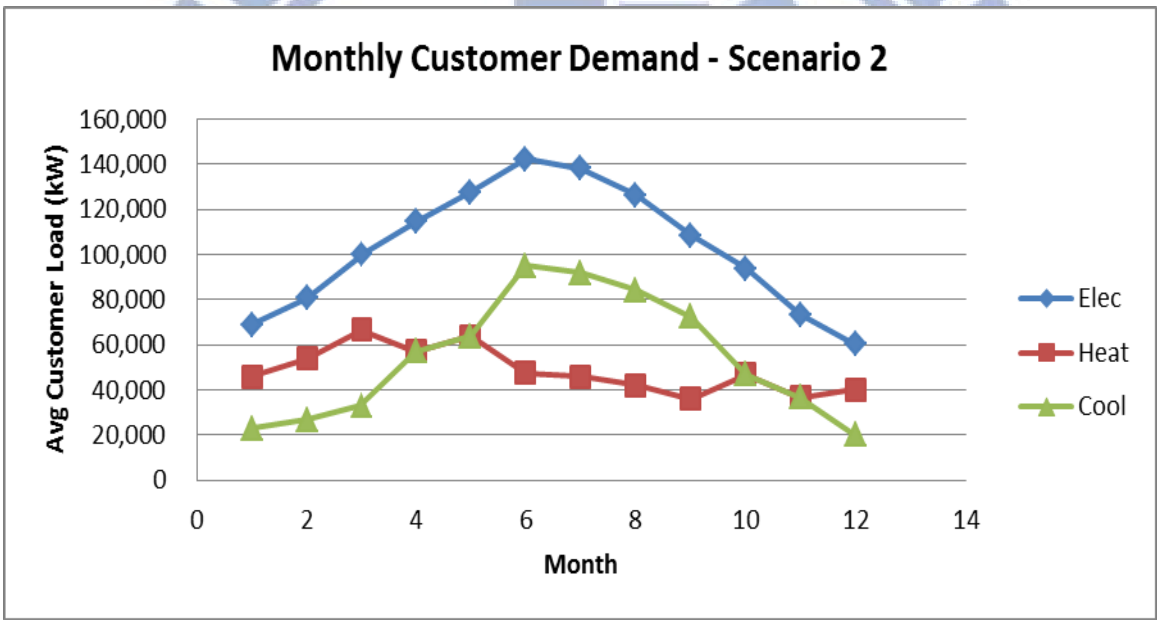
Month				Jul			Aug			Sep		
Item		Unit	Capacity	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Scenario 1	Avg Customer Load	kW	146,800	124,780	41,593	83,187	117,440	39,147	78,293	111,568	37,189	74,379
	Percentage		100%	85%			80%			76%		
Scenario 2	Avg Customer Load	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%		

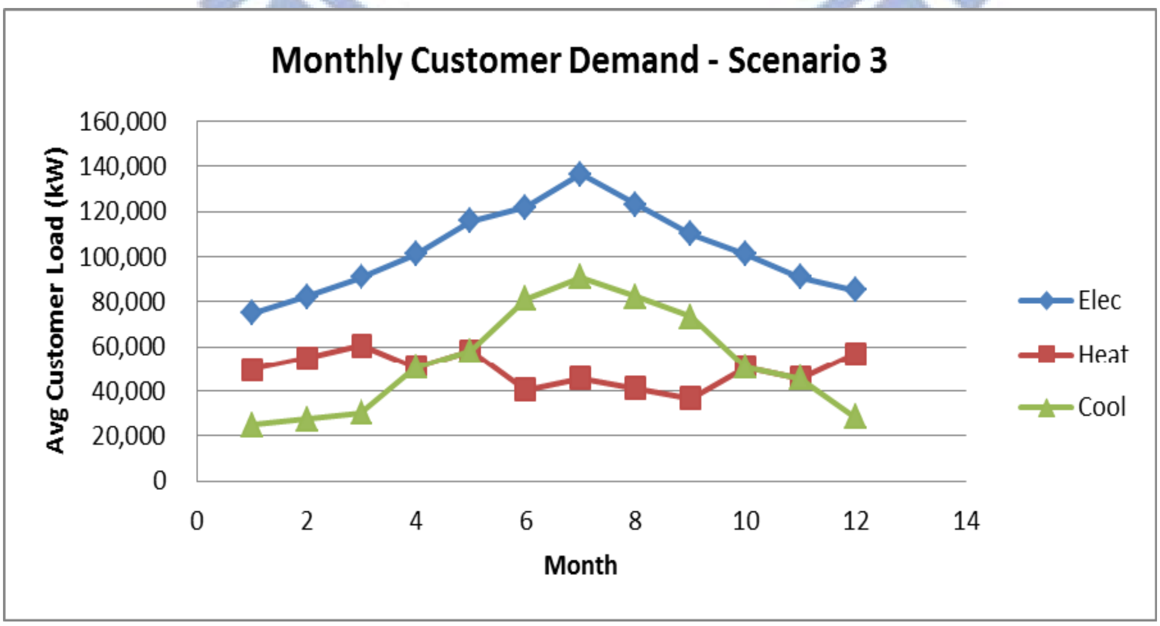
Month				Oct			Nov			Dec		
Item		Unit	Capacity	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Scenario 1	Avg Customer Load	kW	146,800	104,228	52,114	52,114	96,888	48,444	48,444	89,548	59,699	29,849
	Percentage		100%	71%			66%			61%		
Scenario 2	Avg Customer Load	kW	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%		

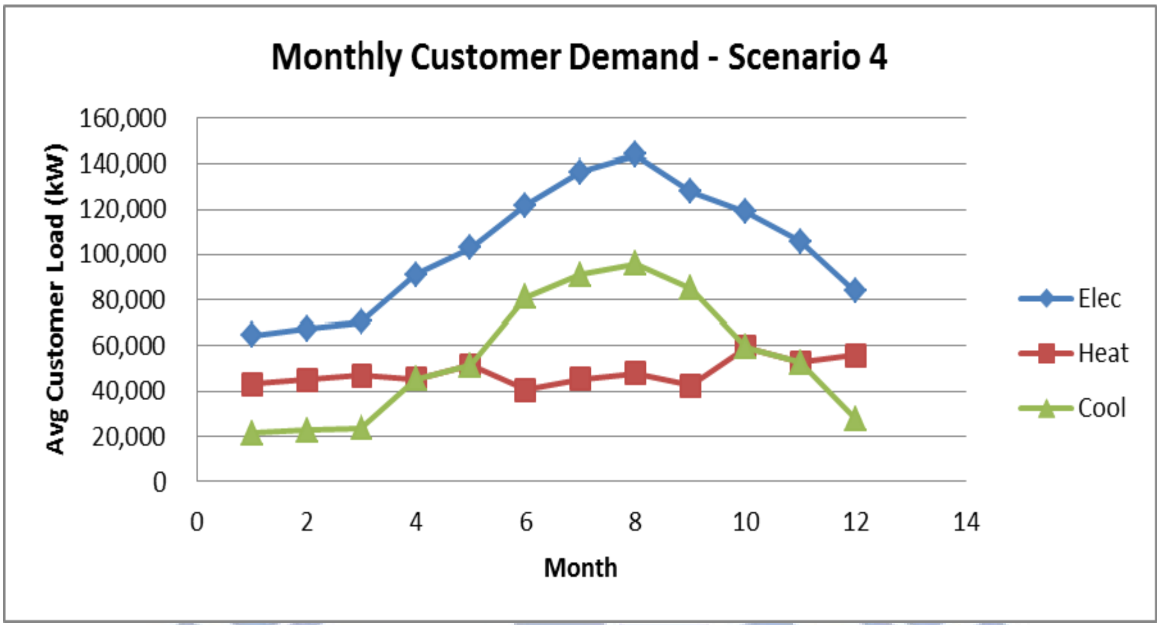
Source: The demand scheme was developed based on the data of current Taipower supply capacity and the total demand of Taichung Industrial Park as of March, 2012

According to the list of hypothesized demand schemes in Table 4, the load-time curve of each scenario can be drawn as illustrated in Figure 9. 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.


Monthly Customer Demand - Scenario 1
Avg Customer Load (kW)
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
2
4
6
8
10
12
14
Month
Elec
Heat
Cool


Monthly Customer Demand - Scenario 2
Avg Customer Load (kW)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
2
4
6
8
10
12
14
Month
Elec
Heat
Cool


Monthly Customer Demand - Scenario 3
Avg Customer Load (kW)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
2
4
6
8
10
12
14
Month
Elec
Heat
Cool



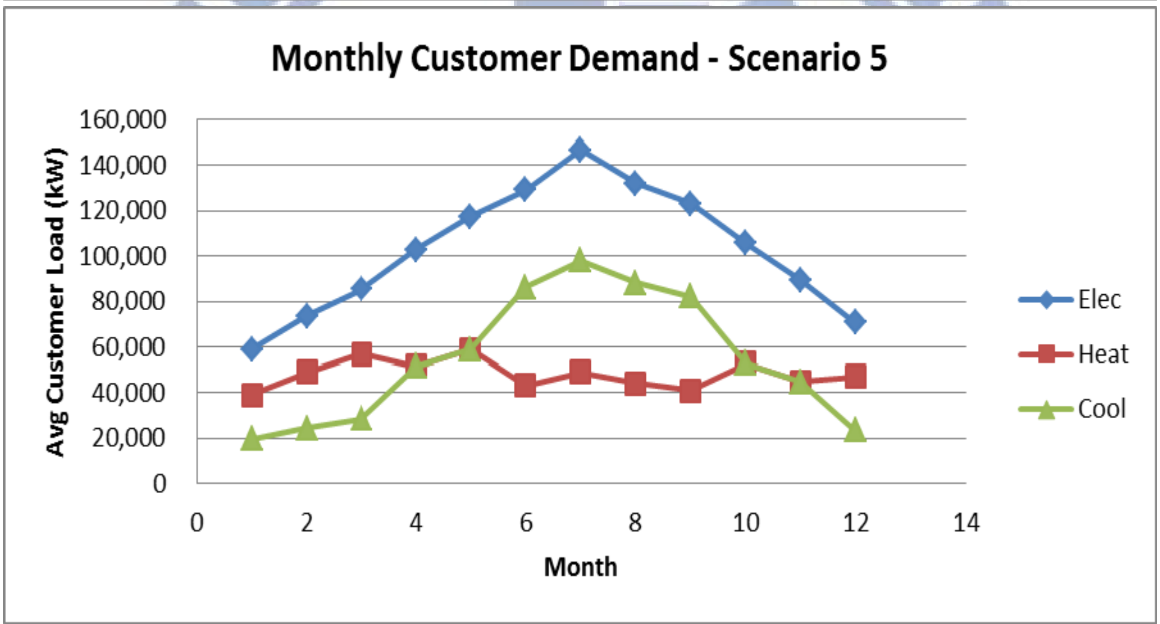


Figure 9: Monthly customer demand curves of Taichung Industrial Park for five scenarios

VI. Analysis and Results

After all the indices and parameters of the microgrid model for Taichung Industrial Park are input as specified in the previous chapter, the MILP model for robust optimization is executed in GAMS 22.4, which is a popular tool of modeling, and solved by using the algorithm of Cplex. The results of the execution are listed in this chapter and a series of analysis is carried out by sections.

6.1 Operation characteristics of the model

One of the simplest ways to check the performance of the proposed model is to observe the operation characteristics of the model from different expects. Since the microgrid model is composed of various components, such as DER power sources, customer loads, energy storage, etc., and subjected to a variety of constraints, the possible outcomes of model operation and optimization can be very complicated. There could be numerous possible arrangements in model components and constraints, and thus many kinds of analyses. It is very important that the model be tested with certain focuses while holding other conditions and factors fixed.

In this section, the microgrid model is analyzed with respect to optimization objectives – minimization of expected cost or minimization of worst-case cost, while other things are held equal (e.g. diversity constraints, probability sets are the same). Different system performance characteristics are observed while the objectives of optimization change. Moreover, to simplify the comparison among data, only the values in scenario 3, which has the highest probability of occurrence, are observed and analyzed.

6.1.1 System performance under expected cost minimization

Other things being equal as stated in 5.3.2 plus B=7 and L=1, the microgrid model for Taichung Industrial Park is optimized as to minimizing the expected cost of 5 scenarios, which are assigned with a probability set (i.e. p_s=(0.15, 0.2, 0.3, 0.25, 0.1) for s=1 to 5, respectively). The resulting planning of the capacity design for each DER power source is listed in Table 5, with the estimated cost of scenario 3 to be \$227,518,720 for a time span of one year. It can be found from this scheme that some DER technologies are deployed with more capacities (i.e. H-ICEL, HC-GE, H-PV, and WT) while the others are assigned less (i.e. H-ICES, FC, HC-FC, HC-GT, and PV). In general, mass power production is allocated to several main sources, which possess more competitive advantages than other sources do from the economic or environmental perspective.

In this case, the diversity constraints require that when one source is operating, at least seven other sources should be operating, unless the power demand of that time period is totally met by electricity purchase from the main grid or energy outflow from the storage. As a result, the least competitive source, fuel cells (FC), is excluded from this plan with zero capacity. The other sources, though picked up by the program, are assigned with different capacities in order to achieve the minimized expected cost.

Table 5: Expected cost minimization – DER sources capacity design (Unit: 10 kW)

DER Source	H-ICES	H-ICEL	FC	HC-FC	HC-GT	HC-GE	PV	H-PV	WT
Capacity	300	2,000	0	294	944	2,000	294	6,000	6,000
Resulting total cost of scenario 3: $227,518,720									

It should be noted that unlike the national grid, microgrids are expected to comprise several distributed major sources, rather than one centralized super-large source, although these major sources are significantly larger than the other distributed sources within the same grid. Cost minimization is generally achieved by economy of scale, but other objectives, such as power supply stability, transmission loss, and environmental impacts, also have to be considered in the microgrid design. Separating the total capacity into several portions helps in reducing the risk of main grid failure or low utility rate of huge capacity.

Under the microgrid design for expected cost minimization, a resulting scheme of grid operation, in terms of electricity flow rate, can be generated by the program. Appendix 4 lists the outcome of the simulated operation for scenario 3 as an example. The total power generated is divided into three parts: immediate usage of electricity, heating, and cooling service (i.e. Efrom), sales to the national grid (i.e. ESal), and inflow to the battery. The electricity flow can be specifically traced to the nine individual power generation sources, and also can be monitored downwards in terms of which kind of customer end use to support and which kind of energy storage to flow in. The schematic distribution of power generation and usage in scenario 3 is shown in Figure 10.

It can be seen from Figure 10 that more power is generated in summer (from May to September in this case) than in other seasons, which basically conforms to the trend in customer demand as shown in Figure 9. Regarding the distribution of power generation, Photovoltaics equipment with heat recovery for heating (H-PV), wind turbines, and large size gas engines with heat recovery (HC-GE) take larger proportions than other sources do. This may not intuitively reflect the current market penetration of solar and wind power equipment. In fact, applications of solar panels and wind turbines to power supply have not gained such popularity in the real world due to a lot of reasons. These sources of renewable energy, though seen to be promising, are currently facing a lot of uncertainties and difficulties. For example, the amount of sunlight in many places is in most time uncertain, deelply affected by the local weather condition; wind power is intermittent and wind direction / speed changes every few seconds. All of these uncertainties impose challenges on enhancing the overall efficiency of solar and wind equipment and impede the revolutionary replacement of the current fuel-firing power generation approaches with solar and wind sources.

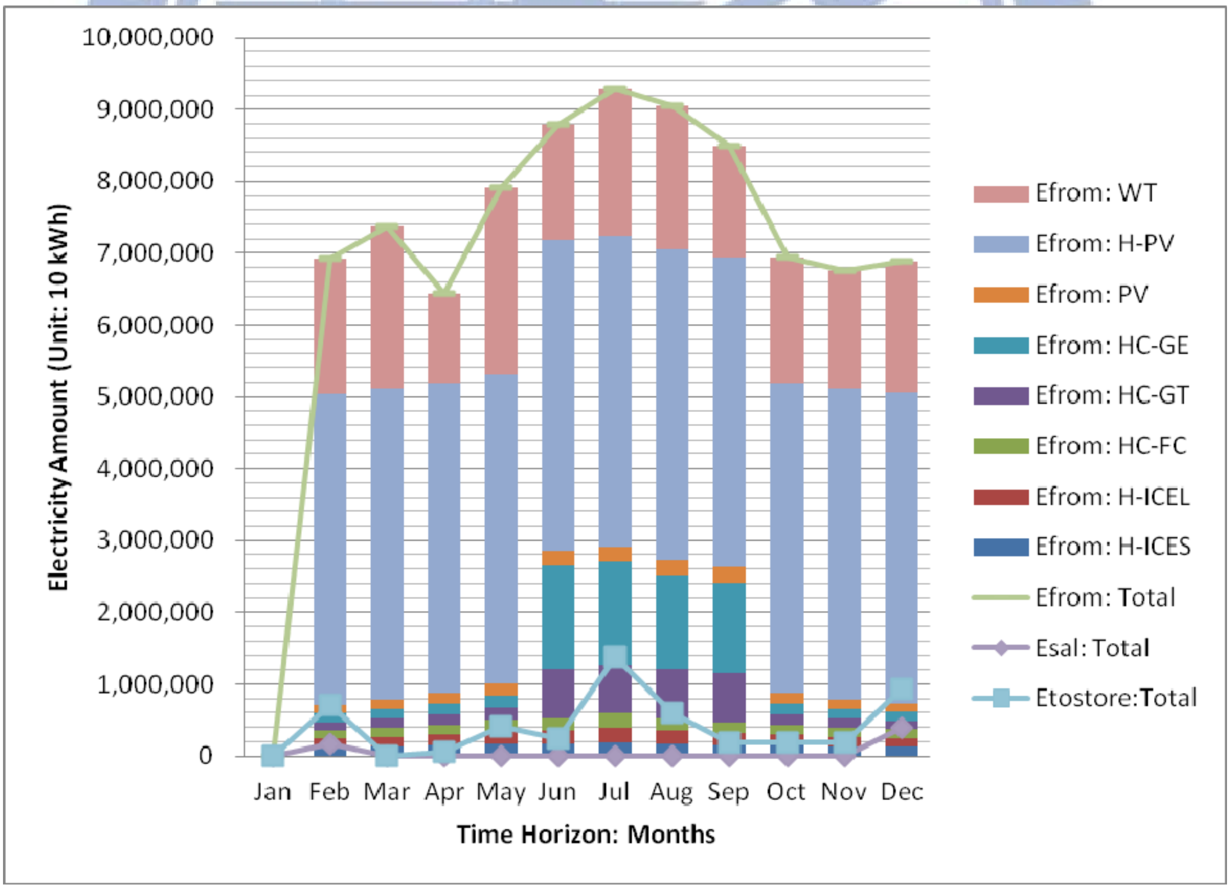


Figure 10: Distribution of power generation and usage under expected cost minimization – Microgrid for Taichung Industrial Park

On the other hand, installation of large-scale (area) PV panels and wind turbines needs a lot of space and even achieving a high coverage of solar panel installation on the roofs is technically and practically not easy, especially in Taiwan. These land issues and current technical obstacles for developing solar and wind energy equipment may together induce a great amount of additional cost to the promotion of renewable energy, which may not be completely covered by the model parameters. However, with their nearly zero variable cost (as assumed in the current model), solar and wind technologies are supposed to be counted as two of the most promising sources in the future.

Another critical part of DER technologies is the application of trigeneration (CHP and CCHP). The more waste heat associated with power generation recovered, the higher efficiency of the grid operation and the lower cost on direct fuel consumption can be achieved. Appendix 5 shows the sources of recovered heat and the corresponding output of these sources under expected cost minimization.

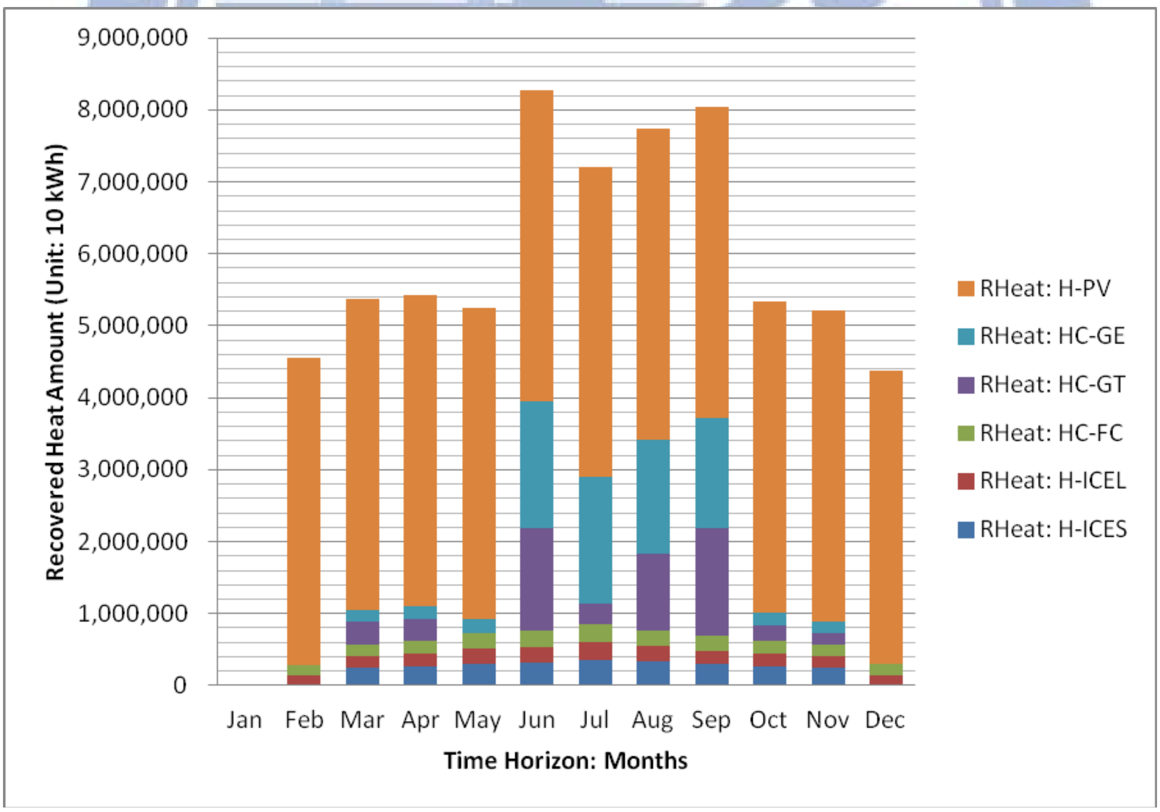


Figure 11: Distribution of recovered heat under expected cost minimization – Microgrid for Taichung Industrial Park

The amount and proportion of recovered heat from different DER sources are illustrated in Figure 11, in which H-PV, HC-GE, and HC-GT dominate over others in the sector of heat recovery.

In addition, it can be observed from Figure 8 and Figure 9 that no power generation and heat recovery occurs in the first month of the entire time span. This can be attributed to the influence of cost of start and stop (CSS) in the objective function, which would intentionally postpone the start-up of DER equipment and make the demand in the initial periods met by electricity purchase from the national grids. DER equipment units, however, once start, will normally operate continuously until the end of the entire time horizon with the least possible numbers of start and stop.

6.1.2 System performance under worst-case cost minimization

With all the conditions held equal as those in 6.1.1, the microgrid model for Taichung Industrial Park is then optimized as to minimizing the worst-case cost of the same five scenarios (i.e. the highest scenario cost). The resulting planning of the capacity design for each DER power source is listed in Table 6, with the estimated cost of scenario 3 to be $300,008,330 for a time span of one year. Although the expected cost of all five scenarios is now higher than that in expected cost minimization, the variations between individual scenario costs are significantly suppressed. And in most cases, the variations can be reduce to zero (like in the current case), which means that the five scenarios may have the same cost.

Table 6: Worst-case cost minimization – DER sources capacity design (Unit: 10 kW)

DER Source	H-ICES	H-ICEL	FC	HC-FC	HC-GT	HC-GE	PV	H-PV	WT
Capacity	300	2,000	0	294	1,781	2,000	294	6,000	6,000
Resulting total cost of scenario 3: $300,008,330									

Comparing the capacity design in Table 6 to that in Table 5, it can be found that the two sets of capacity allocation are very similar. The only difference lies on the capacity of HC-GT, which is 17,810 kW under worst-case cost minimization but only 9,440 kW under expected cost minimization. The difference in capacity of HC-GT contributes to part of the increase in the overall expected cost of the current setting, if compared with the setting in expected cost minimization. However, the increase of the overall expected cost is not only caused by the increased fixed cost in capacity enlargement, but also some other factors, for instance, the less capacity utility rate. On the contrary, the increased system capacity may be helpful in accommodating the possible sudden rise in demand once in a while. The reserved room in capacity for emergency usage may sometimes prevent the local community from suffering a huge loss caused by severe grid failure due to overload, which may also effectively lower the worst-case cost and reduce the variations among different scenario costs.

Appendix 6 shows the predicted distribution of power generation by different DER sources in the microgrid under worst-case cost minimization. Except for fuel cells (FC) which is assigned zero capacity, all the eight power sources installed are recommended to operate continiously from January to December under the demand and conditions in scenario 3. The diagrammatic distribution of power generation among different DER sources and the overall electricity usage is presented in Figure 12. It can be seen from the chart that the internal DER power generation in this scheme does not supply the microgrid with much more amount of electricity in summer than in winter, unlike the scheme shown in Figure 10.

Instead, it can be observed from Figure 12 that a great amount of power generated in summer is sent to storage and the shortage in supply is covered by electricity purchase from the main grid. This phenomenon looks abnormal but is possible to happen, as the microgrid is subjected to too much variation in demand and supply and too many uncertainties in system components. The program would simply take all the input conditions into account and determine which scheme to form, based on economic equivalent concerns. It should be noted that all non-economic factors, such as environmental impacts, are converted to be evaluated on the same monetary units with the other economic factors, as set forth as one of the assumptions in the current model.

Another feature of the DER power generation distribution, as shown in Figure 12, is that the amount of electricity generated from H-PV varies significantly from month to month. Unlike typical internal combustion engines, photovoltaic equipment allows more flexibility in accommodating the sharp changes in throughput from time to time, which makes the PV system capable of fitting in many energy-saving schemes or operation plans and become favorable in robust optimization design.

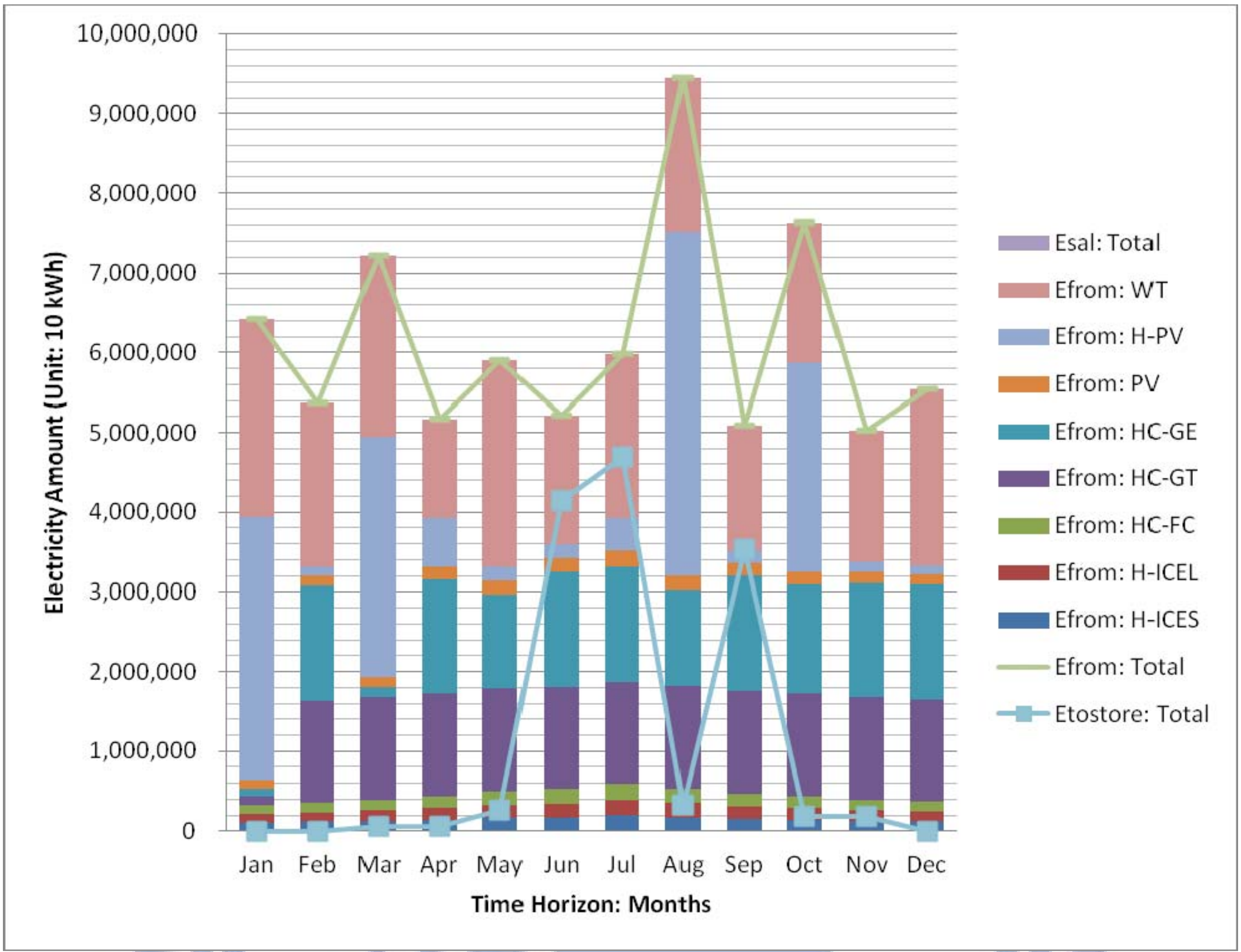


Figure 12: Distribution of power generation and usage under worst-case cost minimization – Microgrid for Taichung Industrial Park

As carried out in the previous section, the system performance of trigeneration (CHP and CCHP) under worst-case minimization is also predicted and listed in Appendix 7. The waste heat collected from power generation can be recovered to support the heating and cooling demand of local community. Some recovered heat is used for heating directly, while the other can be used for cooling through the function of absorption chillers and the rest be reused in generating electricity.

The distribution of heat recovery by different DER power sources under worst-case cost minimization in scenario 3 is illustrated in Figure 13. It can be identified that the scheme of heat recovery here differs significantly from that in Figure 11. In the current case, a large portion of electricity demand in summer is scheduled to be satisfied with power purchase from the national grid or energy outflow from the storage, rather than by DER generation. As a result, not too much heat can be recovered for other use. In addition, it can be seen that the recovered heat from H-PV is significantly less than in the case of expected cost minimization.

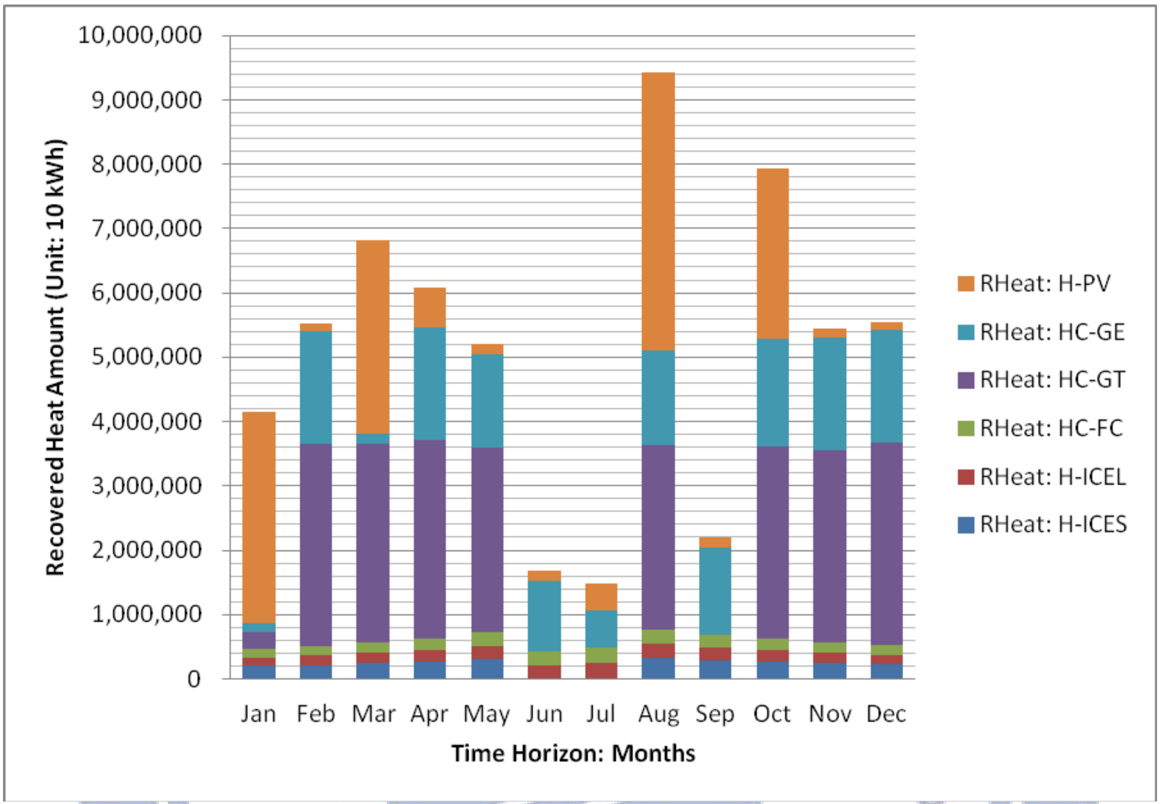


Figure 13: Distribution of recovered heat under worst-case cost minimization – Microgrid for Taichung Industrial Park

6.2 Scenario analysis of the model

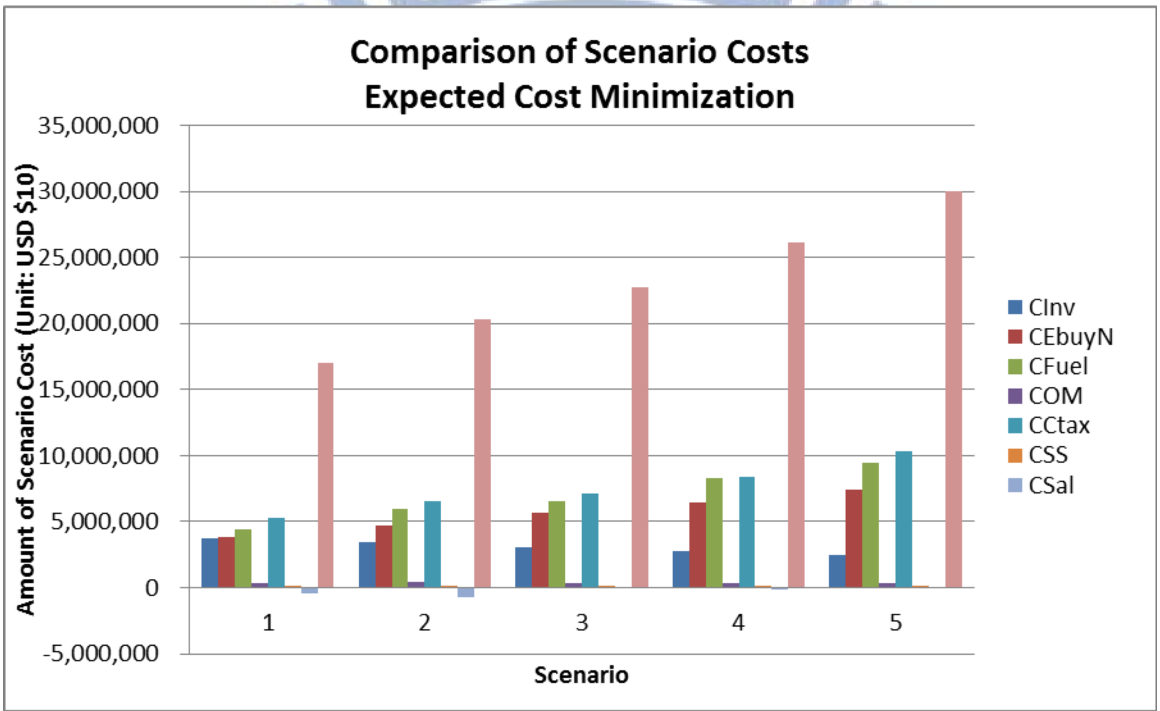
Scenarios are broadly used in robust optimization as they can be constructed in certain ways to account for different conditions that can be incurred to the model. In the current microgrid model for Taichung Industrial Park, the five scenarios have been deliberately developed as listed in Table 7. In general, it can be identified that the conditions in scenario 1 are closer to the real world situation nowadays with the most economic concerns, while the conditions in scenario 2 are more likely to happen in the future and less economically favorable. And in that order, it is defined that scenario 5 is the most environmental friendly but less economically favorable. For example, the fuel prices for biomass, hydrogen, and natural gas in scenario 1 is almost the same as the current level, while these prices are configured to be increased from 1.25 times the current level in scenario 2 to double the current level in scenario 5. The current average carbon tax rate is about \$0.043 per kg C, but this rate is supposed to be increased gradually in the future, with the arousing environmental concerns and the effect of inflation. Similar to fuel prices, it is configured that the carbon tax rate be 1.25 times the current level in scenario 2 and 2 times the current level in scenario 5. The probability set for all five scenarios has been formed in the sense that scenarios closer to the middle have the highest probability than those closer to scenario 1 or 5 do. It can be imagined that in practice, any changes in prices or tax rate should be moderate and step-by-step. It is therefore unlikely to have a sharp change in prices within short time period. It is also unlikely that all the prices and tax rates remain the same level nowadays for too long because of economic growth and inflation. The other factors that differ among scenarios include the prices of electricity purchase from the national grid and prices for building energy storage, etc. Customer demand in different scenarios has been listed in Table 4.

Table 7: List of Differences among Scenarios

Symbol	Condition	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
P(s)	Probability Set		15%	20%	30%	25%	10%
EDchar(s)	Demand Charge of Electricity	USD/kW	$10.33	$12.91	$15.50	$18.08	$20.66
CTax(s)	Carbon Tax Rate	USD/kg C	$0.043	$0.052	$0.060	$0.069	$0.086
Fprice(B,s)	Biomass Price	USD/kg	$0.2	$0.25	$0.3	$0.35	$0.4
Fprice(H,s)	Hydrogen Price	USD/MJ	$0.336	$0.42	$0.504	$0.588	$0.672
Fprice(N,s)	Natural Gas Price	USD/kg	$0.275	$0.344	$0.413	$0.481	$0.550
FCost(PV,s)	Fixed Cost of source 'PV'	USD/kW	$5,000	$4,500	$4,000	$3,500	$3,000
FCost(H-PV,s)	Fixed Cost of source 'H-PV'	USD/kW	$5,714	$5,143	$4,571	$4,000	$3,428
FCost(WT,s)	Fixed Cost of source 'WT'	USD/kW	$3,000	$2,700	$2,400	$2,100	$1,800
Eprice(R,s)	Regular Electricity Tariff Rate	USD/kWh	$0.16	$0.20	$0.24	$0.28	$0.32
Eprice(S,s)	Summer Electricity Tariff Rate	USD/kWh	$0.32	$0.40	$0.48	$0.56	$0.64
ESMax(elec,s)	Max. Power Storage Level	kWh	$2,160,000	$2,520,000	$2,880,000	$3,240,000	$3,600,000
ESMax(heat,s)	Max. Heat Storage Level	kWh	$2,160,000	$2,520,000	$2,880,000	$3,240,000	$3,600,000
ESMin(elec,s)	Min. Power Storage Level	kWh	$216,000	$252,000	$288,000	$324,000	$360,000
ESMin(heat,s)	Min. Heat Storage Level	kWh	$216,000	$252,000	$288,000	$324,000	$360,000
ESInl(elec,s)	Initial Power Storage Level	kWh	$720,000	$900,000	$1,080,000	$1,260,000	$1,440,000
ESInl(heat,s)	Initial Heat Storage Level	kWh	$720,000	$900,000	$1,080,000	$1,260,000	$1,440,000
CLoad(m,u,s)	Average Customer Load	kW	Refer to the Demand List of Taichung Industrial Park				

6.2.1 Scenario analysis under expected cost minimization

A series of scenario analysis is carried out for the five scenarios with different focuses. Figure 14 shows the comparison of individual scenario costs with their cost structures under expected cost minimization. It is obvious that scenario 5, with the nature of its configuration to be subjected to higher fuel prices, electricity prices, and carbon tax rates, basically has higher cost than other scenarios do. The scenario cost decreases from scenario 5 to scenario 1. With most of the cost components increasing from scenario 1 to scenario 5, the cost of capital investments (CInv) slightly decreases due to technology advancement in developing DER equipment utilizing renewable energy.



Scenario	1	2	3	4	5
CInv	3,695,246	3,391,976	3,088,400	2,785,130	2,481,554
CEbuyN	3,780,362	4,677,666	5,687,193	6,471,958	7,404,547
CFuel	4,363,136	5,954,313	6,579,516	8,303,393	9,490,963
COM	336,659	395,561	350,541	372,353	373,448
CCtax	5,272,055	6,572,631	7,087,450	8,365,284	10,303,624
CSS	8,400	8,400	8,400	8,400	8,400
CSal	445,009	698,872	49,628	147,838	37,476
Cost	17,010,848	20,301,675	22,751,872	26,158,678	30,025,060

Figure 14: Scenario analysis under expected cost minimization – Cost structure of each individual scenario (Unit: USD$10)

Scenario analysis is also conducted with regard to distribution of power generation, electricity sold to the national grid, and electricity sent to storage from each power source and in each month. The predicted energy flows for all five scenarios are listed in Appendix 8.

Based on the data shown in Appendix 8, the total amount of DER power generation within each scenario can be drawn by months as shown in Figure 15. It can be observed that the DER sources in scenario 1 and 2 start up from the first month, while the sources in other senarios start up from the second months. These operation arrangements are suggested by the program because the overall expected cost can be minimized under this plan.

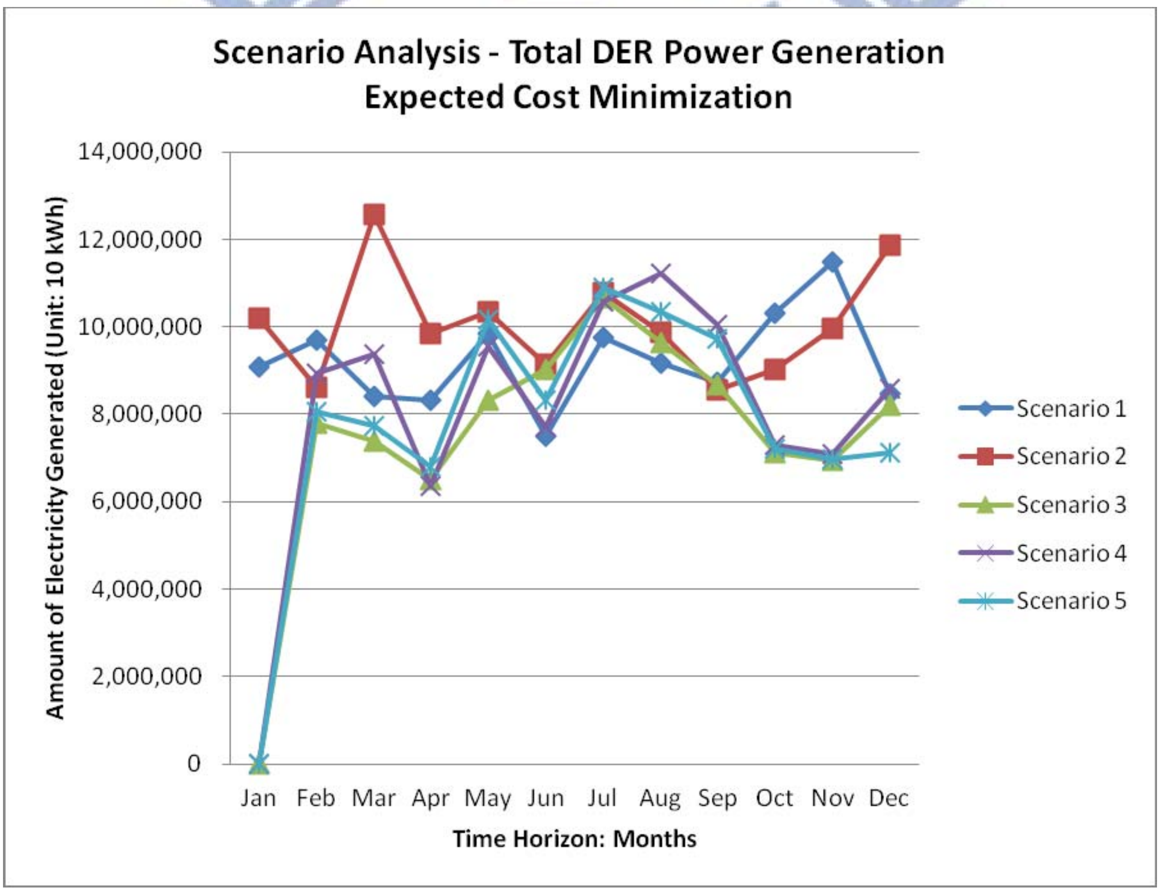


Figure 15: Scenario analysis under expected cost minimization (Taichung Industrial Park) – Comparison of total power generation by months among individual scenarios

On the other hand, the monthly distributions of DER power generation in individual scenarios do not differ much from each other. Even within one scenario, the total amount of power generation does not change substantially between summer and winter, which does not completely match with the trend in customer demand. This can be explained as the result of model optimization, which attempts to plan an operation scheme, by which the power generation can be as uniform as possible through the whole year, such that the excess energy generated in the time period of low demand can be saved for use in the period of high demand. The levelization in energy production may minimize the possibility of having low utility rate of large power generation capacity.

In addition, the composition of power generation with respect to different power sources can be seen in Figure 16, with a comparison among the five scenarios. There is no significant difference among these scenarios in terms of the amount generated and the proportion of generation taken by each source. This can be interpreted with the fact that in the current configuration of this model, renewable energy sources such as WT and H-PV have been running with the maximum capacity possible, therefore leaving no room in increasing their capacity allocation in scenario 4 or 5, where the model conditions turn to become more favorable to renewable energy.

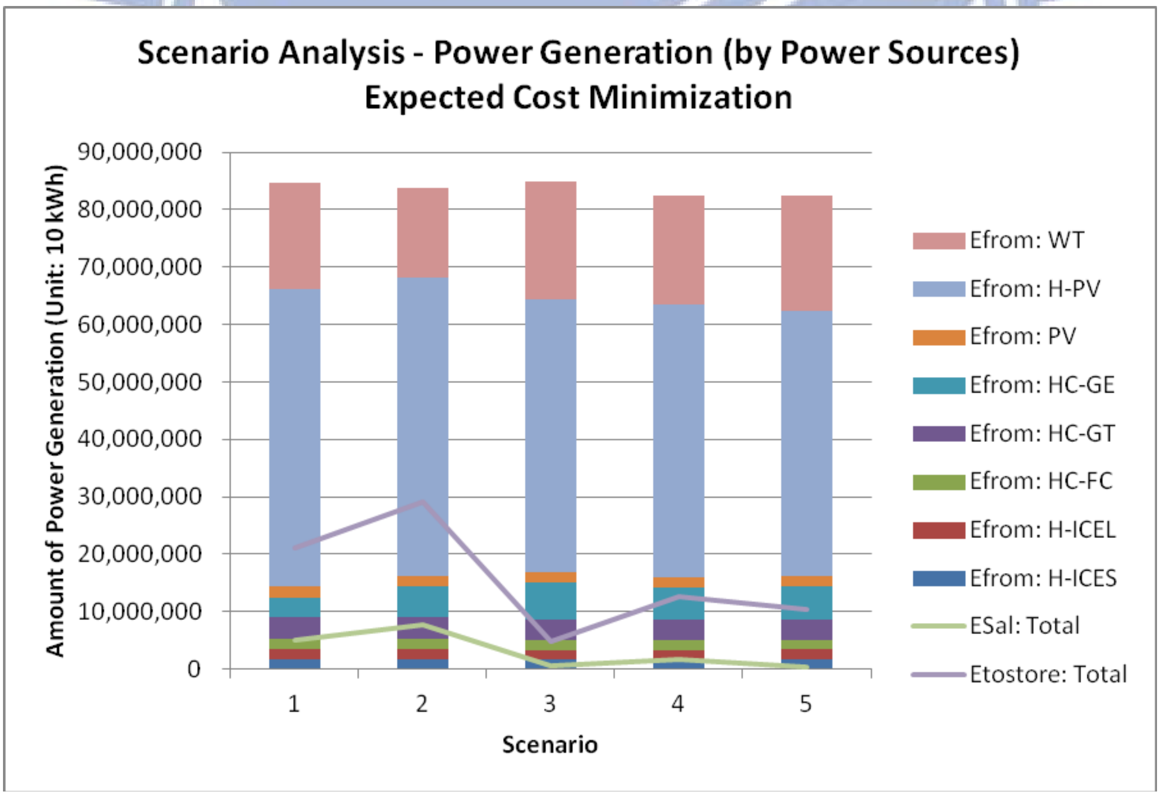


Figure 16: Scenario analysis under expected cost minimization (Taichung Industrial Park) – Comparison of power generation composition by power sources among individual scenarios

Similarly, the scenario analysis of heat recovery in this microgrid is performed under expected cost minimization, and the results are listed in Appendix 9. As mentioned before, only power sources with the prefix (H-) and (HC-) are equipped with heat recovery technology. Based on these output data, the line chart of total recovered heat vs months for five scenarios can be illustrated as shown in Figure 17, while the stacked histogram of recovered heat vs scenarios with respect to different power sources are presented in Figure 18.

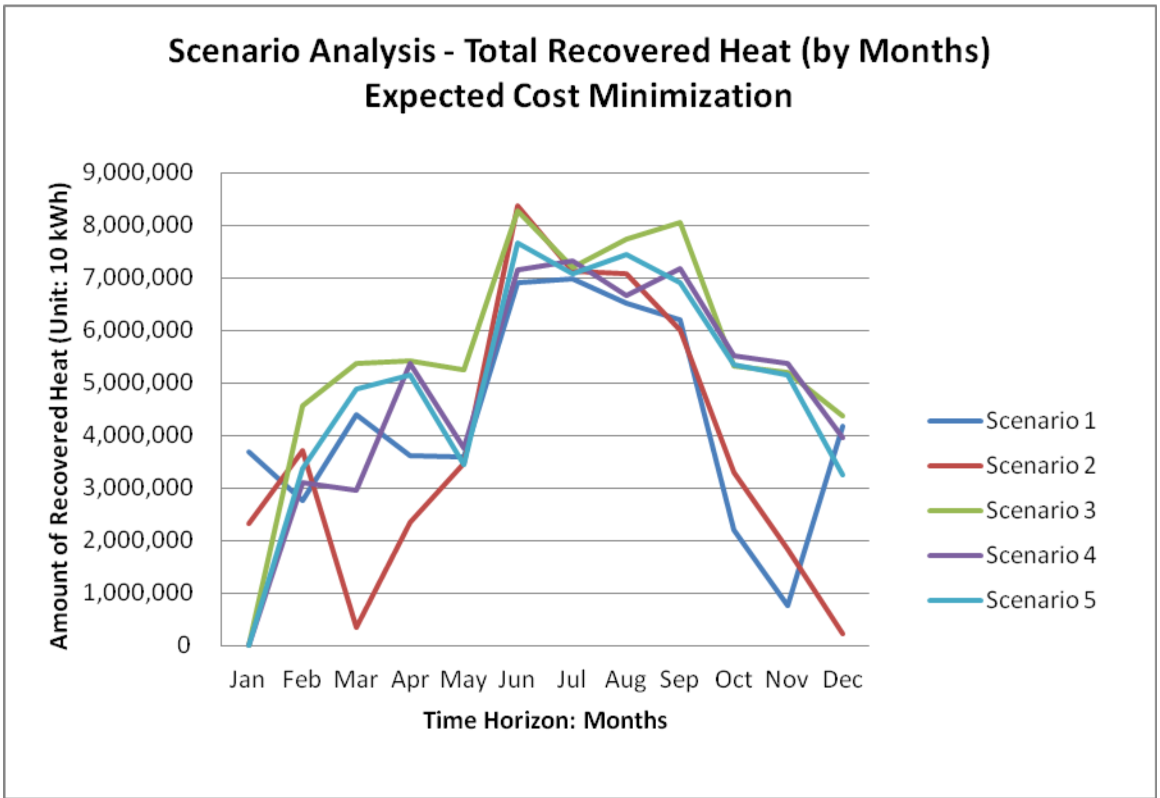


Figure 17: Scenario analysis under expected cost minimization (Taichung Industrial Park) – Comparison of total recovered heat by months among individual scenarios

Different from the distribution of total DER power generation which spreads over the entire time horizon with moderate variation, the distribution of total recovered heat by months fluctuates sharply by seasons for all five scenarios, as can be seen in Figure 17. This distritution of energy supply fits better with the overall distribution of customer demand for heating and cooling and may be explained by the feature that heat is typically more difficult to be kept in storage and subject to larger loss rate when time goes by. Therefore, it makes sense that heat recovered should be directed to meet customer immediately, rather than to storage.

Figure 18 shows that most recovered heat comes from H-PV under expected cost minimization, followed by HC-GE. Heat recovered from the other power sources appear to be immaterial. There is no significant relationship in terms of how much heat to be recovered in different scenarios. It can be inferred that the usage of recovered heat mostly depends on the objective of minimizing expected cost or variations.

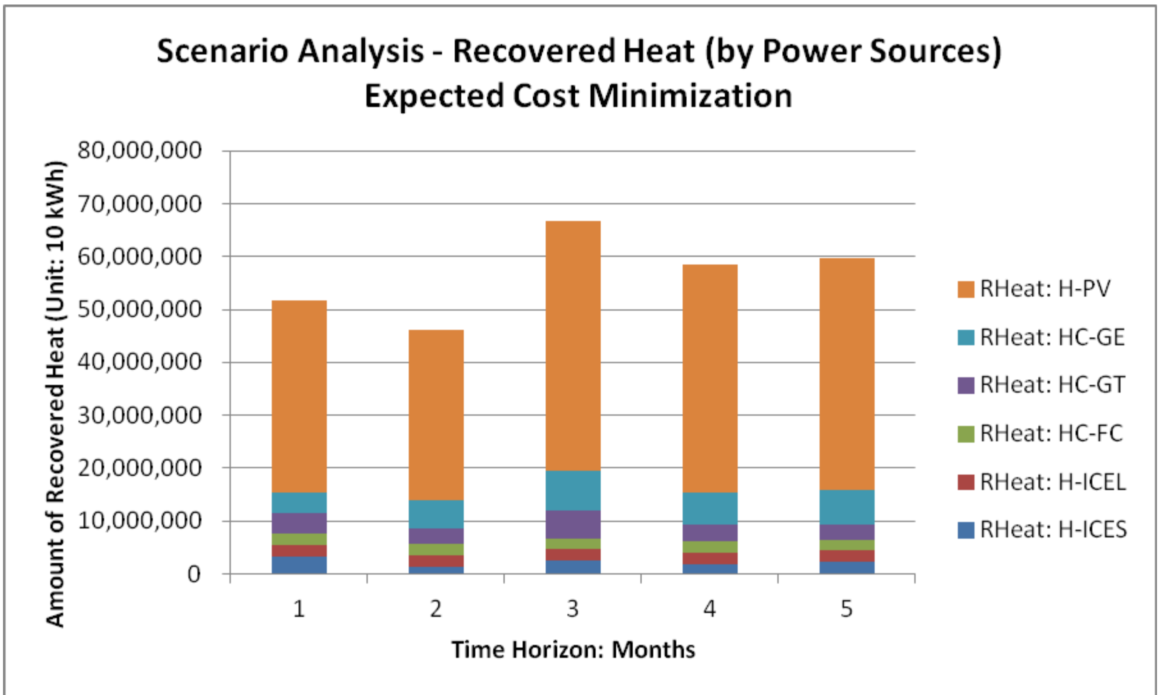


Figure 18: Scenario analysis under expected cost minimization (Taichung Industrial Park) – Comparison of recovered heat composition by power sources among individual scenarios

Customer demand for heating and cooling are typically satisfied by one of the three sources: energy conversion from electricity, application of recovered heat, and direct fuel consumption. When the energy supplied from electricity and heat recovery is not sufficient to meet local demand, direct fuel condumption must be used to provide additional heating and cooling services. The fuels that can be directly used for heating and cooling include biomass, hydrogen, and natural gas. Figure 19 describes the amount of different fuels that would be consumed by the microgrid under expected cost minimization. It can be seen from the chart that only natural gas is needed to generate additional heat for the microgrid and that scenario 3 requires much less natural gas than the other scenarios do.

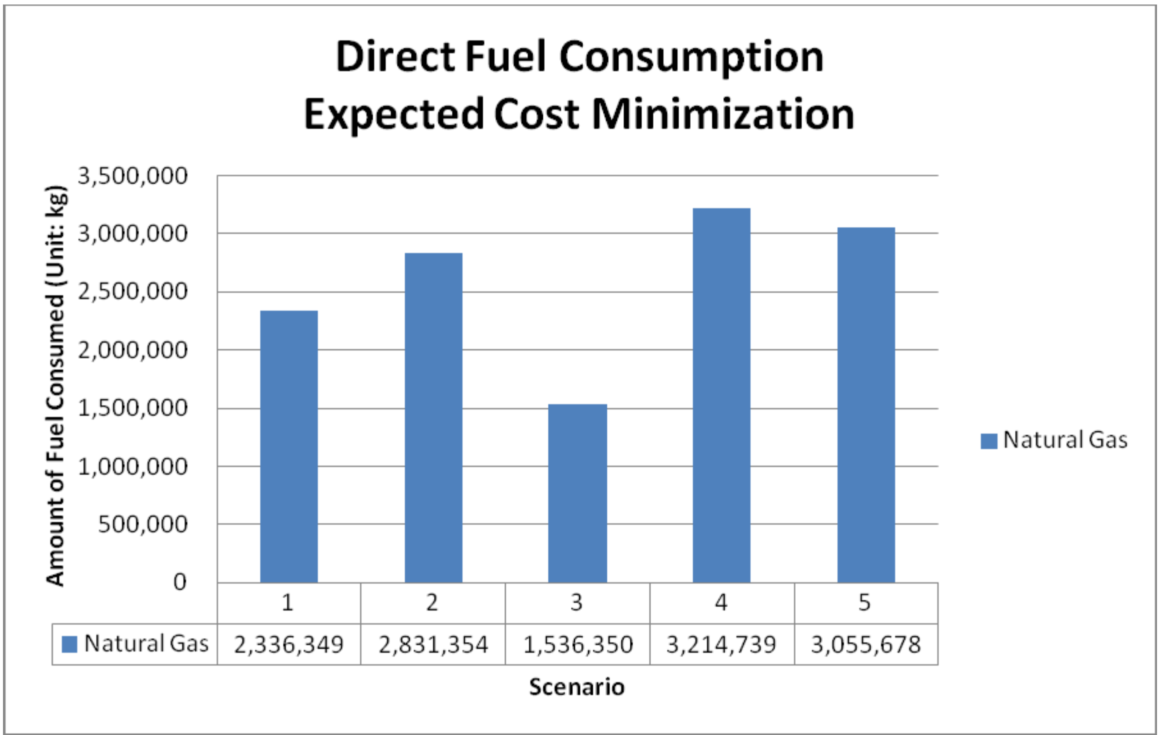
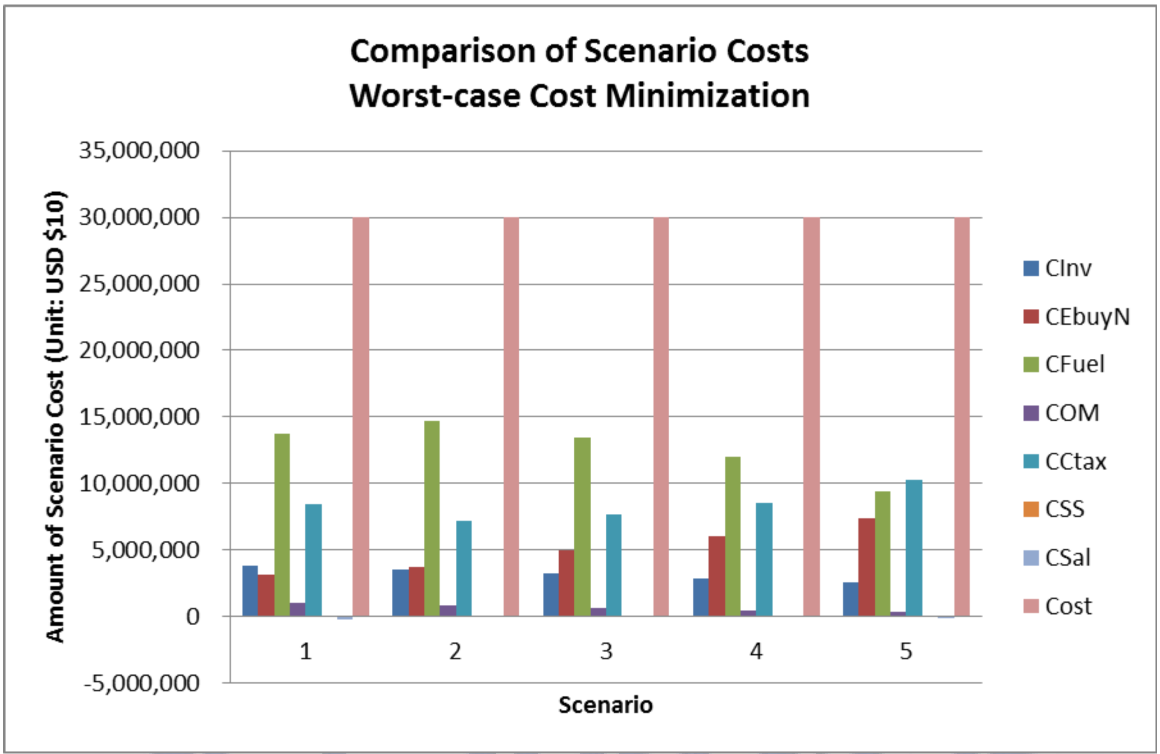


Figure 19: Scenario analysis under expected cost minimization (Taichung Industrial Park) – Comparison of total direct fuel consumption among individual scenarios

6.2.2 Scenario analysis under worst-case cost minimization

Similar steps are conducted for worst-case cost minimization as in 6.2.1. Figure 20 shows the comparison of individual scenario costs with their cost structures. Very different from the results for expected cost minimization, each of the five scenarios has the same total cost, which means that there is no variation among total scenario costs. The difference lies on the distribution of cost components within each scenario. While the cost of capital investments (CInv) slightly decreases due to technology advancement in developing DER equipment utilizing renewable energy, as is the same in expected cost minimization, cost of electricity purchase from the national grid and cost of carbon tax increase from scenario 1 to scenario 5. On the other hand, items such as cost of fuel consumption (including direct consumption and DER usage) and cost of operation and maintenance decrease because the shift of traditional power sources to new power sources such as PV and wind farms can reduce the consumption of fuels and the cost in equipment maintenance.



Scenario	1	2	3	4	5
CInv	3,821,129	3,517,859	3,214,283	2,911,013	2,607,437
CEbuyN	3,120,908	3,767,749	4,972,990	6,051,466	7,400,016
CFuel	13,761,584	14,698,551	13,502,594	11,994,906	9,406,361
COM	1,011,117	828,312	635,667	513,519	386,167
CCtax	8,465,881	7,179,963	7,666,898	8,521,528	10,264,906
CSS	8,400	8,400	8,400	8,400	8,400
CSal	188,186				72,454
Cost	30,000,833	30,000,833	30,000,833	30,000,833	30,000,833

Figure 20: Scenario analysis under worst-case cost minimization – Cost structure of each individual scenario (Unit: USD$10)

The distribution of power generation from each power source, sales of electricity to the national grid, and the storage of electricity in each month under worst-case cost minimization is listed in Appendix 10.

According to the data in Appendix 10, the distribution of toal DER power generation of five scenarios with respect to months can be depicted as shown in Figure 21. The broken-line graph in worst-case cost minimization is significantly different from that in expected cost minimization (Figure 15), with much sharper fluctuations in magnitude.

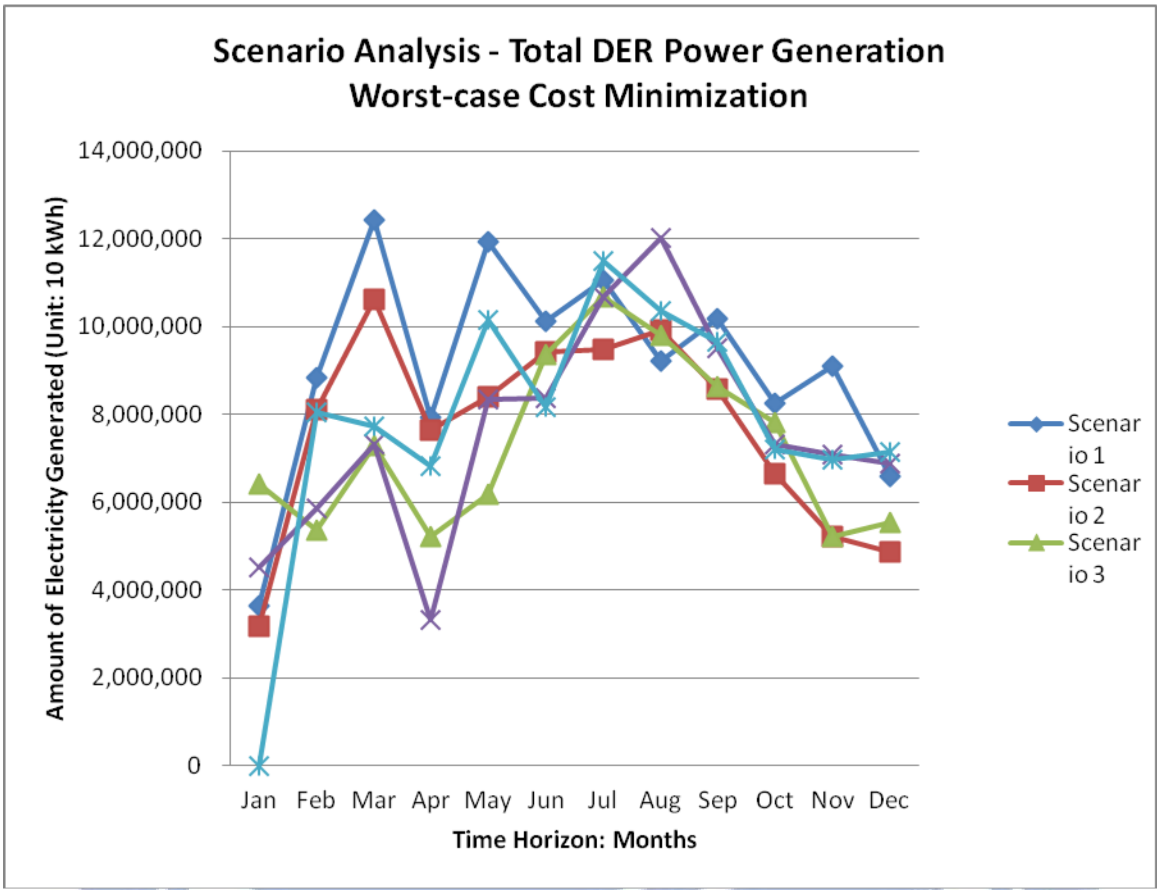


Figure 21: Scenario analysis under worst-case cost minimization (Taichung Industrial Park) – Comparison of total power generation by months among individual scenarios

In addition, there are dramatic changes among seasons, such that the amount of power generated in summer is apparently higher than that in winter. The distribution in this case indicates that the variation of power generation among scenarios in worst-case cost minimization can be larger than that in the expected cost minimization, although the variation among individual scenario costs is supposed to be minimized.

The composition of power generation can also be presented with respect to different scenarios, as shown in Figure 22. It can be found that when the scenario conditions turn out to be more environmental friendly, such as in scenario 4 and 5, the proportion of power generated by H-PV becomes larger. On the contrary, the proportions taken by HC-GT and HC-GE become less from scenario 3 to scenario 5. In general, the total amount of power generated by DER technologies increases from scenario 1 to scenario 5, with an exception happening in scenario 2.

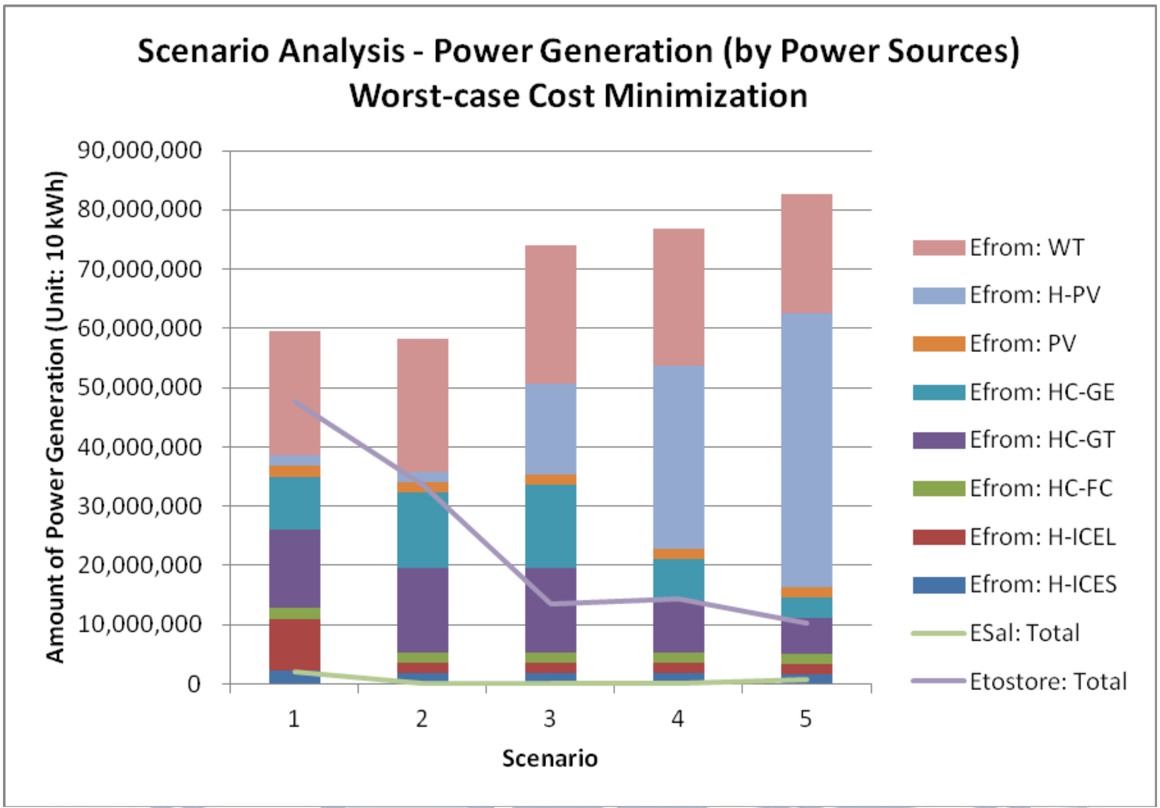


Figure 22: Scenario analysis under worst-case cost minimization (Taichung Industrial Park) – Comparison of power generation composition by power sources among individual scenarios

Next, the scenario analysis of heat recovery in this microgrid is carried out under worst-case cost minimization, and the outcomes are listed in Appendix 11. Based on these output data, the line graph of total recovered heat vs months for five scenarios can be drawn as shown in Figure 23, while the stacked histogram of recovered heat by different power sources in different scenarios are presented in Figure 24.

It can be observed from Figure 23 that the distribution of total recovered heat in the microgrid along the time horizon differs significantly among five scenarios, unlike the case in expected cost minimization. While the lines of scenario 1 and scenario 2 appear to be flatter along the whole year, the lines of scenario 3, 4, and 5 fluctuate sharply, with much more heat recovered in summer than in winter. This graph also implies that the minimization of variation among scenario costs does not necessarily result in a more uniform distribution in heat recovery.

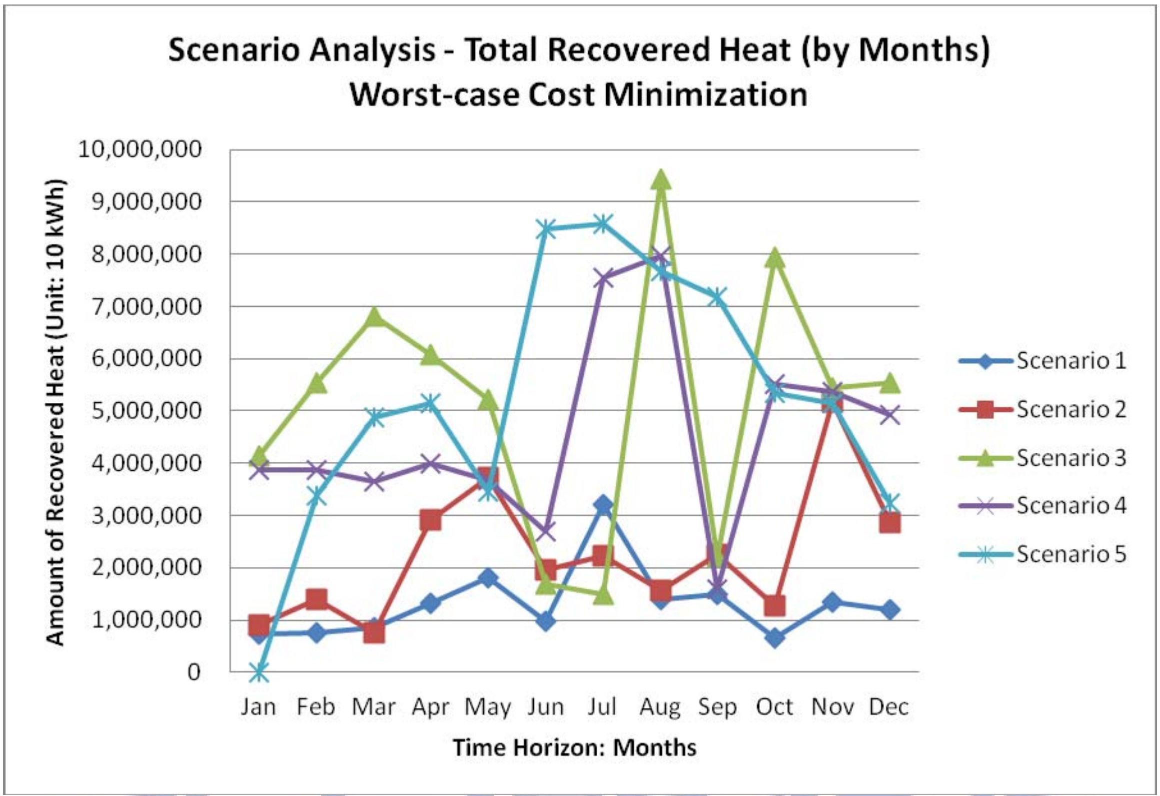


Figure 23: Scenario analysis under worst-case cost minimization (Taichung Industrial Park) – Comparison of total recovered heat by months among individual scenarios

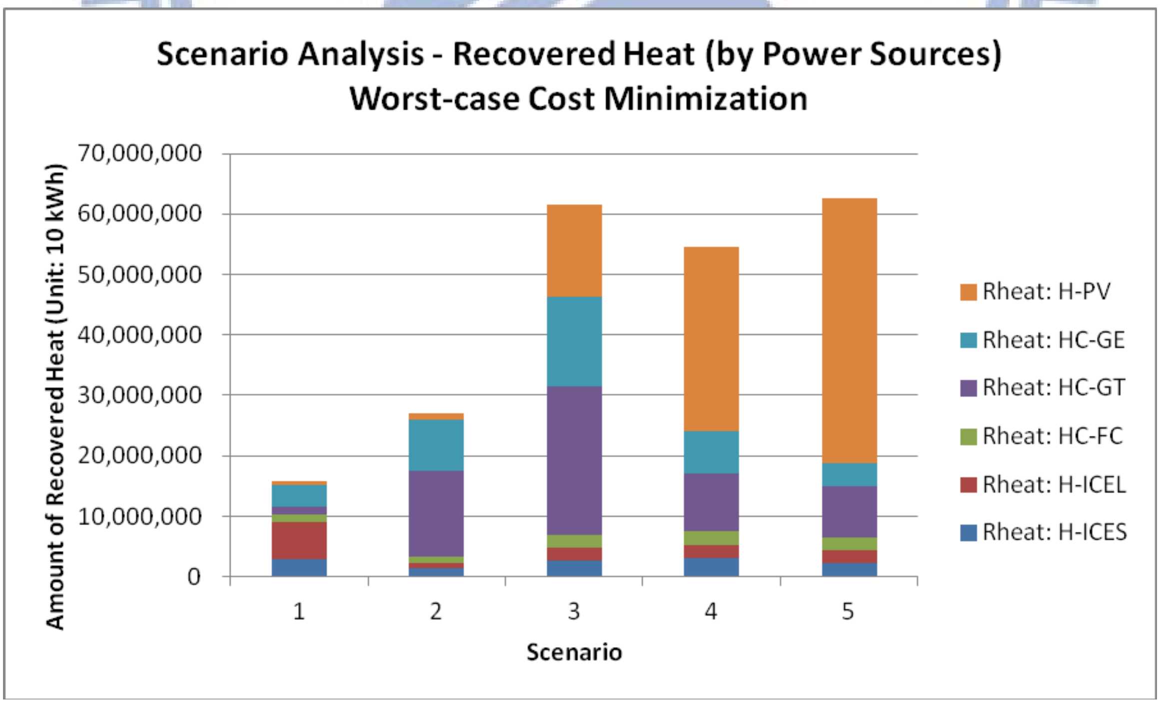
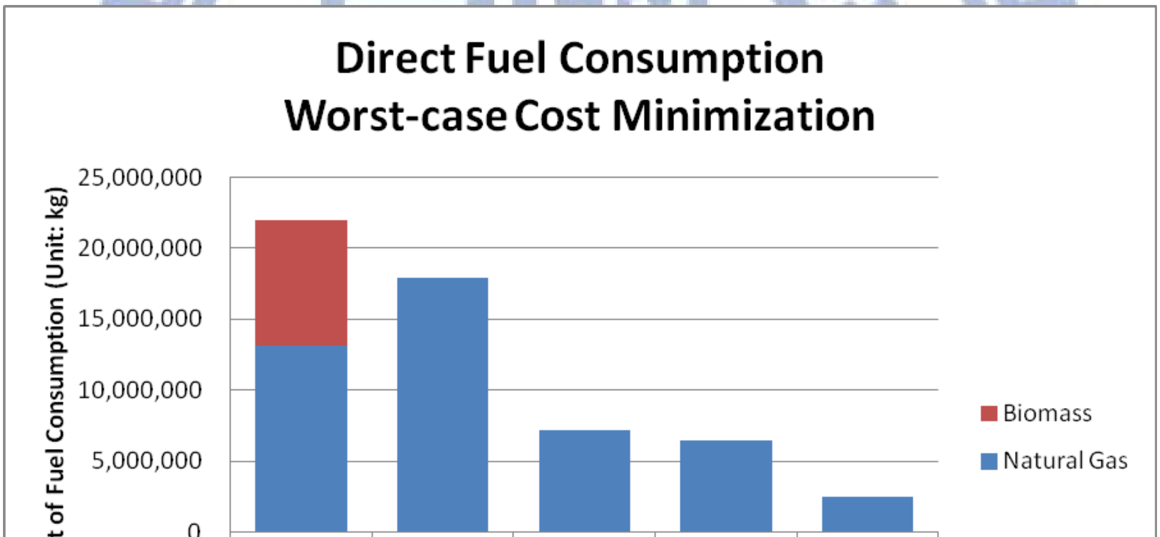


Figure 24: Scenario analysis under worst-case cost minimization (Taichung Industrial Park) – Comparison of recovered heat composition by power sources among individual scenarios

As for the composition of heat recovery from different sources as shown in Figure 24, it can be realized that more heat is recovered in scenario 3, 4, and 5 as in those environmentally friendlier conditions, CCHP technologies are used more frequently for energy-saving and green concerns. The increase of the heat recovery proportion taken by H-PV also supports this viewpoint.

Lastly, the comparison of direct fuel condumption among five scenarios is made in Figure 25 under worst-case cost minimization. It can be seen from the diagram that both biomass and natural gas are used in scenario 1 to generate additional heat for the grid, while only natural gas is needed in the other four scenarios. Moreover, the total amount of fuel consumption decreases from scenario 1 to scenario 5, which conforms to the trend that the use of recovered heat increases from scenario 1 to scenario 5, as indicated by Figure 24.



	1	2	3	4	5
Biomass	8,857,943				
Natural Gas	13,129,882	17,926,634	7,206,314	6,418,114	2,485,147

Figure 25: Scenario analysis under expected cost minimization (Taichung Industrial Park) – Comparison of total direct fuel consumption among individual scenarios

6.3 Influence of diversity constraints

In addition to scenario analysis, the microgrid model can go through another analysis, in which the influence of diversity constraints can be observed and discussed.

Diversity of DER equipment operation are considered one the most important factors in a microgrid model, because the main advantage of distributed generation lies on the simultaneous operation of a number of disperse DER units, which exploits the energy from different kinds of sources and reduce the risk of main grid failure. The influence of dirversity constraints on the microgrid design can be observed from Table 8.

Table 8: Comparison of model layouts with and without diversity constraints

Diversity Constraints: B=7									
Expected cost minimization – DER sources capacity design (Unit: 10 kW)									
DER Source	H-ICES	H-ICEL	FC	HC-FC	HC-GT	HC-GE	PV	H-PV	WT
Capacity	300	2,000	0	294	944	2,000	294	6,000	6,000
Resulting expected cost: $229,796,990; worst-case cost: $300,250,600									
Worst-case cost minimization – DER sources capacity design (Unit: 10 kW)									
DER Source	H-ICES	H-ICEL	FC	HC-FC	HC-GT	HC-GE	PV	H-PV	WT
Capacity	300	2,000	0	294	1,781	2,000	294	6,000	6,000
Resulting expected cost: $300,008,330; worst-case cost: $300,008,330									
No Diversity Constraints									
Expected cost minimization – DER sources capacity design (Unit: 10 kW)									
DER Source	H-ICES	H-ICEL	FC	HC-FC	HC-GT	HC-GE	PV	H-PV	WT
Capacity	0	0	0	0	1878	2,000	1,750	6,000	6,000
Resulting expected cost: $190,657,450; worst-case cost: $246,738,770									
Worst-case cost minimization – DER sources capacity design (Unit: 10 kW)									
DER Source	H-ICES	H-ICEL	FC	HC-FC	HC-GT	HC-GE	PV	H-PV	WT
Capacity	0	0	0	0	2,000	2,085	1,745	6,000	6,000
Resulting expected cost: $246,419,420; worst-case cost: $246,419,420									

In the case that diversity constraints B=7 applies (i.e. when one source is operating, at least seven other sources must be operating), eight out of the nine power options are chosen by the program, with a resulting expected cost of the whole system to be $229,796,990. On the other hand, when no diversity constraints exists, only five out of the nine power sources are selected with much more centralized capacity allocation, with a resulting expected cost of the whole system to be $190,657,450.

It can be realized that when a microgrid is designed with diversity constraints, the overall expected cost of the whole system would be higher than the case without diversity constraints. This can be attributed to the reduced effect of economy of scale, which is normally realized through a centralized power generation system with large capacity and high efficiency. However, sacrificing some of the economic benefits may result in higher reponsiveness of the localized power supply system in dealing with variation in demand and unexpected accidents related to the central power system.

VII. Discussion and Suggestions

In this chapter, the Pareto curve of the multi-objective optimization model will be presented as one of the important criteria in decision making as to the design of a proposed microgrid system. And then the limitation and applicability of the current model will be discussed, followed by some suggestions for future research.

7.1 Formation of the Pareto curve for the multi-objective optimization

As stated in chapter 2, a Pareto curve can be formed as the gathering of optimized solutions for a multi-objective problem. The curve can be presented on a two-dimension plane if it represents the set of optimized solutions for a two-objective problem, such as the microgrid model proposed in this study. The expected cost of multiple scenarios, together with one of the economic robust measures, the worst-case scenario cost, formulate the primary objective function of the proposed model. In the following sub-sections, various Pareto curves, each under different model conditions, will be formed as one of the decision support tools in microgrid design. The influence of different model parameters will also be discussed.

7.1.1 Pareto curve under diversity constraints

As mentioned in 6.3.1, diversity constraints play an important role in a microgrid model. In this section, the Pareto curve of the multi-objective function in the current model for Taichung Industrial Park will be formed under the effect of diversity constraints. Other conditions held equal as stated in 5.3, the model is assigned with the following setting:

Microgrid for Taichung Industrial Park
Diversity Constraints: B=7
P set = (0.15, 0.2, 0.3, 0.25, 0.1)
Upper Limit of Power Source Capacity = 6000 kW

The multiple solutions along the Pareto curve can be derived by changing the weights of the two objectives, which is denoted as L. When the L is given as the weight of expected cost, the weight of worst-case cost is automatically determined as (1-L). The program of the microgrid model is then executed by GAMS recursively by changing the value of L between 1 and 0, or vice versa. The resulting values of objective function, expected cost, worst-case cost, and individual scenario costs are listed in Table 9. Based on the data obtained from the process, the Pareto front can be drawn as shown in Figure 26.

Table 9: List of outcomes of the objective function with diversity constraints

Objective Function: $Min\,\{Obj = L \times Expected + (1-L) \times Cw\}$

Expected Cost		Worst-case Cost		Obj	Unit: USD $10				
Weight	Value	Weight	Value	Value	Cost(1)	Cost(2)	Cost(3)	Cost(4)	Cost(5)
1	22,979,699	0	30,025,060	22,979,699	17,010,848	20,301,675	22,751,872	26,158,678	30,025,060
0.9	22,979,740	0.1	30,023,464	23,684,113	17,014,472	20,303,098	22,752,370	26,155,570	30,023,464
0.8	22,979,907	0.2	30,022,697	24,388,465	17,016,215	20,303,782	22,752,889	26,154,327	30,022,697
0.7	22,980,544	0.3	30,020,486	25,092,526	17,021,238	20,306,086	22,754,390	26,151,102	30,020,486
0.6	22,980,786	0.4	30,020,074	25,796,501	17,022,190	20,306,644	22,754,699	26,150,848	30,020,074
0.5	22,990,927	0.5	30,007,957	26,499,442	17,050,757	20,326,156	22,766,810	26,148,974	30,007,957
0.4	22,996,051	0.6	30,003,526	27,200,536	17,062,654	20,334,406	22,772,352	26,150,856	30,003,526
0.3	22,996,362	0.7	30,003,375	27,901,271	17,063,341	20,334,883	22,772,673	26,150,982	30,003,375
0.2	23,001,443	0.8	30,001,882	28,601,794	17,074,115	20,342,355	22,777,708	26,153,414	30,001,882
0.1	23,006,607	0.9	30,000,833	29,301,410	17,084,429	20,349,446	22,782,621	26,156,736	30,000,833
0.01	23,006,625	0.99	30,000,833	29,930,891	17,084,553	20,349,446	22,782,621	26,156,736	30,000,833
0	30,000,833	1	30,000,833	30,000,833	30,000,833	30,000,833	30,000,833	30,000,833	30,000,833

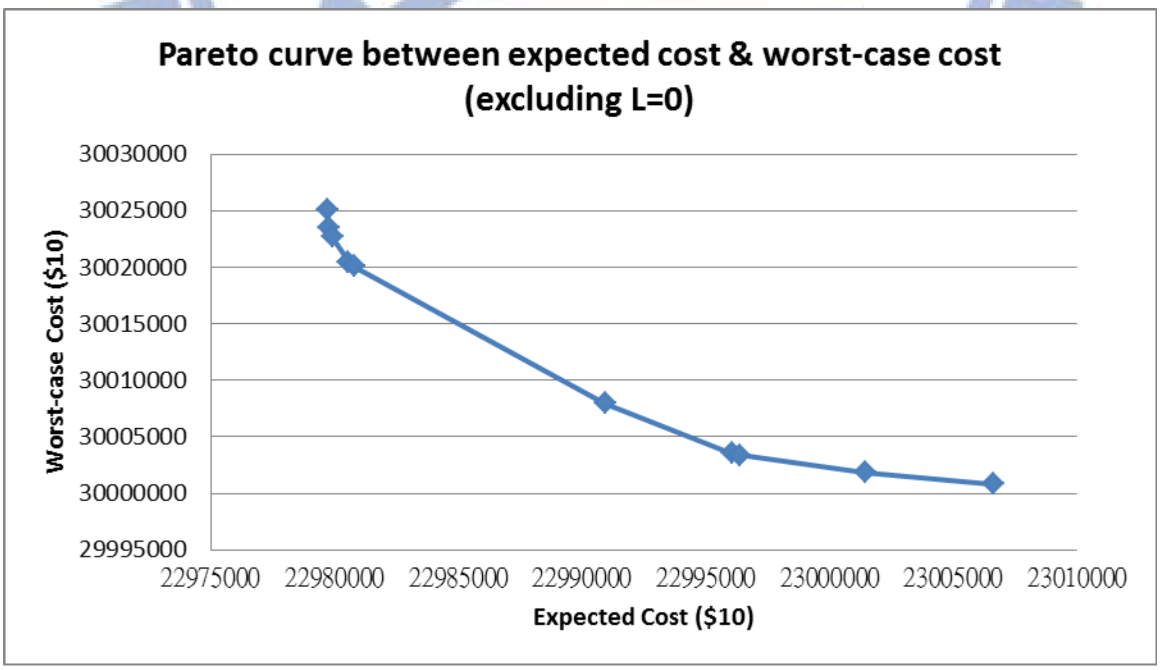


Figure 26: Pareto curve of the dual-objective function (Taichung Industrial Park Microgrid) – Diversity constraints: B=7 / Upper limit of power source capacity = 6000 kW

It can be seen from the graph that the expected cost ranges from $229,796,990 to $230,066,250, while the worst-case cost ranges from $300,250,600 to $300,008,330.

Certainly there can be unlimited number of solutions beyond (above) the Pareto front. However, it has been provn (as stated in chapter 2) that these solutions appear to be sub-optimal. Therefore, the microgrid planner or operator should be dedicated at making arrangements that can move the performance of the system to approach the Pareto curve.

Along the curve which indicates the optimized solutions, the worst-case cost can be reduced only when the expected cost to be increased. This appears to be a trade-off between expected cost minimization and worst-case cost minimization (i.e. reducing the variation among scenario costs). When microgrid planners are using the proposed model, they can make their own judgement as to what value of L should be given, depending on the budget limits, government policies, or other social-economic factors. The model is therefore suitable to be used in various conditions as all the input parameters can be assigned by the model users according to local conditions and their own concerns.

7.1.2 Pareto curve without diversity constraints

When the diversity constraints are removed from the program, there would be some changes to the resulting curve of optimized solutions. Consider the conditions below:

Microgrid for Taichung Industrial Park
No Diversity Constraints
P set = (0.15, 0.2, 0.3, 0.25, 0.1)
Upper Limit of Power Source Capacity = 6000 kW

The microgrid model is again solved repeatedly with different weights of expected cost and worst-case cost. The results of the multi-objective optimization are described in Table 10. According to these data, the Pareto curve is illustrated in Figure 27.

It can be found from Table 10 that there are several segments along the curve where the values of expected cost and worst-case cost stay unchanged (i.e. L = 0.9 ~ 0.8, 0.7~0.6, and 0.5 ~). Another point is that the value of expected cost converges to $190,708,710 as early as when L = 0.5, which means that the value of worst-case cost also converges to $246,419,420 at the same weight. In other words, the Pareto curve appears to be very insensitive to the changes of expected cost and worst-case cost in both dimensions.

Table 10: List of outcomes of the objective function – No Diversity Constraints / 6000 kW

Objective Function: $Min\ \{Obj = L \times Expected + (1-L) \times Cw\}$									
Expected Cost		Worst-case Cost		Obj	Unit: USD $10				
Weight	Value	Weight	Value	Value	Cost(1)	Cost(2)	Cost(3)	Cost(4)	Cost(5)
1	19,065,745	0	24,673,877	19,065,745	14,466,436	17,170,526	18,727,116	21,504,607	24,673,877
0.9	19,067,798	0.1	24,651,441	19,626,163	14,479,811	17,166,140	18,735,151	21,507,636	24,651,441
0.8	19,067,798	0.2	24,651,441	20,184,527	14,479,811	17,166,140	18,735,151	21,507,636	24,651,441
0.7	19,070,409	0.3	24,642,518	20,742,041	14,491,540	17,164,842	18,740,620	21,509,087	24,642,518
0.6	19,070,409	0.4	24,642,518	21,299,252	14,491,540	17,164,842	18,740,620	21,509,087	24,642,518
0.5	19,070,871	0.5	24,641,942	21,856,407	14,486,070	17,163,481	18,741,655	21,514,296	24,641,942
0.4	19,070,871	0.6	24,641,942	22,413,514	14,486,070	17,163,481	18,741,655	21,514,296	24,641,942
0.3	19,070,871	0.7	24,641,942	22,970,621	14,486,070	17,163,481	18,741,655	21,514,296	24,641,942
0.2	19,070,871	0.8	24,641,942	23,527,728	14,486,070	17,163,481	18,741,655	21,514,296	24,641,942
0.1	19,070,871	0.9	24,641,942	24,084,835	14,486,070	17,163,481	18,741,655	21,514,296	24,641,942
0	24,641,942	1	24,641,942	24,641,942	24,641,942	24,641,942	24,641,942	24,641,942	24,641,942

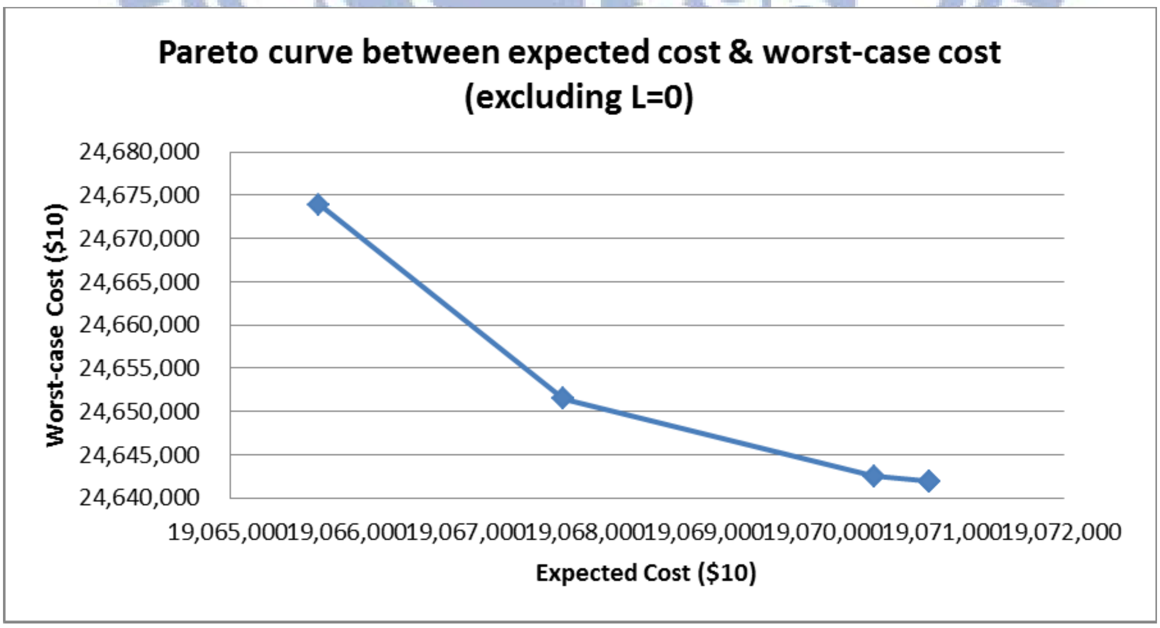


Figure 27: Pareto curve of the dual-objective function (Taichung Industrial Park Microgrid) – No diversity constraints / Upper limit of power source capacity = 6000 kW

In this situation, the function of the model to help the model users in judging the suitable weights between the dual objectives turns out to be insignificant. It can also be observed from Figure 27 that the "curve" appears like a broken-line.

In the last part of this section, the model is assigned with a lifted upper limit of the individual power source capacity of 9000 kW, while other things being equal.

Microgrid for Taichung Industrial Park
No Diversity Constraints
P set = (0.15, 0.2, 0.3, 0.25, 0.1)
Upper Limit of Power Source Capacity = 9000 kW

Table 11: List of outcomes of the objective function – No Diversity Constraints / 9000 kW

Objective Function: $Min\ \{Obj = L \times Expected + (1-L) \times Cw\}$									
Expected Cost		Worst-case Cost		Obj	Unit: USD $10				
Weight	Value	Weight	Value	Value	Cost(1)	Cost(2)	Cost(3)	Cost(4)	Cost(5)
1	16,412,776	0	21,329,873	16,412,776	12,433,129	14,831,236	16,039,421	18,546,984	21,329,873
0.9	16,413,574	0.1	21,318,189	16,904,035	12,442,001	14,829,334	16,047,579	18,541,258	21,318,189
0.8	16,414,464	0.2	21,310,863	17,393,744	12,449,109	14,828,046	16,054,114	18,536,670	21,310,863
0.7	16,420,070	0.3	21,294,293	17,882,337	12,475,947	14,828,413	16,078,866	18,519,625	21,294,293
0.6	16,433,348	0.4	21,269,980	18,368,001	12,517,529	14,832,296	16,118,608	18,506,715	21,269,980
0.5	16,433,348	0.5	21,269,980	18,851,664	12,517,529	14,832,296	16,118,608	18,506,715	21,269,980
0.4	16,451,600	0.6	21,254,605	19,333,403	12,546,803	14,837,394	16,146,550	18,530,700	21,254,605
0.3	16,451,600	0.7	21,254,605	19,813,703	12,546,803	14,837,394	16,146,550	18,530,700	21,254,605
0.2	16,451,600	0.8	21,254,605	20,294,004	12,546,803	14,837,394	16,146,550	18,530,700	21,254,605
0.1	16,451,600	0.9	21,254,605	20,774,304	12,546,803	14,837,394	16,146,550	18,530,700	21,254,605
0	21,254,605	1	21,254,605	21,254,605	21,254,605	21,254,605	21,254,605	21,254,605	21,254,605

The resulting outcomes of the dual-objective optimization are listed in Table 11, and the diagram of the corresponding Pareto curve is presented in Figure 28. The data and graph show that the set of solutions along the Pareto curve appear to be more sensitive to the changes in weights of expected cost and worst-case cost when the maximum power source capacity is increased to a certain level, such as 9,000 kW in this case. The raise of upper limit in capacity may leave the model more flexibility in achieving economy of scale or dealing with uncertainties in parameters.

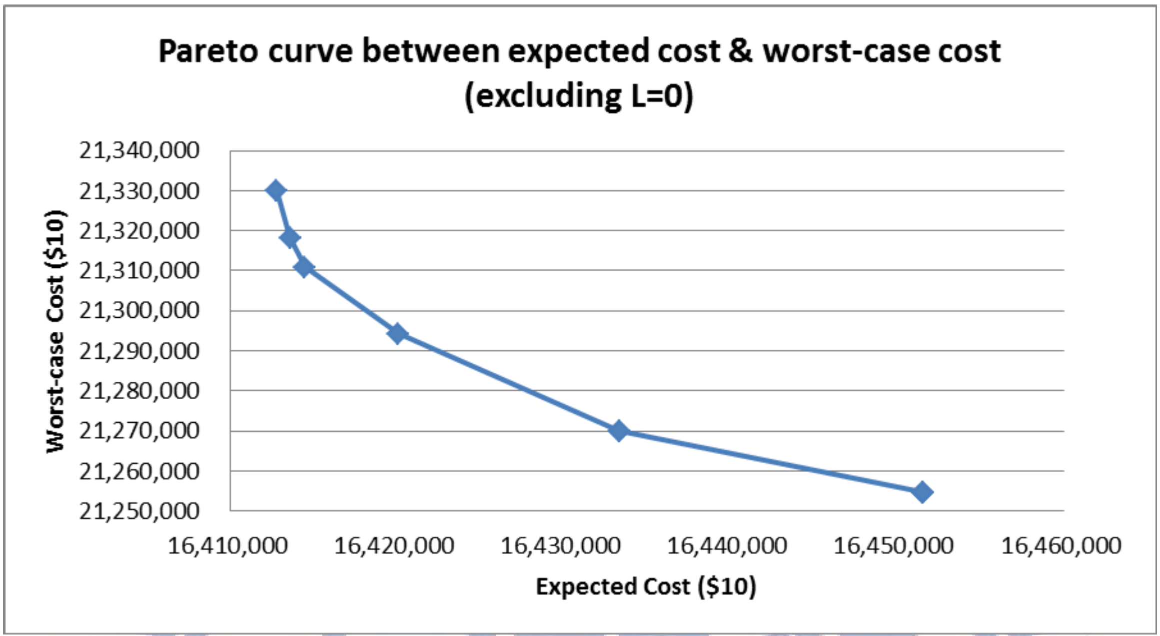


Figure 28: Pareto curve of the dual-objective function (Taichung Industrial Park Microgrid) – No diversity constraints / Upper limit of power source capacity = 9000 kW

7.2 Applicability and limitation of the model

After the methodology, application, and the results of the application of the proposed multi-objective optimization model for microgrid design are illustrated, the workability and limitation of the model can now be discussed.

The applicability of the current model can be verified by monitoring the operation characteristics and performance of the model through a series of analysis as stated in chapter 6 and 7.1. The numerical study on the microgrid for Taichung Industrial Park gives an example of how the proposed model can be applied to a real case by assigning suitable or reasonable parameters to the model. The Pareto curves of the optimized solutions under different conditions, as introduced in previous section, indicates how the multi-objective optimization of the current model can generate a set of useful output and how this output can be used by the microgrid planners to facilitate the process of their decision making.

Although the analysis and discussion of the model output indicate the applicability of the current model, it is necessary to discuss the limitation of the modeling. One critical issue lies on whether to include the optimized solution obtained when the weight of expected cost is zero and the weight of worst-case cost is one (i.e. L=0).

It can be seen from Figure 29 that a curve indicating the trade-off between minimizing expected cost and minimizing worst-case cost normally can be obtained by excluding the point of L=0. On the other hand, the point of L=0 does not seem to lie on any point on the extention of the original curve. This may be attributed to the limitation of the software, such that the ultimate objective of pure worst-case cost minimization without the interaction of cost minimization is to make all the scenario costs equal to each other. Although it makes sense that the variation among different scenarios can be completely eliminated when all scenarios have the same cost, the decoupling of expected cost minimization and worst-case cost minimization may sometimes generate undesired results for the planning of a project. For example, the expected cost of the optimized solution when L=0 can be significantly higher than the expected cost obtained when $0 < L < 1$. Therefore, in reality the solution obtained when L=0 normally will not be adopted.

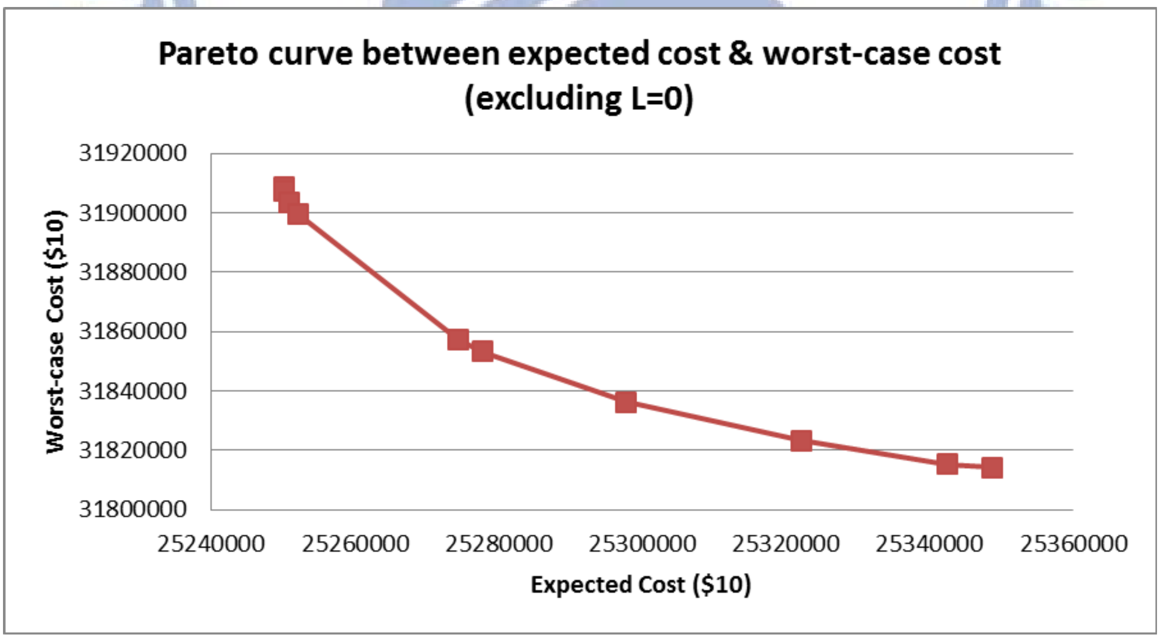


Figure 29: Example of a Pareto curve excluding the point of L=0

Another issue regarding the exclusion and inclusion of L=0 is related to its effect on individual scenario costs. It can be observed from Figure 30 that when L=0 does not apply, the individual scenario costs of the five scenarios gradually converge, to the degree where the possible least worst-case cost is achieved.

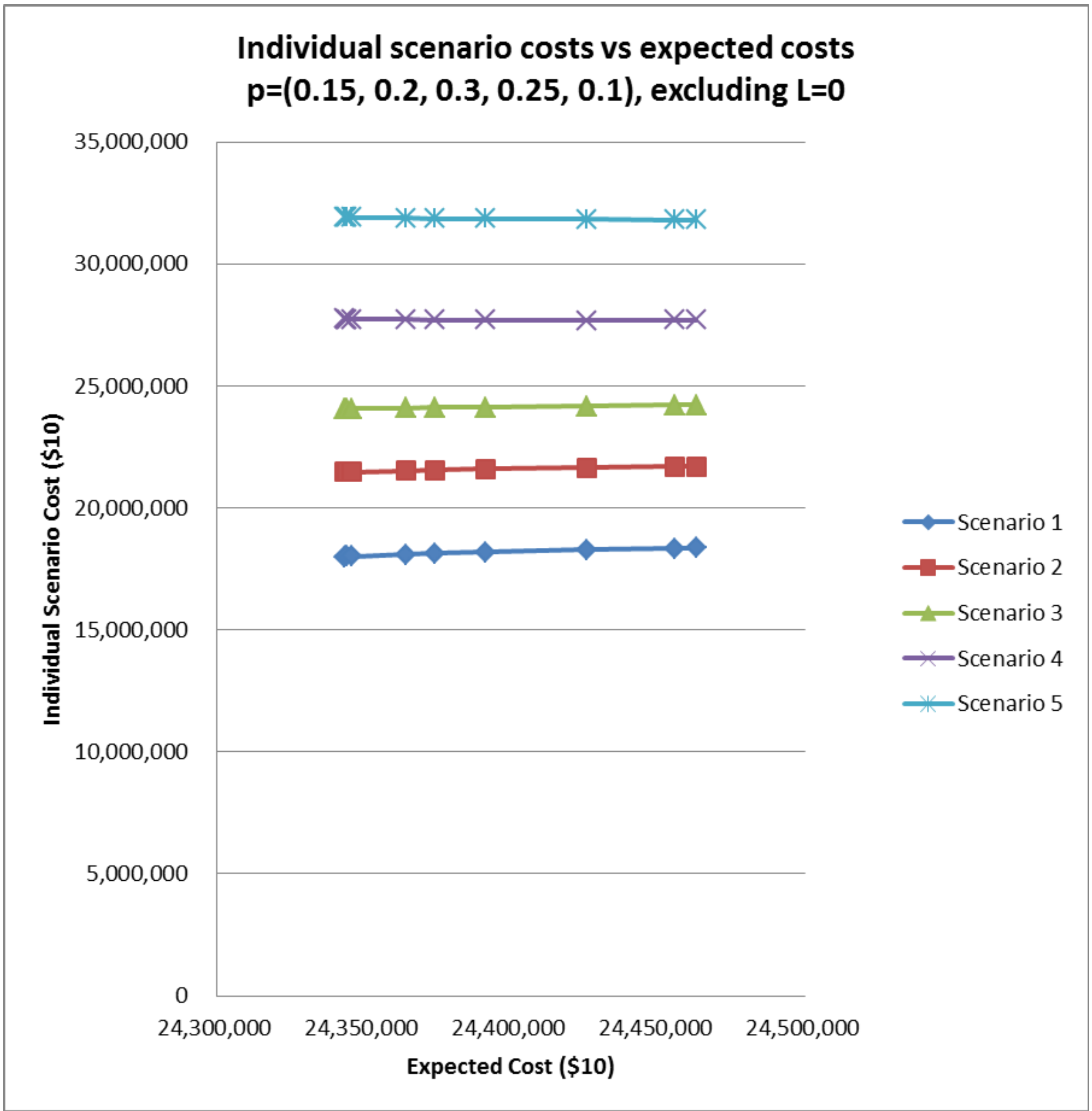


Figure 30: Example of the graph for individual scenario costs vs expected costs (excluding the point of L=0)

By contrast, when L=0 applies, the individual scenario costs of the five scenarios ultimately converge to the same point, where the same lowest worst-case cost is achieved. This is again due to the limitation of the solver. It should be noted that the lowest worst-case cost obtained when L=0 cannot be lower than the lowest worst-case cost obtained when L > 0; however, the application of L=0 induces significantly higher expected cost than any other points along the Pareto curve do.

As indicated in 7.1, sometimes the least worst-case cost can be achieved as early as when L=0.4 or 0.5, but sometimes it cannot be achieved until L=0.1 or less. Nonetheless, the lowest worst-case cost can be obtained in most cases. There are some extreme cases where the Pareto curve of optimized solutions is so insensitive to the changes in expected cost that the curve appears to be a straight line or even one point. In these cases, the conditions assigned to the model may be too tight or too loose in some espects, which leave no flexibility for the optimization series to form the curve. The users are thus recommended to go back to check their input data and see whether there are some parameters and constraints that should be adjusted.

It is thus recommended from this study that when a series of optimizations of the model are carried out as to generate the Pareto curve by adjusting the weight of worst-case cost minimization, the point L=0 should be excluded from the tests (i.e. the solutions can be obtained in any point within the range $0 < L \leqq 1$).

VIII. Conclusion

In this study, a decision support model, which provides a set of optimization solutions and can be used for microgrid planning in the design stage, is developed in order to exploit the various benefits brought by DER technologies and renewable energy.

The literature review of this study identifies the existence of prior research, which can be categorized into three areas: DER system planning approaches, Multi-objective optimization on DER, and Robust optimization on process design. Some studies focus on the investigation of the current status of DER and microgrid development, others focus on developing single or multi-objective optimization model for DER system, and still others focus on the application of robust optimization in engineering process design. It is defined that the current study aims at developing a MILP model that is based on "capacity concern" and can be used even for the preliminary analysis of a proposed project with insufficient equipment data. Formulated to solve a multi-objective problem, the proposed model incorporates the worst-case measure, one of the economic robust measures recommended in prior research, as one component of the dual objective function.

Taiwan is still in the early stage of introducing DER and microgrid concept to the industry. There is lack of green energy information such as accurate biomass or hydrogen prices, as well as detailed DER equipment information. Hence there is a need for an applicable model that would only require generic parameters and can be used as early as in the budgeting or design stage of a project before the planners can obtain comprehensive equipment properties and other technical specifications from various manufacturers. Also, under the situation where detailed equipment and fuel information are not easily available, uncertainties need to be considered and therefore the robustness measure should be included for risk control.

The proposed model is positioned as spanning from the design optimization stage to part of the operation optimization stage, which is between the synthesis optimization stage and the detailed operation optimization stage of the microgrid planning. The comprehensive mathematical formulation of this model is illustrated in chapter 3.

After the methodology of the current research is addressed, the proposed microgrid model is applied to Taichung Industrial Park, one of the major industrial districts in Taiwan. An overview of Taichung Industrial Park is conducted and the hypothesized layouts and settings of the microgrid for the park are proposed. In addition, five scenarios are constructed with all the parameters assigned, including the predicted customer demands and historical local weather data.

The multi-objective optimization model is solved under various conditions and its operation characteristics, such as the distribution of power generation and heat recovery within the microgrid and how the cost minimization deals with uncertainties, are observed and discussed. The results of the model implementation indicate that no apparent patterns which can apply to all conditions including expected cost minimization and worst-case cost minimization exist, in terms of how the power generated and heat recovered are to be distributed and used. Some trends within certain conditions can be identified and explained, but they cannot justify all given conditions. Since the model has been formulated with a certain level of flexibility and the input elements, model components, and output data are numerous, it can be realized that the outcomes of the optimization can be influenced by a great amount of factors, such that the resulting planned layouts and operation can be almost of any forms (i.e. no absolute patterns) and are only arranged to achieve the objectives of the model (i.e. minimizing expected cost and minimizing worst-case cost).

In the scenario analysis of the model, five scenarios are constructed such that scenario 1 is closest to the current real world conditions (i.e. more economic-oriented) while scenario 5 is more environmentally friendlier. The influence of differences among the five scenarios on the model performance is tested and observed. It is the same as mentioned above that no absolute patterns exist for justifying all the outcomes in different model conditions. All the resulting plans of DER deployment and the predicted outcomes of the operation are only affected and directed by the objective functions and constraints of the program to achieve the set goals.

In the analysis of diversity constraints, the effects of with or without diversity constraints on the current model are examined. It is found that diversity constraints have a significant impact on the design of a microgrid. The number of DER technologies to be selected and included in the microgrid layout when no diversity constraints present is apparently less than the number to be selected when effective diversity constraints are activated.

In the last part of the analysis, the Pareto curves between expected costs and worst-case costs under different conditions are formed. It is suggested that the decision makers can seek solutions along the curve, based on their own evaluation and real situations about how much weight they should place on expected cost and worst-case cost. Then the proposed model may become a helpful decision support tool, which can be used by the microgrid planners to render possible optimized solutions.

A first trial of applying the proposed model to an existing industrial park (i.e. Taichung Industrial Park) and the results thereof verify the model applicability. However, it is suggested that when a series of optimizations of the model are executed by adjusting the weights of minimizing expected cost (i.e. L) and minimizing worst-case cost (i.e. 1-L) in order to generate the Pareto curve, the weight of L=0 should be excluded from the analysis for a better and more reasonable presentation of the results.

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Appendices

Appendix 1: Model Parameters for Taichung Industrial Park

Symbol	Value	Unit	
p_s (Set 1)	s=1, 0.15; s=2, 0.2; s=3, 0.3; s=4, 0.25; s=5, 0.1		
p_s (Set 2)	s=1, 0.1; s=2, 0.15; s=3, 0.5; s=4, 0.2; s=5, 0.05		
Inst	0.03		
$EDchar_s$	s=1, 10.33; s=2, 12.91; s=3, 15.50; s=4, 18.08; s=5, 20.66	USD	
ECInt	1[55]	kg C/kWh	
$CTax_s$	s=1, 0.043[56]; s=2, 0.052; s=3, 0.060; s=4, 0.069; s=5, 0.086	USD/kg C	
A	99999999999		
B	1 ~ 8, depending on the scenario configuration		
C	1.25 in this model, depending on the case analyzed		
D	8.96		
G	93, depending on the design strategy for the microgrid		
L	0 ~ 1, controlling the weights of expected and worst-case costs		
$Fprice_{fs}$: f=Biomass	s=1, 0.200[18]; s=2, 0.250; s=3, 0.300; s=4, 0.350; s=5, 0.400	USD/kg	
$Fprice_{fs}$: f=Hydrogen	s=1, 0.336[18]; s=2, 0.420; s=3, 0.504; s=4, 0.588; s=5, 0.672	USD/MJ	
$Fprice_{fs}$: f=Natural-gas	s=1, 0.275[18]; s=2, 0.344; s=3, 0.413; s=4, 0.481; s=5, 0.550	USD/kg	
$Fprice_{fs}$: f=Solar	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0		
$Fprice_{fs}$: f=Wind	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0		
eff_{if}	H-ICES vs Biomass: 0.31 H-ICEL vs Biomass: 0.37 FC vs Hydrogen: 0.36 HC-FC vs Hydrogen: 0.40		[5]

	HC-GT vs Natural-gas: 0.26 HC-GE vs Natural-gas: 0.34 PV vs Solar: 0.12 H-PV vs Solar: 0.20		
$FCost_{is}$: i=H-ICES	s=1, 1458; s=2, 1458; s=3, 1458; s=4, 1458; s=5, 1458	USD/kW	[5]
$FCost_{is}$: i=H-ICEL	s=1, 1118; s=2, 1118; s=3, 1118; s=4, 1118; s=5, 1118	USD/kW	[5]
$FCost_{is}$: i=FC	s=1, 5243; s=2, 5243; s=3, 5243; s=4, 5243; s=5, 5243	USD/kW	[5]
$FCost_{is}$: i=HC-FC	s=1, 5622; s=2, 5622; s=3, 5622; s=4, 5622; s=5, 5622	USD/kW	[5]
$FCost_{is}$: i=HC-GT	s=1, 2238; s=2, 2238; s=3, 2238; s=4, 2238; s=5, 2238	USD/kW	[5]
$FCost_{is}$: i=HC-GE	s=1, 1087; s=2, 1087; s=3, 1087; s=4, 1087; s=5, 1087	USD/kW	[5]
$FCost_{is}$: i=PV	s=1, 5000; s=2, 4500; s=3, 4000; s=4, 3500; s=5, 3000	USD/kW	
$FCost_{is}$: i=H-PV	s=1, 5714; s=2, 5143; s=3, 4571; s=4, 4000; s=5, 3428	USD/kW	
$FCost_{is}$: i=WT	s=1, 3000; s=2, 2700; s=3, 2400; s=4, 2100; s=5, 1800	USD/kW	
$LTime_{is}$: i=H-ICES	s=1, 20; s=2, 20; s=3, 20; s=4, 20; s=5, 20	Year	[5]
$LTime_{is}$: i=H-ICEL	s=1, 20; s=2, 20; s=3, 20; s=4, 20; s=5, 20	Year	[5]
$LTime_{is}$: i=FC	s=1, 10; s=2, 10; s=3, 10; s=4, 10; s=5, 10	Year	[5]
$LTime_{is}$: i=HC-FC	s=1, 10; s=2, 10; s=3, 10; s=4, 10; s=5, 10	Year	[5]
$LTime_{is}$: i=HC-GT	s=1, 20; s=2, 20; s=3, 20; s=4, 20; s=5, 20	Year	[5]
$LTime_{is}$: i=HC-GE	s=1, 20; s=2, 20; s=3, 20; s=4, 20; s=5, 20	Year	[5]
$LTime_{is}$: i=PV	s=1, 30; s=2, 30; s=3, 30; s=4, 30; s=5, 30	Year	[5]
$LTime_{is}$: i=H-PV	s=1, 30; s=2, 30; s=3, 30; s=4, 30; s=5, 30	Year	[5]
$LTime_{is}$: i=WT	s=1, 20; s=2, 20; s=3, 20; s=4, 20; s=5, 20	Year	[5]
OMf_{is}: i=H-ICES	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	USD/kW/yr	[5]
OMf_{is}: i=H-ICEL	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	USD/kW/yr	[5]

OMf_{is}: i=FC	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	USD/kW/yr	5
OMf_{is}: i=HC-FC	s=1, 10.15; s=2, 10.15; s=3, 10.15; s=4, 10.15; s=5, 10.15	USD/kW/yr	5
OMf_{is}: i=HC-GT	s=1, 10.86; s=2, 10.86; s=3, 10.86; s=4, 10.86; s=5, 10.86	USD/kW/yr	5
OMf_{is}: i=HC-GE	s=1, 4.58; s=2, 4.58; s=3, 4.58; s=4, 4.58; s=5, 4.58	USD/kW/yr	5
OMf_{is}: i=PV	s=1, 9.0; s=2, 9.0; s=3, 9.0; s=4, 9.0; s=5, 9.0	USD/kW/yr	
OMf_{is}: i=H-PV	s=1, 9.52; s=2, 9.52; s=3, 9.52; s=4, 9.52; s=5, 9.52	USD/kW/yr	5
OMf_{is}: i=WT	s=1, 6.52; s=2, 6.52; s=3, 6.52; s=4, 6.52; s=5, 6.52	USD/kW/yr	
OMv_{is}: i=H-ICES	s=1, 0.01; s=2, 0.01; s=3, 0.01; s=4, 0.01; s=5, 0.01	USD/kWh	5
OMv_{is}: i=H-ICEL	s=1, 0.01; s=2, 0.01; s=3, 0.01; s=4, 0.01; s=5, 0.01	USD/kWh	5
OMv_{is}: i=FC	s=1, 0.03; s=2, 0.03; s=3, 0.03; s=4, 0.03; s=5, 0.03	USD/kWh	5
OMv_{is}: i=HC-FC	s=1, 0.03; s=2, 0.03; s=3, 0.03; s=4, 0.03; s=5, 0.03	USD/kWh	5
OMv_{is}: i=HC-GT	s=1, 0.01; s=2, 0.01; s=3, 0.01; s=4, 0.01; s=5, 0.01	USD/kWh	5
OMv_{is}: i=HC-GE	s=1, 0.01; s=2, 0.01; s=3, 0.01; s=4, 0.01; s=5, 0.01	USD/kWh	5
OMv_{is}: i=PV	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	USD/kWh	5
OMv_{is}: i=H-PV	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	USD/kWh	
OMv_{is}: i=WT	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	USD/kWh	
$MaxEqm_{is}$: i=H-ICES	s=1, 20,000; s=2, 20,000; s=3, 20,000; s=4, 20,000; s=5, 20,000	kW	
$MaxEqm_{is}$: i=H-ICEL	s=1, 60,000; s=2, 60,000; s=3, 60,000; s=4, 60,000; s=5, 60,000	kW	
$MaxEqm_{is}$: i=FC	s=1, 20,000; s=2, 20,000; s=3, 20,000; s=4, 20,000; s=5, 20,000	kW	

$MaxEqm_{is}$: i=HC-FC	s=1, 30,000; s=2, 30,000; s=3, 30,000; s=4, 30,000; s=5, 30,000	kW	
$MaxEqm_{is}$: i=HC-GT	s=1, 20,000; s=2, 20,000; s=3, 20,000; s=4, 20,000; s=5, 20,000	kW	
$MaxEqm_{is}$: i=HC-GE	s=1, 60,000; s=2, 60,000; s=3, 60,000; s=4, 60,000; s=5, 60,000	kW	
$MaxEqm_{is}$: i=PV	s=1, 60,000; s=2, 60,000; s=3, 60,000; s=4, 60,000; s=5, 60,000	kW	
$MaxEqm_{is}$: i=H-PV	s=1, 60,000; s=2, 60,000; s=3, 60,000; s=4, 60,000; s=5, 60,000	kW	
$MaxEqm_{is}$: i=WT	s=1, 60,000; s=2, 60,000; s=3, 60,000; s=4, 60,000; s=5, 60,000	kW	
$MinEqm_{is}$: i=H-ICES	s=1, 3,000; s=2, 3,000; s=3, 3,000; s=4, 3,000; s=5, 3,000	kW	
$MinEqm_{is}$: i=H-ICEL	s=1, 20,000; s=2, 20,000; s=3, 20,000; s=4, 20,000; s=5, 20,000	kW	
$MinEqm_{is}$: i=FC	s=1, 2,000; s=2, 2,000; s=3, 2,000; s=4, 2,000; s=5, 2,000	kW	
$MinEqm_{is}$: i=HC-FC	s=1, 2,000; s=2, 2,000; s=3, 2,000; s=4, 2,000; s=5, 2,000	kW	
$MinEqm_{is}$: i=HC-GT	s=1, 1,000; s=2, 1,000; s=3, 1,000; s=4, 1,000; s=5, 1,000	kW	
$MinEqm_{is}$: i=HC-GE	s=1, 20,000; s=2, 20,000; s=3, 20,000; s=4, 20,000; s=5, 20,000	kW	
$MinEqm_{is}$: i=PV	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	kW	
$MinEqm_{is}$: i=H-PV	s=1, 0; s=2, 0; s=3, 0; s=4, 0; s=5, 0	kW	
$MinEqm_{is}$: i=WT	s=1, 2,000; s=2, 2,000; s=3, 2,000; s=4, 2,000; s=5, 2,000	kW	
$ESMax_{ts}$: t=elec	s=1, 21,600,000; s=2, 25,200,000; s=3, 28,800,000; s=4, 32,400,000; s=5, 36,000,000	kWh	
$ESMax_{ts}$: t=heat	s=1, 21,600,000; s=2, 25,200,000; s=3, 28,800,000; s=4, 32,400,000;	kWh	

	s=5, 36,000,000		
$ESMin_{ts}$: t=elec	s=1, 2,160,000; s=2, 2,520,000; s=3, 2,880,000; s=4, 3,240,000; s=5, 3,600,000	kWh	
$ESMin_{ts}$: t=heat	s=1, 2,160,000; s=2, 2,520,000; s=3, 2,880,000; s=4, 3,240,000; s=5, 3,600,000	kWh	
$ESInl_{ts}$: t=elec	s=1, 7,200,000; s=2, 9,000,000; s=3, 10,800,000; s=4, 12,600,000; s=5, 14,400,000	kWh	
$ESInl_{ts}$: t=heat	s=1, 7,200,000; s=2, 9,000,000; s=3, 10,800,000; s=4, 12,600,000; s=5, 14,400,000	kWh	
$Sprice_{is}$: i=H-ICES	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=H-ICEL	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=FC	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=HC-FC	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=HC-GT	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=HC-GE	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=PV	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=H-PV	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$Sprice_{is}$: i=WT	s=1, 0.09; s=2, 0.09; s=3, 0.09; s=4, 0.09; s=5, 0.09	USD/kWh	
$FCInt_{fs}$: f=Biomass	s=1, 4.266; s=2, 4.266; s=3, 4.266; s=4, 4.266; s=5, 4.266	kg C/kg	57
$FCInt_{fs}$: f=Hydrogen	s=1, 0.497; s=2, 0.497; s=3, 0.497; s=4, 0.497; s=5, 0.497	kg C/MJ	58
$FCInt_{fs}$: f=Natural-gas	s=1, 2.844; s=2, 2.844; s=3, 2.844; s=4, 2.844; s=5, 2.844	kg C/kg	59

$FCInt_{fs}$: f=Solar	s=1, 0.217; s=2, 0.217; s=3, 0.217; s=4, 0.217; s=5, 0.217	kg C/kWh	60
$FCInt_{fs}$: f=Wind	s=1, 0.032; s=2, 0.032; s=3, 0.032; s=4, 0.032; s=5, 0.032	kg C/kWh	61
$Eprice_{ms}$: m=Jan	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
$Eprice_{ms}$: m=Feb	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
$Eprice_{ms}$: m=Mar	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
$Eprice_{ms}$: m=Apr	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
$Eprice_{ms}$: m=May	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
$Eprice_{ms}$: m=Jun	s=1, 0.32; s=2, 0.40; s=3, 0.48; s=4, 0.56; s=5, 0.64	USD/kWh	
$Eprice_{ms}$: m=Jul	s=1, 0.32; s=2, 0.40; s=3, 0.48; s=4, 0.56; s=5, 0.64	USD/kWh	
$Eprice_{ms}$: m=Aug	s=1, 0.32; s=2, 0.40; s=3, 0.48; s=4, 0.56; s=5, 0.64	USD/kWh	
$Eprice_{ms}$: m=Sep	s=1, 0.32; s=2, 0.40; s=3, 0.48; s=4, 0.56; s=5, 0.64	USD/kWh	
$Eprice_{ms}$: m=Oct	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
$Eprice_{ms}$: m=Nov	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
$Eprice_{ms}$: m=Dec	s=1, 0.16; s=2, 0.20; s=3, 0.24; s=4, 0.28; s=5, 0.32	USD/kWh	
Vc_{is}: i=WT	s=1, 2.0; s=2, 2.0; s=3, 2.0; s=4, 2.0; s=5, 2.0	m/s	
Vn_{is}: i=WT	s=1, 10.0; s=2, 10.0; s=3, 10.0; s=4, 10.0; s=5, 10.0	m/s	
Vf_{is}: i=WT	s=1, 14.0; s=2, 14.0; s=3, 14.0; s=4, 14.0; s=5, 14.0	m/s	

Appendix 2: Model Parameters in Greek Letters

Symbol	Value	Unit	
α_i	i=H-ICES, 1.85; i= H-ICEL, 1.22; i=FC, 0.00; i=HC-FC, 1.25; i=HC-GT, 2.45; i=HC-GE, 1.22; i=PV, 0.00; i=H-PV, 1.00; i=WT, 0.00		[5]
β_{fu}: f=Biomass	u=heat, 1.439; u=cool, 1.233		
β_{fu}: f=Hydrogen	u=heat, 0.450; u=cool, 0.394		
β_{fu}: f=Hydrogen	u=heat, 3.591; u=cool, 3.078		
γ_{iu}: i=H-ICES	u=elec, 0.80; u=heat, 0.85; u=cool, 0.00		
γ_{iu}: i=H-ICEL	u=elec, 0.90; u=heat, 0.95; u=cool, 0.00		
γ_{iu}: i=FC	u=elec, 1.00; u=heat, 0.00; u=cool, 0.00		
γ_{iu}: i=HC-FC	u=elec, 1.00; u=heat, 1.00; u=cool, 1.00		
γ_{iu}: i=HC-GT	u=elec, 0.70; u=heat, 0.75; u=cool, 0.70		
γ_{iu}: i=HC-GE	u=elec, 0.80; u=heat, 0.85; u=cool, 0.80		
γ_{iu}: i=PV	u=elec, 1.00; u=heat, 0.00; u=cool, 0.00		
γ_{iu}: i=H-PV	u=elec, 1.00; u=heat, 1.00; u=cool, 0.95		
γ_{iu}: i=WT	u=elec, 0.00; u=heat, 0.00; u=cool, 0.00		
δ_{tu}: t=elec	u=elec, 0.81[18]; u=heat, 0.81; u=cool, 0.81		
δ_{tu}: t=heat	u=elec, 0.71; u=heat, 0.71; u=cool, 0.71		
ε_t	t=elec, 0.9; t=heat, 0.8		
θ	0.2		
ω_i	i=H-ICES, 1000; i= H-ICEL, 3000; i=FC, 200; i=HC-FC, 200; i=HC-GT, 1000; i=HC-GE, 3000; i=PV, 0; i=H-PV, 0; i=WT, 200	USD/Time	

Note: β_{fu} should be calculated as the heat conversion factor multiplied by the equipment efficiency for each type of fuel and each type of end use.

Conversion Factor (including fixed costs)

Biomass: 4.111[18]

Hydrogen: 1.125[18]

Natural-gas: 10.26[18]

Equipment Efficiency

Judgement	Optimistic		Conservative	
End Use	Heating	Cooling	Heating	Cooling
Biomass	0.35	0.3	0.25	0.2
Hydrogen	0.4	0.35	0.35	0.3
Natural-gas	0.35	0.3	0.25	0.2

Appendix 3: Model Parameters – Local Weather Data of Taichung in the Year of 2011

Symbol	Value	Unit	
R_{ms}: m=Jan	s=1, 91.86; s=2, 91.86; s=3, 91.86; s=4, 91.86; s=5, 91.86	kW/m^2	
R_{ms}: m=Feb	s=1, 105.46; s=2, 105.46; s=3, 105.46; s=4, 105.46; s=5, 105.46	kW/m^2	
R_{ms}: m=Mar	s=1, 108.84; s=2, 108.84; s=3, 108.84; s=4, 108.84; s=5, 108.84	kW/m^2	
R_{ms}: m=Apr	s=1, 133.60; s=2, 133.60; s=3, 133.60; s=4, 133.60; s=5, 133.60	kW/m^2	
R_{ms}: m=May	s=1, 131.43; s=2, 131.43; s=3, 131.43; s=4, 131.43; s=5, 131.43	kW/m^2	
R_{ms}: m=Jun	s=1, 157.18; s=2, 157.18; s=3, 157.18; s=4, 157.18; s=5, 157.18	kW/m^2	
R_{ms}: m=Jul	s=1, 159.39; s=2, 159.39; s=3, 159.39; s=4, 159.39; s=5, 159.39	kW/m^2	
R_{ms}: m=Aug	s=1, 136.21; s=2, 136.21; s=3, 136.21; s=4, 136.21; s=5, 136.21	kW/m^2	
R_{ms}: m=Sep	s=1, 136.08; s=2, 136.08; s=3, 136.08; s=4, 136.08; s=5, 136.08	kW/m^2	
R_{ms}: m=Oct	s=1, 127.07; s=2, 127.07; s=3, 127.07; s=4, 127.07; s=5, 127.07	kW/m^2	
R_{ms}: m=Nov	s=1, 91.80; s=2, 91.80; s=3, 91.80; s=4, 91.80; s=5, 91.80	kW/m^2	
R_{ms}: m=Dec	s=1, 96.58; s=2, 96.58; s=3, 96.58; s=4, 96.58; s=5, 96.58	kW/m^2	
Vw_{ms}: m=Jan	s=1, 6.6; s=2, 6.6; s=3, 6.6; s=4, 6.6; s=5, 6.6	m/s	
Vw_{ms}: m=Feb	s=1, 5.8; s=2, 5.8; s=3, 5.8; s=4, 5.8; s=5, 5.8	m/s	
Vw_{ms}: m=Mar	s=1, 6.2; s=2, 6.2; s=3, 6.2; s=4, 6.2; s=5, 6.2	m/s	
Vw_{ms}: m=Apr	s=1, 4.3; s=2, 4.3; s=3, 4.3; s=4, 4.3; s=5, 4.3	m/s	
Vw_{ms}: m=May	s=1, 6.8; s=2, 6.8; s=3, 6.8; s=4, 6.8; s=5, 6.8	m/s	
Vw_{ms}: m=Jun	s=1, 5.0; s=2, 5.0; s=3, 5.0; s=4, 5.0; s=5, 5.0	m/s	
Vw_{ms}: m=Jul	s=1, 5.8; s=2, 5.8; s=3, 5.8; s=4, 5.8; s=5, 5.8	m/s	
Vw_{ms}: m=Aug	s=1, 5.7; s=2, 5.7; s=3, 5.7; s=4, 5.7; s=5, 5.7	m/s	
Vw_{ms}: m=Sep	s=1, 4.9; s=2, 4.9; s=3, 4.9; s=4, 4.9; s=5, 4.9	m/s	
Vw_{ms}: m=Oct	s=1, 5.3; s=2, 5.3; s=3, 5.3; s=4, 5.3; s=5, 5.3	m/s	
Vw_{ms}: m=Nov	s=1, 5.1; s=2, 5.1; s=3, 5.1; s=4, 5.1; s=5, 5.1	m/s	
Vw_{ms}: m=Dec	s=1, 6.1; s=2, 6.1; s=3, 6.1; s=4, 6.1; s=5, 6.1	m/s	

Source: Central Weather Bureau, Taiwan R.O.C.

Appendix 4: Expected cost minimization – Distribution of power generation (Unit: 10 kWh)

DER source	End use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H-ICES	elec		59,191	65,534	72,929	83,498	87,725	98,294	88,783	79,272	72,929	65,534	61,301
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	0	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
H-ICEL	elec		59,191	65,534	72,929	83,498	87,725	98,294	88,783	79,272	72,929	65,534	61,301
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	0	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
FC	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-FC	elec		59,191	65,534	72,929	83,498	87,725	98,294	88,783	79,272	72,929	65,534	61,301
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	0	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
HC-GT	elec		59,191	65,534	72,929	83,498	591,923	581,354	590,865	600,376	72,929	65,534	61,301
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	0	118,382	131,069	145,858	166,997	679,648	679,648	679,648	679,648	145,858	131,069	122,602
HC-GE	elec		59,191	65,534	72,929	83,498	1,352,275	1,341,706	1,212,406	1,181,109	72,929	65,534	61,301
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	0	118,382	131,069	145,858	166,997	1,440,000	1,440,000	1,301,189	1,260,381	145,858	131,069	122,602
PV	elec		59,191	65,534	72,929	83,498	123,667	113,098	122,609	132,120	72,929	65,534	61,301
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	0	118,382	131,069	145,858	166,997	211,392	211,392	211,392	211,392	145,858	131,069	122,602
H-PV	elec		3,329,002	4,254,466	4,247,071	4,236,502	4,232,275	4,221,706	4,231,217	4,240,728	4,247,071	3,230,100	4,258,699
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		951,535	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	1,057,132	20,434
	Subtotal	0	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000
WT	elec		1,825,602	1,340,142	1,169,071	83,498	1,532,275	1,953,706	1,909,217	1,457,928	89,892	1,579,666	473,523
	heat		39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool		19,728	884,168	36,461	2,466,749	58,478	65,527	59,191	52,848	1,626,840	32,767	1,315,391
	Subtotal	0	1,884,793	2,268,000	1,242,000	2,592,000	1,620,000	2,052,000	1,998,000	1,537,200	1,753,200	1,645,200	1,829,781
	Gen-Total	0	6,915,087	7,374,413	6,437,146	7,913,981	8,797,389	9,292,807	9,042,929	8,484,253	6,948,346	6,751,613	6,885,391
H-ICES	Esal												
H-ICEL	Esal												
FC	Esal												
HC-FC	Esal												
HC-GT	Esal												
HC-GE	Esal												
PV	Esal												
H-PV	Esal												
WT	Esal		167,207										384,219
	Esal-Total	0	167,207	0	0	0	0	0	0	0	0	0	384,219
H-ICES	elec-store												
	heat-store		219,007										226,813
	Subtotal	0	219,007	0	0	0	0	0	0	0	0	0	226,813
H-ICEL	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
FC	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-FC	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-GT	elec-store												
	heat-store		290,037		57,600	409,142	234,855	1,380,589	603,257	163,523	156,910	156,910	300,374
	Subtotal	0	290,037	0	57,600	409,142	234,855	1,380,589	603,257	163,523	156,910	156,910	300,374
HC-GE	elec-store												
	heat-store		144,427										149,574
	Subtotal	0	144,427	0	0	0	0	0	0	0	0	0	149,574
PV	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
H-PV	elec-store												
	heat-store		52,705										247,911
	Subtotal	0	52,705	0	0	0	0	0	0	0	0	0	247,911
WT	elec-store									28,800	28,800	28,800	
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	28,800	28,800	28,800	0
	Etostore-Total	0	706,176	0	57,600	409,142	234,855	1,380,589	603,257	192,323	185,710	185,710	924,672
	Total	0	7,788,471	7,374,413	6,494,746	8,323,123	9,032,244	10,673,395	9,646,186	8,676,576	7,134,056	6,937,323	8,194,281

Appendix 5: Expected cost minimization – Distribution of recovered heat (Unit: 10 kWh)

DER source	End use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H-ICES	elec							209,765					
	heat			242,477	269,837	308,944	324,582	153,924	328,498	293,306	269,837	242,477	
	cool												
	Subtotal	0	0	242,477	269,837	308,944	324,582	363,689	328,498	293,306	269,837	242,477	0
H-ICEL	elec							239,838					
	heat		144,427	159,904	177,946	203,736	214,049		216,631	193,424	177,946	159,904	149,574
	cool												
	Subtotal	0	144,427	159,904	177,946	203,736	214,049	239,838	216,631	193,424	177,946	159,904	149,574
FC	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-FC	elec												
	heat												
	cool		147,978	163,836	182,322	208,746	219,312	245,736	221,958	198,180	182,322	163,836	153,252
	Subtotal	0	147,978	163,836	182,322	208,746	219,312	245,736	221,958	198,180	182,322	163,836	153,252
HC-GT	elec												
	heat			321,119	299,751		1,430,283		1,061,881	1,501,614	200,441	164,208	
	cool							284,549					
	Subtotal	0	0	321,119	299,751	0	1,430,283	284,549	1,061,881	1,501,614	200,441	164,208	0
HC-GE	elec												
	heat			159,904	177,946	203,736	228,755			835,592	177,946	159,904	
	cool						1,528,045	1,756,800	1,587,451	702,072			
	Subtotal	0	0	159,904	177,946	203,736	1,756,800	1,756,800	1,587,451	1,537,664	177,946	159,904	0
PV	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
H-PV	elec						174,458		158,240	1,918			
	heat		3,493,409	3,284,672	2,580,578	3,211,930					2,655,061	2,397,493	3,617,687
	cool		773,885	1,035,328	1,739,422	1,108,070	4,145,542	4,320,000	4,161,760	4,318,082	1,664,939	1,922,507	454,402
	Subtotal	0	4,267,295	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,072,089
WT	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
	RHeat	0	4,559,699	5,367,240	5,427,802	5,245,162	8,265,025	7,210,613	7,736,419	8,044,189	5,328,492	5,210,329	4,374,915

Appendix 6: Worst-case cost minimization – Distribution of power generation (Unit: 10 kWh)

DER source	End use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H-ICES	elec	53,906	59,191	65,534	72,929	83,498	87,725	98,294	88,783	79,272	72,929	65,534	61,301
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	17,971	19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
H-ICEL	elec	53,906	59,191	65,534	72,929	83,498	87,725	98,294	88,783	79,272	72,929	65,534	61,301
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	17,971	19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
FC	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-FC	elec	53,906	59,191	65,534	72,929	83,498	87,725	98,294	88,783	79,272	72,929	65,534	61,301
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	17,971	19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
HC-GT	elec	53,906	1,222,975	1,216,632	1,209,237	150,469	1,194,441	1,183,872	1,193,383	1,202,894	1,209,237	1,016,305	1,220,865
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	17,971	19,728	21,845	36,461	1,089,945	58,478	65,527	59,191	52,848	36,461	233,094	20,434
	Subtotal	107,813	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166
HC-GE	elec	53,906	1,380,809	65,534	670,984	1,106,107	1,352,275	1,341,706	1,101,316	1,360,728	1,303,862	1,374,466	1,378,699
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	17,971	19,728	21,845	732,548	41,746	58,478	65,527	76,995	52,848	36,461	32,767	20,434
	Subtotal	107,813	1,440,000	131,069	1,440,000	1,189,605	1,440,000	1,440,000	1,207,903	1,440,000	1,376,791	1,440,000	1,440,000
PV	elec	53,906	59,191	65,534	72,929	83,498	87,725	98,294	88,783	79,272	72,929	65,534	61,301
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	17,971	19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
H-PV	elec	3,233,790	59,191	2,944,817	538,012	83,498	87,725	325,295	4,231,217	79,272	2,563,299	65,534	61,301
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	17,971	19,728	21,845	36,461	41,746	58,478	65,527	59,191	52,848	36,461	32,767	20,434
	Subtotal	3,287,697	118,382	3,010,351	610,941	166,997	175,450	423,589	4,320,000	158,544	2,636,228	131,069	122,602
WT	elec	1,329,411	878,532	2,064,320	72,929	83,498	1,532,275	1,953,706	1,848,417	1,486,728	1,680,271	65,534	831,672
	heat	35,935	39,463	43,690	36,468	41,753	29,246	32,767	29,592	26,424	36,468	32,767	40,867
	cool	1,118,654	1,134,004	159,991	1,132,603	2,466,749	58,478	65,527	59,191	52,848	36,461	1,546,898	1,341,461
	Subtotal	2,484,000	2,052,000	2,268,000	1,242,000	2,592,000	1,620,000	2,052,000	1,937,200	1,566,000	1,753,200	1,645,200	2,214,000
	Gen-Total	6,418,574	5,366,078	7,215,861	5,158,537	5,898,755	5,219,414	5,984,110	9,457,535	5,080,886	7,631,815	5,022,710	5,549,174
H-ICES	Esal												
H-ICEL	Esal												
FC	Esal												
HC-FC	Esal												
HC-GT	Esal												
HC-GE	Esal												
PV	Esal												
H-PV	Esal												
WT	Esal												
	Esal-Total	0	0	0	0	0	0	0	0	0	0	0	0
H-ICES	elec-store												
	heat-store						324,582	363,689					
	Subtotal	0	0	0	0	0	324,582	363,689	0	0	0	0	0
H-ICEL	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
FC	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-FC	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-GT	elec-store												
	heat-store			57,600	57,600	272,660	3,141,307	3,141,307	267,255	3,141,307	156,910	156,910	
	Subtotal	0	0	57,600	57,600	272,660	3,141,307	3,141,307	267,255	3,141,307	156,910	156,910	0
HC-GE	elec-store												
	heat-store						674,528	1,184,289		396,783			
	Subtotal	0	0	0	0	0	674,528	1,184,289	0	396,783	0	0	0
PV	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
H-PV	elec-store												
	heat-store												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
WT	elec-store								60,800		28,800	28,800	
	heat-store												
	Subtotal	0	0	0	0	0	0	0	60,800	0	28,800	28,800	0
	Etostore-Total	0	0	57,600	57,600	272,660	4,140,417	4,689,285	328,055	3,538,090	185,710	185,710	0
	Total	6,418,574	5,366,078	7,273,461	5,216,137	6,171,415	9,359,831	10,673,395	9,785,590	8,618,976	7,817,526	5,208,420	5,549,174

Appendix 7: Worst-case cost minimization – Distribution of recovered heat (Unit: 10 kWh)

DER source	End use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H-ICES	elec									293,306			
	heat	199,454	219,007	242,477	269,837	308,944			328,498		269,837	242,477	226,813
	cool												
	Subtotal	199,454	219,007	242,477	269,837	308,944	0	0	328,498	293,306	269,837	242,477	226,813
H-ICEL	elec						214,049	239,838		193,424			
	heat	131,532	144,427	159,904	177,946	203,736			216,631		177,946	159,904	149,574
	cool												
	Subtotal	131,532	144,427	159,904	177,946	203,736	214,049	239,838	216,631	193,424	177,946	159,904	149,574
FC	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
HC-FC	elec							245,736		198,180			
	heat												
	cool	134,766	147,978	163,836	182,322	208,746	219,312		221,958		182,322	163,836	153,252
	Subtotal	134,766	147,978	163,836	182,322	208,746	219,312	245,736	221,958	198,180	182,322	163,836	153,252
HC-GT	elec												
	heat	264,141	3,141,307	3,083,707	3,083,707	2,868,647			2,874,052		2,984,396	2,984,396	3,141,307
	cool												
	Subtotal	264,141	3,141,307	3,083,707	3,083,707	2,868,647	0	0	2,874,052	0	2,984,396	2,984,396	3,141,307
HC-GE	elec						1,082,272	572,511		304,865			
	heat	131,532	1,119,145	159,904	757,489	1,451,318			96,356		845,116	492,083	1,257,548
	cool		637,655		999,311				1,377,285	1,055,152	834,569	1,264,717	499,252
	Subtotal	131,532	1,756,800	159,904	1,756,800	1,451,318	1,082,272	572,511	1,473,642	1,360,017	1,679,685	1,756,800	1,756,800
PV	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
H-PV	elec	146,160	73,543				175,450	423,589		158,544			116,064
	heat	2,701,640		1,212,730									
	cool	439,897	44,839	1,797,621	610,941	166,997			4,320,000		2,636,228	131,069	6,538
	Subtotal	3,287,697	118,382	3,010,351	610,941	166,997	175,450	423,589	4,320,000	158,544	2,636,228	131,069	122,602
WT	elec												
	heat												
	cool												
	Subtotal	0	0	0	0	0	0	0	0	0	0	0	0
	RHeat	4,149,121	5,527,901	6,820,179	6,081,552	5,208,388	1,691,082	1,481,675	9,434,780	2,203,471	7,930,414	5,438,482	5,550,347

Appendix 8: Scenario analysis under expected cost minimization – Distribution of power generation (Unit: 10 kWh)

	DER source	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Scenario 1	H-ICES	118,382	126,835	135,288	145,858	156,427	166,997	179,683	169,114	160,661	150,091	139,522	128,952
	H-ICEL	118,382	126,835	135,288	145,858	156,427	166,997	179,683	169,114	160,661	150,091	139,522	128,952
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	118,382	126,835	135,288	145,858	156,427	166,997	179,683	169,114	160,661	150,091	139,522	128,952
	HC-GT	118,382	126,835	135,288	145,858	156,427	679,648	679,648	679,648	679,648	150,091	139,522	128,952
	HC-GE	118,382	126,835	135,288	145,858	156,427	166,997	974,009	571,995	445,145	150,091	139,522	128,952
	PV	118,382	126,835	135,288	145,858	156,427	211,392	211,392	211,392	211,392	150,091	139,522	128,952
	H-PV	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000
	WT	1,863,903	1,319,217	1,987,044	711,660	2,592,000	1,580,229	2,052,000	1,998,000	1,566,000	763,187	334,598	1,788,418
	Gen-Total	6,894,198	6,400,228	7,118,772	5,906,805	7,850,563	7,459,257	8,776,099	8,288,376	7,704,168	5,983,734	5,491,728	6,882,130
	Esal-Total	620,097	732,783	280,956	530,340	0	39,771	0	0	0	997,213	1,317,802	425,582
	Etostore-Total	1,573,525	2,570,038	1,012,015	1,871,959	1,987,200	0	969,994	886,958	1,014,715	3,341,366	4,683,428	1,167,360
	Total	9,087,819	9,703,049	8,411,743	8,309,105	9,837,763	7,499,027	9,746,093	9,175,334	8,718,883	10,322,313	11,492,958	8,475,072
Scenario 2	H-ICES	99,360	116,266	143,741	164,880	183,917	205,056	198,706	181,800	156,427	135,288	105,696	86,674
	H-ICEL	99,360	116,266	143,741	164,880	183,917	205,056	198,706	181,800	156,427	135,288	105,696	86,674
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	99,360	116,266	143,741	164,880	183,917	205,056	198,706	181,800	156,427	135,288	105,696	86,674
	HC-GT	99,360	116,266	143,741	164,880	183,917	679,648	679,648	679,648	679,648	135,288	105,696	86,674
	HC-GE	99,360	116,266	143,741	164,880	183,917	1,440,000	1,440,000	1,089,458	288,908	135,288	105,696	86,674
	PV	99,360	116,266	143,741	164,880	183,917	211,392	211,392	211,392	211,392	135,288	105,696	86,674
	H-PV	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000
	WT	964,007	1,622,673	799,716	304,554	2,592,000	1,620,000	2,052,000	1,998,000	1,540,800	1,184,242	722,319	302,842
	Gen-Total	5,880,167	6,640,266	5,982,161	5,613,834	8,015,501	8,886,208	9,299,157	8,843,898	7,510,030	6,315,970	5,676,495	5,142,883
	Esal-Total	1,519,993	429,327	1,468,284	937,446	0	0	0	0	0	572,558	926,481	1,911,158
	Etostore-Total	2,801,233	1,530,839	5,113,449	3,282,971	2,318,400	255,630	1,481,345	1,023,702	1,037,839	2,136,833	3,357,257	4,798,438
	Total	10,201,393	8,600,432	12,563,894	9,834,251	10,333,901	9,141,838	10,780,502	9,867,600	8,547,869	9,025,361	9,960,233	11,852,480
Scenario 3	H-ICES	0	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
	H-ICEL	0	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	0	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
	HC-GT	0	118,382	131,069	145,858	166,997	679,648	679,648	679,648	679,648	145,858	131,069	122,602
	HC-GE	0	118,382	131,069	145,858	166,997	1,440,000	1,440,000	1,301,189	1,260,381	145,858	131,069	122,602
	PV	0	118,382	131,069	145,858	166,997	211,392	211,392	211,392	211,392	145,858	131,069	122,602
	H-PV	0	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000
	WT	0	1,884,793	2,268,000	1,242,000	2,592,000	1,620,000	2,052,000	1,998,000	1,537,200	1,753,200	1,645,200	1,829,781
	Gen-Total	0	6,915,087	7,374,413	6,437,146	7,913,981	8,797,389	9,292,807	9,042,929	8,484,253	6,948,346	6,751,613	6,885,391
	Esal-Total	0	167,207	0	0	0	0	0	0	0	0	0	384,219
	Etostore-Total	0	706,176	0	57,600	409,142	234,855	1,380,589	603,257	192,323	185,710	185,710	924,672
	Total	0	7,788,471	7,374,413	6,494,746	8,323,123	9,032,244	10,673,395	9,646,186	8,676,576	7,134,056	6,937,323	8,194,281
Scenario 4	H-ICES	0	97,243	101,462	131,069	147,974	175,450	196,589	207,158	183,917	171,230	152,208	120,499
	H-ICEL	0	97,243	101,462	131,069	147,974	175,450	196,589	207,158	183,917	171,230	152,208	120,499
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	0	97,243	101,462	131,069	147,974	175,450	196,589	207,158	183,917	171,230	152,208	120,499
	HC-GT	0	97,243	101,462	131,069	147,974	679,648	679,648	679,648	679,648	171,230	152,208	120,499
	HC-GE	0	97,243	101,462	131,069	147,974	340,865	1,440,000	1,440,000	1,413,060	171,230	152,208	120,499
	PV	0	97,243	101,462	131,069	147,974	211,392	211,392	211,392	183,917	171,230	152,208	120,499
	H-PV	0	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000
	WT	0	923,310	2,268,000	771,219	2,592,000	1,620,000	2,052,000	1,998,000	1,561,075	1,749,600	1,641,600	1,700,041
	Gen-Total	0	5,826,769	7,196,774	5,877,631	7,799,846	7,698,254	9,292,807	9,270,515	8,709,450	7,096,982	6,874,848	6,743,037
	Esal-Total	0	1,128,690	0	0	0	0	0	0	0	0	0	513,959
	Etostore-Total	0	1,987,363	2,175,030	470,781	1,738,010	0	1,274,672	1,962,203	1,351,657	208,924	208,924	1,322,023
	Total	0	8,942,822	9,371,804	6,348,413	9,537,857	7,698,254	10,567,478	11,232,718	10,061,107	7,305,907	7,083,772	8,579,018
Scenario 5	H-ICES	0	105,696	122,602	147,974	169,114	186,019	211,392	190,253	177,566	152,208	128,952	101,462
	H-ICEL	0	105,696	122,602	147,974	169,114	186,019	211,392	190,253	177,566	152,208	128,952	101,462
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	0	105,696	122,602	147,974	169,114	186,019	211,392	190,253	177,566	152,208	128,952	101,462
	HC-GT	0	105,696	122,602	147,974	169,114	679,648	679,648	679,648	679,648	152,208	128,952	101,462
	HC-GE	0	105,696	122,602	147,974	169,114	808,532	1,440,000	1,440,000	1,159,870	152,208	128,952	101,462
	PV	0	105,696	122,602	147,974	169,114	211,392	211,392	211,392	211,392	152,208	128,952	101,462
	H-PV	0	3,947,321	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	3,369,890
	WT	0	1,663,359	2,169,194	1,157,744	2,592,000	1,620,000	2,052,000	1,998,000	1,530,000	1,746,000	1,638,000	1,797,595
	Gen-Total	0	6,244,856	7,224,803	6,365,591	7,926,682	8,197,630	9,337,216	9,219,799	8,433,609	6,979,248	6,731,712	5,776,260
	Esal-Total	0	0	0	0	0	0	0	0	0	0	0	416,405
	Etostore-Total	0	1,800,783	511,517	446,793	2,225,076	121,268	1,573,577	1,125,853	1,298,976	232,138	232,138	935,602
	Total	0	8,045,639	7,736,321	6,812,384	10,151,758	8,318,897	10,910,793	10,345,651	9,732,586	7,211,386	6,963,850	7,128,266

Appendix 9: Scenario analysis under expected cost minimization – Recovered heat usage (Unit: 10 kWh)

	DER source	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Scenario 1	H-ICES	0	399,600	0	269,837	308,994	397,284	332,414	399,600	0	277,669	0	399,600	2,784,998
	H-ICEL	144,427	191,762	0	0	1,316,101	203,736	1,756,800	0	1,482,034	183,111	1,023,423	0	6,301,396
	HC-FC	147,978	158,544	237,240	0	195,534	208,746	0	0	0	187,614	0	161,190	1,296,846
	HC-GT	290,037	0	0	0	0	0	0	434,129	0	0	0	479,110	1,203,276
	HC-GE	144,427	0	605,627	1,039,393	0	0	1,123,276	401,720	0	0	170,216	157,321	3,641,981
	H-PV	0	0	0	0	0	166,997	0	169,114	0	0	139,522	0	475,632
	Total RHeat	726,868	749,906	842,867	1,309,230	1,820,630	976,763	3,212,490	1,404,563	1,482,034	648,394	1,333,161	1,197,222	15,704,129
Scenario 2	H-ICES	183,816	215,091	265,920	0	0	0	0	336,330	289,390	0	0	160,346	1,450,894
	H-ICEL	121,219	141,844	175,364	0	0	0	0	221,796	0	0	45,618	0	705,841
	HC-FC	124,200	0	179,676	0	229,896	0	0	45,858	195,534	169,110	132,120	108,342	1,184,736
	HC-GT	243,432	0	0	1,162,363	3,141,307	0	2,235,731	790,665	0	1,089,604	3,141,307	2,395,445	14,199,854
	HC-GE	121,219	1,040,303	0	1,756,800	166,547	1,756,800	0	0	1,756,800	0	1,756,800	105,742	8,461,010
	H-PV	99,360	0	143,741	0	183,917	205,056	0	181,800	0	0	105,696	86,674	1,006,243
	Total RHeat	893,246	1,397,238	764,701	2,919,163	3,721,666	1,961,856	2,235,731	1,576,449	2,241,724	1,258,714	5,181,540	2,856,549	27,008,579
Scenario 3	H-ICES	199,454	219,007	242,477	269,837	308,944	0	0	328,498	293,306	269,837	242,477	226,813	2,600,650
	H-ICEL	131,532	144,427	159,904	177,946	203,736	214,049	239,838	216,631	193,424	177,946	159,904	149,574	2,168,910
	HC-FC	134,766	147,978	163,836	182,322	208,746	219,312	245,736	221,958	198,180	182,322	163,836	153,252	2,222,244
	HC-GT	264,141	3,141,307	3,083,707	3,083,707	2,868,647	0	0	2,874,052	0	2,984,396	2,984,396	3,141,307	24,425,659
	HC-GE	131,532	1,756,800	159,904	1,756,800	1,451,318	1,082,272	572,511	1,473,642	1,360,017	1,679,685	1,756,800	1,756,800	14,938,080
	H-PV	3,287,697	118,382	3,010,351	610,941	166,997	175,450	423,589	4,320,000	158,544	2,636,228	131,069	122,602	15,161,849
	Total RHeat	4,149,121	5,527,901	6,820,179	6,081,552	5,208,388	1,691,082	1,481,675	9,434,780	2,203,471	7,930,414	5,438,482	5,550,347	61,517,393
Scenario 4	H-ICES	172,068	179,900	0	242,477	273,753	324,582	363,689	383,243	340,246	316,776	281,585	222,924	3,101,242
	H-ICEL	113,472	118,637	123,784	159,904	180,529	214,049	239,838	252,733	224,378	208,901	185,694	147,009	2,168,928
	HC-FC	116,262	121,554	126,828	163,836	184,968	219,312	245,736	258,948	229,896	214,038	190,260	150,624	2,222,262
	HC-GT	3,009,303	173,446	0	3,141,307	0	0	1,486,804	1,005,859	0	242,990	196,385	295,223	9,551,317
	HC-GE	113,472	118,637	0	159,904	180,529	1,756,800	1,756,800	1,756,800	602,424	208,901	185,694	147,009	6,986,969
	H-PV	337,820	3,153,220	3,400,402	131,069	2,845,770	175,450	3,465,571	4,320,000	183,917	4,320,000	4,320,000	3,953,363	30,606,581
	Total RHeat	3,862,396	3,865,393	3,651,015	3,998,497	3,665,548	2,690,192	7,558,438	7,977,584	1,580,861	5,511,607	5,359,618	4,916,152	54,637,300
Scenario 5	H-ICES	0	0	114,476	273,753	0	344,136	391,075	351,968	328,498	281,585	238,561	0	2,324,051
	H-ICEL	0	128,949	149,574	180,529	206,319	226,943	257,898	232,108	216,631	185,694	157,321	123,784	2,065,751
	HC-FC	0	132,120	153,252	184,968	211,392	232,524	264,240	237,816	221,958	190,260	161,190	126,828	2,116,548
	HC-GT	0	0	0	0	0	3,141,307	1,593,873	1,787,291	1,703,701	176,772	119,794	0	8,522,738
	HC-GE	0	0	149,574	180,529	0	226,943	1,756,800	743,369	379,082	185,694	157,321	0	3,779,312
	H-PV	0	3,118,622	4,320,000	4,320,000	3,041,165	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	2,994,360	43,714,147
	Total RHeat	0	3,379,691	4,886,876	5,139,778	3,458,876	8,491,853	8,583,886	7,672,552	7,169,870	5,340,004	5,154,189	3,244,972	62,522,546

Appendix 10: Scenario analysis under worst-case cost minimization – Distribution of power generation (Unit: 10 kWh)

	DER source	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Scenario 1	H-ICES	118,382	216,000	216,000	145,858	167,024	214,748	179,683	216,000	216,000	150,091	216,000	216,000
	H-ICEL	118,382	157,182	1,440,000	145,858	1,078,772	166,997	1,440,000	1,440,000	1,214,782	150,091	1,211,580	128,952
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	118,382	126,835	189,792	211,392	156,427	166,997	211,392	211,392	160,661	150,091	139,522	128,952
	HC-GT	118,382	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	177,196	1,282,166	1,282,166	1,282,166	1,282,166
	HC-GE	118,382	668,049	496,416	851,961	1,440,000	1,440,000	1,370,022	1,440,000	667,792	150,091	139,522	128,952
	PV	118,382	126,835	135,288	145,858	156,427	166,997	179,683	169,114	160,661	150,091	139,522	128,952
	H-PV	118,382	126,835	135,288	145,858	156,427	166,997	179,683	169,114	160,661	150,091	139,522	128,952
	WT	2,484,000	1,019,463	2,268,000	1,242,000	2,422,052	1,089,010	2,052,000	1,998,000	1,566,000	1,782,000	1,674,000	1,504,812
	Gen-Total	3,312,677	3,723,367	6,162,950	4,170,950	6,859,295	4,693,911	6,894,629	5,820,815	5,428,723	3,964,713	4,941,832	3,647,738
	Esal-Total	0	0	819,699	0	0	509,390	0	0	0	761,866	0	0
	Etostore-Total	337,390	5,115,699	5,454,595	3,750,951	5,076,134	4,919,707	4,154,980	3,397,720	4,738,700	3,520,109	4,170,013	2,948,470
	Total	3,650,067	8,839,066	12,437,243	7,921,900	11,935,429	10,123,008	11,049,610	9,218,534	10,167,422	8,246,688	9,111,845	6,596,208
Scenario 2	H-ICES	99,360	116,266	143,741	164,880	183,917	216,000	198,706	181,800	156,427	135,288	105,696	86,674
	H-ICEL	99,360	116,266	143,741	164,880	183,917	205,056	198,706	181,800	156,427	135,288	105,696	86,674
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	99,360	116,266	143,741	164,880	183,917	205,056	198,706	181,800	156,427	135,288	105,696	86,674
	HC-GT	99,360	1,264,820	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166
	HC-GE	99,360	852,707	1,440,000	1,440,000	1,440,000	1,440,000	1,440,000	1,440,000	1,440,000	135,288	1,440,000	86,674
	PV	99,360	116,266	143,741	164,880	183,917	205,056	198,706	181,800	156,427	135,288	105,696	86,674
	H-PV	99,360	116,266	143,741	164,880	183,917	205,056	198,706	181,800	156,427	135,288	105,696	86,674
	WT	2,484,000	2,052,000	1,417,053	1,242,000	2,592,000	1,620,000	2,026,800	1,972,800	1,540,800	1,756,800	1,648,800	2,214,000
	Gen-Total	3,179,520	4,750,855	4,857,923	4,788,566	6,233,750	5,378,390	5,742,494	5,603,966	5,045,102	3,850,694	4,899,446	4,016,208
	Esal-Total	0	0	0	0	0	0	0	0	0	0	0	0
	Etostore-Total	0	3,360,406	5,749,054	2,856,105	2,154,878	4,047,395	3,744,689	4,314,034	3,513,775	2,792,576	304,069	851,603
	Total	3,179,520	8,111,261	10,606,977	7,644,671	8,388,628	9,425,785	9,487,183	9,918,000	8,558,877	6,643,270	5,203,515	4,867,811
Scenario 3	H-ICES	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
	H-ICEL	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
	HC-GT	107,813	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166	1,282,166
	HC-GE	107,813	1,440,000	131,069	1,440,000	1,189,605	1,440,000	1,440,000	1,207,903	1,440,000	1,376,791	1,440,000	1,440,000
	PV	107,813	118,382	131,069	145,858	166,997	175,450	196,589	177,566	158,544	145,858	131,069	122,602
	H-PV	3,287,697	118,382	3,010,351	610,941	166,997	175,450	423,589	4,320,000	158,544	2,636,228	131,069	122,602
	WT	2,484,000	2,052,000	2,268,000	1,242,000	2,592,000	1,620,000	2,052,000	1,937,200	1,566,000	1,753,200	1,645,200	2,214,000
	Gen-Total	6,418,574	5,366,078	7,215,861	5,158,537	5,898,755	5,219,414	5,984,110	9,457,535	5,080,886	7,631,815	5,022,710	5,549,174
	Esal-Total	0	0	0	0	0	0	0	0	0	0	0	0
	Etostore-Total	0	0	57,600	57,600	272,660	4,140,417	4,689,285	328,055	3,538,090	185,710	185,710	0
	Total	6,418,574	5,366,078	7,273,461	5,216,137	6,171,415	9,359,831	10,673,395	9,785,590	8,618,976	7,817,526	5,208,420	5,549,174
Scenario 4	H-ICES	93,010	97,243	101,462	131,069	147,974	175,450	196,589	207,158	183,917	171,230	152,208	120,499
	H-ICEL	93,010	97,243	101,462	131,069	147,974	175,450	196,589	207,158	183,917	171,230	152,208	120,499
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	93,010	97,243	101,462	131,069	147,974	175,450	196,589	207,158	183,917	171,230	152,208	120,499
	HC-GT	1,228,287	97,243	101,462	1,282,166	627,652	1,282,166	1,282,166	1,282,166	1,282,166	171,230	152,208	120,499
	HC-GE	93,010	97,243	101,462	131,069	147,974	1,440,000	1,440,000	1,440,000	1,440,000	171,230	152,208	120,499
	PV	93,010	97,243	101,462	131,069	147,974	175,450	196,589	207,158	183,917	171,230	152,208	120,499
	H-PV	337,820	3,153,220	3,644,942	131,069	2,845,770	175,450	3,465,571	4,320,000	183,917	4,320,000	4,320,000	3,953,363
	WT	2,484,000	2,052,000	2,268,000	1,089,156	2,592,000	1,620,000	2,052,000	1,929,600	1,566,000	1,749,600	1,641,600	2,214,000
	Gen-Total	4,515,155	5,788,679	6,521,717	3,157,734	6,805,294	5,219,414	9,026,092	9,800,400	5,207,750	7,096,982	6,874,848	6,890,358
	Esal-Total	0	0	0	0	0	0	0	0	0	0	0	0
	Etostore-Total	0	64,800	804,612	152,844	1,537,747	3,141,307	1,654,503	2,203,847	4,295,683	208,924	208,924	0
	Total	4,515,155	5,853,479	7,326,329	3,310,579	8,343,041	8,360,721	10,680,595	12,004,247	9,503,433	7,305,907	7,083,772	6,890,358
Scenario 5	H-ICES	0	105,696	122,602	147,974	169,114	186,019	211,392	190,253	177,566	152,208	128,952	101,462
	H-ICEL	0	105,696	122,602	147,974	169,114	186,019	211,392	190,253	177,566	152,208	128,952	101,462
	FC	0	0	0	0	0	0	0	0	0	0	0	0
	HC-FC	0	105,696	122,602	147,974	169,114	186,019	211,392	190,253	177,566	152,208	128,952	101,462
	HC-GT	0	105,696	122,602	147,974	169,114	1,282,166	1,282,166	1,282,166	1,282,166	152,208	128,952	101,462
	HC-GE	0	105,696	122,602	147,974	169,114	186,019	1,440,000	609,319	310,723	152,208	128,952	101,462
	PV	0	105,696	122,602	147,974	169,114	211,392	211,392	211,392	211,392	152,208	128,952	101,462
	H-PV	0	3,947,321	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	3,369,890
	WT	0	1,663,359	2,169,194	1,157,744	2,592,000	1,620,000	2,052,000	1,998,000	1,566,000	1,746,000	1,638,000	1,797,595
	Gen-Total	0	6,244,856	7,224,803	6,365,591	7,926,682	8,177,635	9,939,734	8,991,635	8,222,980	6,979,248	6,731,712	5,776,260
	Esal-Total	0	388,641	0	0	0	0	0	0	0	0	0	416,405
	Etostore-Total	0	1,412,142	511,517	446,793	2,212,342	0	1,547,434	1,354,016	1,437,605	232,138	232,138	935,602
	Total	0	8,045,639	7,736,321	6,812,384	10,139,024	8,177,635	11,487,168	10,345,651	9,660,586	7,211,386	6,963,850	7,128,266

Appendix 11: Scenario analysis under worst-case cost minimization – Recovered heat usage (Unit: 10 kWh)

	DER source	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Scenario 1	H-ICES	0	399,600	0	269,837	308,994	397,284	332,414	399,600	0	277,669	0	399,600	2,784,998
	H-ICEL	144,427	191,762	0	0	1,316,101	203,736	1,756,800	0	1,482,034	183,111	1,023,423	0	6,301,396
	HC-FC	147,978	158,544	237,240	0	195,534	208,746	0	0	0	187,614	0	161,190	1,296,846
	HC-GT	290,037	0	0	0	0	0	0	434,129	0	0	0	479,110	1,203,276
	HC-GE	144,427	0	605,627	1,039,393	0	0	1,123,276	401,720	0	0	170,216	157,321	3,641,981
	H-PV	0	0	0	0	0	166,997	0	169,114	0	0	139,522	0	475,632
	Total RHeat	726,868	749,906	842,867	1,309,230	1,820,630	976,763	3,212,490	1,404,563	1,482,034	648,394	1,333,161	1,197,222	15,704,129
Scenario 2	H-ICES	183,816	215,091	265,920	0	0	0	0	336,330	289,390	0	0	160,346	1,450,894
	H-ICEL	121,219	141,844	175,364	0	0	0	0	221,796	0	0	45,618	0	705,841
	HC-FC	124,200	0	179,676	0	229,896	0	0	45,858	195,534	169,110	132,120	108,342	1,184,736
	HC-GT	243,432	0	0	1,162,363	3,141,307	0	2,235,731	790,665	0	1,089,604	3,141,307	2,395,445	14,199,854
	HC-GE	121,219	1,040,303	0	1,756,800	166,547	1,756,800	0	0	1,756,800	0	1,756,800	105,742	8,461,010
	H-PV	99,360	0	143,741	0	183,917	205,056	0	181,800	0	0	105,696	86,674	1,006,243
	Total RHeat	893,246	1,397,238	764,701	2,919,163	3,721,666	1,961,856	2,235,731	1,576,449	2,241,724	1,258,714	5,181,540	2,856,549	27,008,579
Scenario 3	H-ICES	199,454	219,007	242,477	269,837	308,944	0	0	328,498	293,306	269,837	242,477	226,813	2,600,650
	H-ICEL	131,532	144,427	159,904	177,946	203,736	214,049	239,838	216,631	193,424	177,946	159,904	149,574	2,168,910
	HC-FC	134,766	147,978	163,836	182,322	208,746	219,312	245,736	221,958	198,180	182,322	163,836	153,252	2,222,244
	HC-GT	264,141	3,141,307	3,083,707	3,083,707	2,868,647	0	0	2,874,052	0	2,984,396	2,984,396	3,141,307	24,425,659
	HC-GE	131,532	1,756,800	159,904	1,756,800	1,451,318	1,082,272	572,511	1,473,642	1,360,017	1,679,685	1,756,800	1,756,800	14,938,080
	H-PV	3,287,697	118,382	3,010,351	610,941	166,997	175,450	423,589	4,320,000	158,544	2,636,228	131,069	122,602	15,161,849
	Total RHeat	4,149,121	5,527,901	6,820,179	6,081,552	5,208,388	1,691,082	1,481,675	9,434,780	2,203,471	7,930,414	5,438,482	5,550,347	61,517,393
Scenario 4	H-ICES	172,068	179,900	0	242,477	273,753	324,582	363,689	383,243	340,246	316,776	281,585	222,924	3,101,242
	H-ICEL	113,472	118,637	123,784	159,904	180,529	214,049	239,838	252,733	224,378	208,901	185,694	147,009	2,168,928
	HC-FC	116,262	121,554	126,828	163,836	184,968	219,312	245,736	258,948	229,896	214,038	190,260	150,624	2,222,262
	HC-GT	3,009,303	173,446	0	3,141,307	0	0	1,486,804	1,005,859	0	242,990	196,385	295,223	9,551,317
	HC-GE	113,472	118,637	0	159,904	180,529	1,756,800	1,756,800	1,756,800	602,424	208,901	185,694	147,009	6,986,969
	H-PV	337,820	3,153,220	3,400,402	131,069	2,845,770	175,450	3,465,571	4,320,000	183,917	4,320,000	4,320,000	3,953,363	30,606,581
	Total RHeat	3,862,396	3,865,393	3,651,015	3,998,497	3,665,548	2,690,192	7,558,438	7,977,584	1,580,861	5,511,607	5,359,618	4,916,152	54,637,300
Scenario 5	H-ICES	0	0	114,476	273,753	0	344,136	391,075	351,968	328,498	281,585	238,561	0	2,324,051
	H-ICEL	0	128,949	149,574	180,529	206,319	226,943	257,898	232,108	216,631	185,694	157,321	123,784	2,065,751
	HC-FC	0	132,120	153,252	184,968	211,392	232,524	264,240	237,816	221,958	190,260	161,190	126,828	2,116,548
	HC-GT	0	0	0	0	0	3,141,307	1,593,873	1,787,291	1,703,701	176,772	119,794	0	8,522,738
	HC-GE	0	0	149,574	180,529	0	226,943	1,756,800	743,369	379,082	185,694	157,321	0	3,779,312
	H-PV	0	3,118,622	4,320,000	4,320,000	3,041,165	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	4,320,000	2,994,360	43,714,147
	Total RHeat	0	3,379,691	4,886,876	5,139,778	3,458,876	8,491,853	8,583,886	7,672,552	7,169,870	5,340,004	5,154,189	3,244,972	62,522,546

Appendix 12:

The GAMS Codes

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Set
i power source /H-ICES, H-ICEL, FC, HC-FC, HC-GT, HC-GE, PV, H-PV, WT/
pv(i) solar source /PV, H-PV/
w(i) wind source /WT/
m month in a year /Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec/
f index of fuel type /Biomass, Hydrogen, Natural-gas, Solar, Wind/
t storage type including electricity and heat /elec, heat/
u end uses of energy including electricity and heating and cooling /elec, heat, cool/
s scenario /1*5/
;

alias(i,j);

Parameter
p(s) probability of the scenario /1 0.15, 2 0.2, 3 0.3, 4 0.25, 5 0.1/
Inst Interest Rate /0.03/
EDchar(s) Regulated demand charge of electricity /1 10.33, 2 12.91, 3 15.50, 4 18.08, 5
20.66/
ECInt Carbon intensity of electricity in kgC per kWh /1/
CTax(s) Carbon tax per kg of carbon credit /1 0.043, 2 0.052, 3 0.060, 4 0.069, 5 0.086/
A A large number /99999999999/
B The number of other sources that must be operating when a source is in use /7/
C Assumed multiplied factor of peak electricity demand over average electricity demand
/1.25/
D Conversion factor of area of PV panels vs. 1kW electricity capacity /8.96/
G Proportion factor that is used to control the minimum power output of each source /93/
L The weight of expected value in the dual objective function /1/

alpha(i) heat recovery efficiency /H-ICES 1.85, H-ICEL 1.22, FC 0.00, HC-FC 1.25, HC-GT
2.45,
HC-GE 1.22, PV 0.00, H-PV 1.00, WT 0.00/
epsilon(t) storage coefficient /elec 0.9, heat 0.8/
theta minimum percentage of electricity purchase /0.2/
omega(i) unit start and stop cost /H-ICES 1000, H-ICEL 3000, FC 200, HC-FC 200, HC-GT
1000,
HC-GE 3000, PV 0, H-PV 0, WT 200/

table beta(f,u) "heat efficiency from direct fuel consumption"
                      elec      heat      cool
Biomass                  0     1.439     1.233
Hydrogen                 0     0.450     0.394
Natural-gas              0     3.591     3.078
Solar                    0         0         0
Wind                     0         0         0
;
$ontext
Note: beta should be calculated as the heat conversion factor multiplied by the equipment
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efficiency
Conversion Factor (including fixed costs)
Biomass: 4.111 => 2.056
Hydrogen: 1.125
Natural-gas 10.26 => 5.13
Equipment Efficiency
Biomass: Heating - 0.35; Cooling - 0.3 => Heating - 0.25; Cooling - 0.2
Hydrogen: Heating - 0.4; Cooling - 0.35 => Heating - 0.35; Cooling - 0.3
Natural-gas: Heating - 0.35; Cooling - 0.3 => Heating - 0.25; Cooling - 0.2
$offtext

table gamma(i,u) "utilization efficiency of recovered heat"
                elec      heat      cool
H-ICES          0.80      0.85      0.00
H-ICEL          0.90      0.95      0.00
FC              1.00      0.00      0.00
HC-FC           1.00      1.00      1.00
HC-GT           0.70      0.75      0.70
HC-GE           0.80      0.85      0.80
PV              1.00      0.00      0.00
H-PV            1.00      1.00      0.95
WT              0.00      0.00      0.00
;

table delta(t,u) "utilization efficiency of stored energy"
        elec      heat      cool
elec    0.81      0.81      0.81
heat    0.71      0.71      0.71
;

table Fprice(f,s) "unit fuel charge"
                    1         2         3         4         5
Biomass         0.200     0.250     0.300     0.350     0.400
Hydrogen        0.336     0.420     0.504     0.588     0.672
Natural-gas     0.275     0.344     0.413     0.481     0.550
Solar           0.000     0.000     0.000     0.000     0.000
Wind            0.000     0.000     0.000     0.000     0.000
;

table eff(i,f) "Efficiency of DER technology i"
            Biomass      Hydrogen    Natural-gas        Solar         Wind
H-ICES         0.31             0              0            0            0
H-ICEL         0.37             0              0            0            0
FC                0          0.36              0            0            0
HC-FC             0          0.40              0            0            0
HC-GT             0             0           0.26            0            0
HC-GE             0             0           0.34            0            0
PV                0             0              0         0.12            0
H-PV              0             0              0         0.20            0
WT                0             0              0            0            1
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```
;

table effRF(i,f) "Conversion factor of fuel consumption"
            Biomass     Hydrogen    Natural-gas     Solar       Wind
H-ICES      1.452       0           0               0           0
H-ICEL      1.216       0           0               0           0
FC          0           3.087       0               0           0
HC-FC       0           2.778       0               0           0
HC-GT       0           0           0.641           0           0
HC-GE       0           0           0.490           0           0
PV          0           0           0               8.333       0
H-PV        0           0           0               5           0
WT          0           0           0               0           1
;
$ontext
Note: effRF(i,f) should be calculated as the "Reciprocal of eff(i,f)"(kWh) divided by the fuel
to electricity conversion factor
Biomass: 2.222
Hydrogen: 0.9
Natural-gas: 6.00
$offtext

table FCost(i,s) "Fixed cost of source i in $ per kW in scenario s"
            1       2       3       4       5
H-ICES      1458    1458    1458    1458    1458
H-ICEL      1118    1118    1118    1118    1118
FC          5243    5243    5243    5243    5243
HC-FC       5622    5622    5622    5622    5622
HC-GT       2238    2238    2238    2238    2238
HC-GE       1087    1087    1087    1087    1087
PV          5000    4500    4000    3500    3000
H-PV        5714    5143    4571    4000    3428
WT          3000    2700    2400    2100    1800
;

table LTime(i,s) "Life time period of equipment in year"
            1    2    3    4    5
H-ICES      20   20   20   20   20
H-ICEL      20   20   20   20   20
FC          10   10   10   10   10
HC-FC       10   10   10   10   10
HC-GT       20   20   20   20   20
HC-GE       20   20   20   20   20
PV          30   30   30   30   30
H-PV        30   30   30   30   30
WT          20   20   20   20   20
;

table OMf(i,s) "Fixed operation and maintenance cost in USD per kW per year"
            1       2       3       4       5
```

```
H-ICES        0.00     0.00     0.00     0.00     0.00
H-ICEL        0.00     0.00     0.00     0.00     0.00
FC            0.00     0.00     0.00     0.00     0.00
HC-FC        10.15    10.15    10.15    10.15    10.15
HC-GT        10.86    10.86    10.86    10.86    10.86
HC-GE         4.58     4.58     4.58     4.58     4.58
PV            9.00     9.00     9.00     9.00     9.00
H-PV          9.52     9.52     9.52     9.52     9.52
WT            6.52     6.52     6.52     6.52     6.52
;

table OMv(i,s) "Variable operation and maintenance cost in USD per kWh"
                 1        2        3        4        5
H-ICES        0.01     0.01     0.01     0.01     0.01
H-ICEL        0.01     0.01     0.01     0.01     0.01
FC            0.03     0.03     0.03     0.03     0.03
HC-FC         0.03     0.03     0.03     0.03     0.03
HC-GT         0.01     0.01     0.01     0.01     0.01
HC-GE         0.01     0.01     0.01     0.01     0.01
PV            0.00     0.00     0.00     0.00     0.00
H-PV          0.00     0.00     0.00     0.00     0.00
WT            0.00     0.00     0.00     0.00     0.00
;

table MaxEqm(i,s) "Maximum power capacity of DER technology i in scenario s in kW"
                 1        2        3        4        5
H-ICES        2000     2000     2000     2000     2000
H-ICEL        6000     6000     6000     6000     6000
FC            2000     2000     2000     2000     2000
HC-FC         3000     3000     3000     3000     3000
HC-GT         2000     2000     2000     2000     2000
HC-GE         6000     6000     6000     6000     6000
PV            6000     6000     6000     6000     6000
H-PV          6000     6000     6000     6000     6000
WT            6000     6000     6000     6000     6000
;

table MinEqm(i,s) "Minimum power capacity of DER technology i in scenario s in kW"
                 1        2        3        4        5
H-ICES         300      300      300      300      300
H-ICEL        2000     2000     2000     2000     2000
FC             200      200      200      200      200
HC-FC          200      200      200      200      200
HC-GT          100      100      100      100      100
HC-GE         2000     2000     2000     2000     2000
PV               0        0        0        0        0
H-PV             0        0        0        0        0
WT             200      200      200      200      200
;
```

```
table ESMax(t,s) "Maximum energy storage level in kWh"
              1          2          3          4          5
elec    2160000    2520000    2880000    3240000    3600000
heat    2160000    2520000    2880000    3240000    3600000
;

table ESMin(t,s) "Minimum energy storage level"
              1          2          3          4          5
elec     216000     252000     288000     324000     360000
heat     216000     252000     288000     324000     360000
;

table ESInl(t,s) "Initial energy storage level"
              1          2          3          4          5
elec     720000     900000    1080000    1260000    1440000
heat     720000     900000    1080000    1260000    1440000
;

table Sprice(i,s) "electricity selling price in USD per kWh"
             1        2        3        4        5
H-ICES     0.09     0.09     0.09     0.09     0.09
H-ICEL     0.09     0.09     0.09     0.09     0.09
FC         0.09     0.09     0.09     0.09     0.09
HC-FC      0.09     0.09     0.09     0.09     0.09
HC-GT      0.09     0.09     0.09     0.09     0.09
HC-GE      0.09     0.09     0.09     0.09     0.09
PV         0.09     0.09     0.09     0.09     0.09
H-PV       0.09     0.09     0.09     0.09     0.09
WT         0.09     0.09     0.09     0.09     0.09
;
$ontext
table Sprice(i,s) "electricity selling price in USD per kWh"
             1        2        3        4        5
H-ICES     0.09     0.09     0.09     0.09     0.09
H-ICEL     0.09     0.09     0.09     0.09     0.09
FC         0.43     0.43     0.43     0.43     0.43
HC-FC      0.43     0.43     0.43     0.43     0.43
HC-GT      0.08     0.08     0.08     0.08     0.08
HC-GE      0.08     0.08     0.08     0.08     0.08
PV         0.32     0.40     0.48     0.40     0.32
H-PV       0.32     0.40     0.48     0.40     0.32
WT         0.09     0.14     0.18     0.14     0.09
;
$offtext

table FCInt(f,s) "Carbon intensity of fuel in kgC per unit of fuel"
                  1         2         3         4         5
Biomass       4.266     4.266     4.266     4.266     4.266
Hydrogen      0.497     0.497     0.497     0.497     0.497
Natural-gas   2.844     2.844     2.844     2.844     2.844
```

```
Solar             0.217     0.217     0.217     0.217     0.217
Wind                0.032     0.032     0.032     0.032     0.032
;

table Vc(i,s) "Cut in wind speed of wind turbine i in m per s"
                  1          2          3          4          5
WT              2.0       2.0       2.0       2.0       2.0
;

table Vn(i,s) "Nominal wind speed of wind turbine i"
                  1           2           3           4           5
WT              10.0       10.0       10.0       10.0       10.0
;

table Vf(i,s) "Cut off wind speed of wind turbine i"
                  1           2           3           4           5
WT              14.0       14.0       14.0       14.0       14.0
;

table Eprice(m,s) "unit rate for electricity purchase from the national grid per kWh"
                1          2          3          4          5
Jan        0.16       0.20       0.24       0.28       0.32
Feb         0.16       0.20       0.24       0.28       0.32
Mar          0.16       0.20       0.24       0.28       0.32
Apr         0.16       0.20       0.24       0.28       0.32
May          0.16       0.20       0.24       0.28       0.32
Jun        0.32       0.40       0.48       0.56       0.64
Jul        0.32       0.40       0.48       0.56       0.64
Aug         0.32       0.40       0.48       0.56       0.64
Sep         0.32       0.40       0.48       0.56       0.64
Oct         0.16       0.20       0.24       0.28       0.32
Nov          0.16       0.20       0.24       0.28       0.32
Dec          0.16       0.20       0.24       0.28       0.32
;

table CLoad(m,u,s) "Average customer load in kW in scenario s"
                         1          2          3          4          5
Jan. elec       8221       6900       7487       6459       5872
Jan. heat       5481       4600       4991       4306       3915
Jan. cool       2740       2300       2496       2153       1957
Feb. elec       8808       8074       8221       6753       7340
Feb. heat       5872       5383       5481       4502       4893
Feb. cool       2936       2691       2740       2251       2447
Mar. elec       9395       9982       9102       7046       8514
Mar. heat       6264       6655       6068       4698       5676
Mar. cool       3131       3327       3034       2348       2838
Apr. elec      10129      11450      10129       9102      10276
Apr. heat       5065       5725       5065       4551       5138
Apr. cool       5064       5725       5064       4551       5138
May. elec      10863      12772      11597      10276      11744
```

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May. heat      5432     6386     5799     5138     5872
May. cool      5431     6386     5798     5138     5872
Jun. elec     11597    14240    12184    12184    12918
Jun. heat      3866     4747     4062     4062     4306
Jun. cool      7731     9493     8122     8122     8612
Jul. elec     12478    13799    13652    13652    14680
Jul. heat      4159     4600     4551     4551     4893
Jul. cool      8319     9199     9101     9101     9787
Aug. elec     11744    12625    12331    14386    13212
Aug. heat      3915     4208     4110     4796     4404
Aug. cool      7829     8417     8221     9590     8808
Sep. elec     11157    10863    11010    12772    12331
Sep. heat      3719     3621     3670     4257     4110
Sep. cool      7438     7242     7340     8515     8221
Oct. elec     10423     9395    10129    11891    10570
Oct. heat      5211     4698     5065     5945     5285
Oct. cool      5212     4697     5064     5946     5285
Nov. elec      9689     7340     9102    10570     8955
Nov. heat      4844     3670     4551     5285     4477
Nov. cool      4845     3670     4551     5285     4478
Dec. elec      8955     6019     8514     8368     7046
Dec. heat      5970     4013     5676     5578     4698
Dec. cool      2985     2006     2838     2790     2348
;

table R(m,s) "irradiation data in kW per square meter"
             1         2         3         4         5
Jan      91.86     91.86     91.86     91.86     91.86
Feb     105.46    105.46    105.46    105.46    105.46
Mar     108.84    108.84    108.84    108.84    108.84
Apr     133.60    133.60    133.60    133.60    133.60
May     131.43    131.43    131.43    131.43    131.43
Jun     157.18    157.18    157.18    157.18    157.18
Jul     159.39    159.39    159.39    159.39    159.39
Aug     136.21    136.21    136.21    136.21    136.21
Sep     136.08    136.08    136.08    136.08    136.08
Oct     127.07    127.07    127.07    127.07    127.07
Nov      91.80     91.80     91.80     91.80     91.80
Dec      96.58     96.58     96.58     96.58     96.58
;

table Vw(m,s) "On-site wind speed in m per s"
           1       2       3       4       5
Jan      6.6     6.6     6.6     6.6     6.6
Feb      5.8     5.8     5.8     5.8     5.8
Mar      6.2     6.2     6.2     6.2     6.2
Apr      4.3     4.3     4.3     4.3     4.3
May      6.8     6.8     6.8     6.8     6.8
Jun      5.0     5.0     5.0     5.0     5.0
Jul      5.8     5.8     5.8     5.8     5.8
```

```
Aug      5.7     5.7     5.7     5.7     5.7
Sep      4.9     4.9     4.9     4.9     4.9
Oct      5.3     5.3     5.3     5.3     5.3
Nov      5.1     5.1     5.1     5.1     5.1
Dec      6.1     6.1     6.1     6.1     6.1
;


Positive variables
Efrom(i,m,u,s) Amount of electricity produced from source i for end use u in month m in scenario s
ESal(i,m,s) Amount of electricity sold to national grid
EbuyN(m,u,s) Amount of electricity bought from national grid in kWh in month m in scenario s
MaxEbuyN(m,s) Peak electricity demand in every month
Fuel(f,m,u,s) Amount of fuel consumption
RHeat(i,m,u,s) Recovered heat from DER equipments
prodSolar(i,m,s) Possible power output from solar sources in scenario s
prodWind(i,m,s) Possible power output from wind sources in scenario s
EStore(t,m,s) Amount of energy stored in the battery or heat storage in scenario s
Etostore(i,t,m,s) Amount of excess energy sent to the storage in scenario s
Efromstore(t,m,u,s) Amount of energy output from the storage in scenario s
Cap(i) Capacity of adopted DER source i
Allot(i,m,s) Allocation of capacity of source i to the operation in month m in scenario s
APV(i,m,s) Area of solar panel in scenario s
;

Binary variable
x(i,m,s) equals 1 when source i is operating in month m in scenario s otherwise 0
EqStart(i,m,s) equals to 1 when source i starts up in month m in scenario s otherwise 0
EqStop(i,m,s) equals to 1 when source i stops in month m in scenario s otherwise 0
;

Variable
Cost(s) Total cost of scenario s
CInv(s) Cost of capital investments in scenario s
CEbuyN(s) Cost of purchasing national grid electricity in scenario s
CFuel(s) Cost of fuel consumption in scenario s
COM(s) Cost of operation and maintenance in scenario s
CCtax(s) Cost of carbon tax in scenario s
CSS(s) Cost of start and stop in scenario s
CSal(s) Revenue from sales of energy in scenario s
Cw Worst case in terms of cost
Expected Expected cost of scenario s
Obj Value of objective function
;

Equations
DualObj        Dual objective function of expected and Cw
DualObj..      Obj =e= (1-L)*Cw + L*expected;
```

```
Exp         Expected cost of s scenarios with regard to their probabilities
Exp..       Expected =e= sum(s, p(s)*Cost(s));

Const(s)        The worst case of cost(s)
Const(s)..      Cw =g= Cost(s);

ObjFun(s)       Cost of energy used for the microgrid in scenario s
ObjFun(s)..     Cost(s) =e= Inv(s)+CEbuyN(s)+CFuel(s)+COM(s)+CCtax(s)+CSS(s)-CSal(s);

Where
CostInv(s)      Cost of capital investments
CostInv(s)..    CInv(s) =e= sum(i,Cap(i)*FCost(i,s)*(Inst/(1-(1/((1+Inst)**LTime(i,s))))));

CostEbuyN(s)        Cost of purchasing national grid electricity
CostEbuyN(s)..       CEbuyN(s) =e= sum(m,EDchar(s)*MaxEbuyN(m,s)) +
                     sum(m,sum(u,EbuyN(m,u,s))*Eprice(m,s));

MaxEbuyNDemand(m,s)      Peak electricity demand in every month
MaxEbuyNDemand(m,s)..    MaxEbuyN(m,s) =e= sum(u,EbuyN(m,u,s)/720)*C;

CostFuel(s)       Cost of fuel consumption
CostFuel(s)..     CFuel(s) =e= sum(f,(sum(m,sum(u,Fuel(f,m,u,s))) +
                  sum(i,(sum(m,sum(u,Efrom(i,m,u,s)) + ESal(i,m,s) +
                  Etostore(i,'elec',m,s))*effRF(i,f))))*Fprice(f,s));

CostOandM(s)        Cost of equipment operation and maintenance
CostOandM(s)..       COM(s) =e= sum(i,sum(m,(sum(u,Efrom(i,m,u,s))+ESal(i,m,s) +
                     sum(t,Etostore(i,t,m,s))))*OMv(i,s)) + sum(i,Cap(i)*OMf(i,s));

CostCarbonTax(s)          Cost of carbon tax
CostCarbonTax(s)..        CCtax(s) =e= sum(f,(sum(m,sum(u,Fuel(f,m,u,s))) +
  sum(i,(sum(m,sum(u,Efrom(i,m,u,s))+ESal(i,m,s)+Etostore(i,'elec',m,s))*effRF(i,f))))*CTax
  (s)*FCInt(f,s))    + sum(m,sum(u,EbuyN(m,u,s)))*CTax(s)*ECInt;

CostStartStop(s)     Cost of equipment start and stop
CostStartStop(s)..   CSS(s) =e= sum(i,sum(m,((EqStart(i,m,s)+EqStop(i,m,s))*omega(i))));

IncomeSales(s)       Income from sales of electricity to the national grid
IncomeSales(s)..     CSal(s) =e= sum(i,sum(m,ESal(i,m,s)*Sprice(i,s)));


EneBal(m,u,s)        Energy balance and supply-demand relationships
EneBal(m,u,s)..       CLoad(m,u,s)*720 =l= sum(i,Efrom(i,m,u,s)) + EbuyN(m,u,s) +
                      sum(f,beta(f,u)*Fuel(f,m,u,s)) + sum(i,gamma(i,u)*RHeat(i,m,u,s)) +
                      sum(t,delta(t,u)*Efromstore(t,m,u,s));

BinaryEne(i,t,m,s)          Makes binary equal to 1 if energy is produced
BinaryEne(i,t,m,s)..        sum(u,Efrom(i,m,u,s))+ESal(i,m,s)+Etostore(i,'elec',m,s)-A*x(i,m,s)
                      =l= 0;
```

BinaryElec(i,m,s) Makes binary equal to 1 if electricity is produced from source i in month m
BinaryElec(i,m,s).. sum(u,Efrom(i,m,u,s)) =l= A*x(i,m,s);

Allotandx(i,m,s) Relationship between Allot and x
Allotandx(i,m,s).. Allot(i,m,s) =g= x(i,m,s);

BinaryEqStart1(i,m,s) Makes binary equal to 1 if equipment i starts in month m
BinaryEqStart1(i,m,s)$(ORD(m)=1).. x(i,m,s)-0 =e= EqStart(i,m,s);

BinaryEqStart2(i,m,s) Makes binary equal to 1 if equipment i starts in month m
BinaryEqStart2(i,m,s)$(ORD(m)>=2).. x(i,m,s)-x(i,m-1,s) =e= EqStart(i,m,s);

BinaryEqStop(i,m,s) Makes binary equal to 1 if equipment i stops in month m
BinaryEqStop(i,m,s)$(ORD(m)=1).. EqStop(i,m,s) =e= 0;

StartandStop(i,m,s) Start and stop of equipments
StartandStop(i,m,s)$(ORD(m)>=2).. x(i,m,s)-x(i,m-1,s) =e= EqStart(i,m,s)-EqStop(i,m,s);

Ebuyandsell1(m,s) The balance of demand and supply on electricity
Ebuyandsell1(m,s).. sum(u,CLoad(m,'elec',s))*720 + sum(i,ESal(i,m,s)) + sum(i,Etostore(i,'elec',m,s)) =e= sum((u,i),Efrom(i,m,'elec',s)) + EbuyN(m,'elec',s) + sum(t,Efromstore(t,m,'elec',s));

Ebuyandsell2(i,m,s) The excess electricity sold to the national grid cannot be less than zero
Ebuyandsell2(i,m,s).. ESal(i,m,s) =g= 0;

EbuyNShare(s) The electricity purchase has to be not lower than a specific share of the total demand
EbuyNShare(s).. sum(m,sum(u,EbuyN(m,u,s))) =g= theta*sum(m,sum(u,(EbuyN(m,u,s) + sum(i,Efrom(i,m,u,s)) + delta('elec',u)*Efromstore('elec',m,u,s))));

OperCap1(i,s) The capacity of source i has an upper limit
OperCap1(i,s).. Cap(i) =l= MaxEqm(i,s);

OperCap2(i,t,m,s) Lower bound – the amount of power generated should be non-negative
OperCap2(i,t,m,s).. 0 =l= (sum(u,Efrom(i,m,u,s))+ESal(i,m,s)+Etostore(i,'elec',m,s));
OperCap3(i,t,m,s) The amount of power generated should be covered by allocation of source capacity
OperCap3(i,t,m,s).. (sum(u,Efrom(i,m,u,s))+ESal(i,m,s)+Etostore(i,'elec',m,s)) =l= Allot(i,m,s)*720;

OperLmt1(i,m,s) The performance constraint for each of the power source
OperLmt1(i,m,s).. Allot(i,m,s) =l= MinEqm(i,s)+MaxEqm(i,s)*x(i,m,s);

```
OperLmt2(i,m,s)          The performance constraint for each of the power source
OperLmt2(i,m,s)..        Allot(i,m,s) =g= MinEqm(i,s)-MaxEqm(i,s)*(1-x(i,m,s));

OperLmt3(i,m,s)      The allocation of source capacity cannot exceed the total capacity of that
                     DER technology
OperLmt3(i,m,s)..    Allot(i,m,s) =l= Cap(i);
OperLmt4(i,m,s)      The allocation of source capacity cannot be less than zero
OperLmt4(i,m,s)..    Allot(i,m,s) =g= 0;

PVCap(pv,t,m,s)      Electricity produced from PV cannot exceed the total power generation
                     of PV technology
PVCap(pv,t,m,s)..    (sum(u,Efrom(pv,m,u,s))+ESal(pv,m,s)+Etostore(pv,'elec',m,s)) =l=
                     prodSolar(pv,m,s);

PVProd1(pv,f,m,s)        Amount of PV production
PVProd1(pv,f,m,s)..      prodSolar(pv,m,s) =e= APV(pv,m,s)*R(m,s)*eff(pv,'solar')*720;

PVProd2(pv,m,s)          Assume linear relationship between APV and capacity
PVProd2(pv,m,s)..        Allot(pv,m,s) =e= APV(pv,m,s)/D;

WindCap(w,t,m,s)     Electricity produced from wind cannot exceed the total power generation
                     of wind power technology
WindCap(w,t,m,s)..   (sum(u,Efrom(w,m,u,s))+ESal(w,m,s)+Etostore(w,'elec',m,s)) =l=
                     prodWind(w,m,s);

WindProd1(w,m,s)     On-site wind speed is between the cut in speed and nominal speed of the
                     wind turbine
WindProd1(w,m,s)$(Vw(m,s) ge Vc(w,s) and Vw(m,s) le Vn(w,s))..
prodWind(w,m,s) =e= Allot(w,m,s)*((Vw(m,s)-Vc(w,s))/(Vn(w,s)-Vc(w,s)))*720;

WindProd2(w,m,s)     On-site wind speed is between the nominal speed and cut off speed of the
                     wind turbine
WindProd2(w,m,s)$(Vw(m,s) ge Vn(w,s) and Vw(m,s) le Vf(w,s))..
prodWind(w,m,s) =e= Allot(w,m,s)*720;

WindProd3(w,m,s)     On-site wind speed is less than the cut in speed or greater than the cut off
                     speed of the wind turbine
WindProd3(w,m,s)$(Vw(m,s) lt Vc(w,s) or Vw(m,s) gt Vf(w,s))..      prodWind(w,m,s) =e= 0;

HeatRecovery(i,t,m,s)    The limit of heat that can be recovered for immediate usage or
                     storage
HeatRecovery(i,t,m,s)..  (sum(u,RHeat(i,m,u,s))+Etostore(i,'heat',m,s)) =l=
                     alpha(i)*sum(u,Efrom(i,m,u,s));

EneStore1(t,m,s)                      Set initial amount of energy in the storage
EneStore1(t,m,s)$(ORD(m)=1)..         EStore(t,m,s) =e= ESInl(t,s);

EneStore2(t,m,s)     Energy balance of the battery and heat storage
EneStore2(t,m,s)..   EStore(t,m+1,s) =e= epsilon(t)*EStore(t,m,s) + sum(i,Etostore(i,t,m,s)) -
                     sum(u,Efromstore(t,m,u,s));
```

MinStore(t,m,s)   Battery and heat storage must always have at least the minimum amount reserved to be added on to the supply if necessary
MinStore(t,m,s)..   EStore(t,m,s) =g= ESMin(t,s);
MaxStore(t,m,s)   The battery storage capacity has a limit
MaxStore(t,m,s)..   EStore(t,m,s) =l= ESMax(t,s);

Diversity(i,m,s)   Ensure that power and heat supply is diverse
Diversity(i,m,s)..   B*x(i,m,s) =l= sum(j$(not sameas(i,j)),x(j,m,s));

DiverseDist(i,m,u,s)   Ensure that power supplied from each source is of reasonable proportion of the demand
DiverseDist(i,m,u,s)..   Efrom(i,m,u,s) =g= (CLoad(m,u,s)/(B+G))*x(i,m,s);

MODEL TAICHUNG /ALL/;
OPTION LP = CPLEX;
OPTION MIP = CPLEX;
OPTION optcr = 0.00;
OPTION iterlim = 100000;
SOLVE TAICHUNG USING MIP minimizing Obj;

Equation omitted:

If $\sum_u \sum_i Efrom(i,m,u,s) < \sum_u CLoad(m,u,s)$, then $ESal(i,m,s) = 0 \quad \forall i,m,s \ \ if \ \ u \in \{elec\}$

Ebuyandsell(i,m,s)   The customer is not allowed to sell and buy electricity at the same time

Curriculum Vitae

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Born in Taoyuan, Taiwan on April 22, 1973

Education

09/2010-06/2012	**National Chiao Tung University,** Hsinchu, Taiwan Master of Business Administration degree, June, 2012 Global MBA Program, College of Management
09/2001-09/2002	**Stanford University,** Stanford, CA, USA Master of Science degree in Structural Engineering, September 2002 Structural Engineering and Geomechanics Program Department of Civil and Environmental Engineering
09/1993-06/1997	**Chung Yuan Christian University,** Chungli, Taiwan Bachelor of Science degree in Civil Engineering, 1997 Awarded Certificate of Completion in Construction Management Program

Professional Experience

10/2007-03/2010	**Joy O Keys, Inc.,** Taoyuan, Taiwan *General Manager*
04/2004-09/2007	**Pan Asia Corporation, Engineers & Constructors,** Taipei, Taiwan
Stage II	*Quality Control Engineer, Site Office*
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02/2004-04/2004	**T.Y. Lin Taiwan Consulting Engineers, Inc.,** Taipei, Taiwan *Structural Engineer*
01/2003-02/2004	**Obayashi Corp. - Fu Tsu Construction Co. Ltd. Joint Venture** **Taiwan High Speed Rail Project C215**, Taoyuan, Taiwan
Stage II	*Design Engineer*
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Specialties

- Managerial skills: financial statement analysis, financial management, marketing management, strategic management, construction management, and supply chain management
- Engineering fields: renewable energy and microgrid, structural analysis, structural design, etc.