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UNIT COMMITMENT RECOURSE MODEL FOR ELECTRIC POWER SYSTEM WITH RENEWABLE ENERGY

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พลังงานทดแทนเช่น พลังงานลม พลังงานแสงอาทิตย์ เข้ามามีบทบาทสำคัญในระบบพลังงานไฟฟ้าสมัยใหม่ เนื่องจากพลังงานทดแทนมีความน่าเชื่อถือได้ต่ำ เป็นผลให้ความไม่แน่นอนในระบบเพิ่มขึ้น ปัญหาการจัดการระบบไฟฟ้าที่มีพลังงานทดแทนถูกแก้ปัญหาด้วยตัวแบบหลายชนิด อย่างไรก็ตาม ตัวแบบเหล่านั้นมีความซับซ้อนและไม่มีประสิทธิภาพในการคำนวณเมื่อประยุกต์ใช้กับปัญหาขนาดใหญ่ ในการศึกษานี้ได้นำเสนอตัวแบบสโทแคสติกที่รวมเอาความไม่แน่นอนในพลังงานทดแทนเข้าไว้ด้วย ตัวแบบรีคอร์สแบบสองระยะที่มีจำนวนเหตุการณ์ที่เป็นไปได้จำกัดถูกนำมาใช้เพื่อการสร้างตัวแบบสโทแคสติกนั้น นอกจากนี้เราเพิ่มพลังงานสำรองของระบบโดยเพิ่มการสำรองจากพลังงานทดแทน พลังงานสำรองที่เพิ่มเข้าไปคำนวณได้จากค่าเฉลี่ยของพลังงานทดแทนที่เข้าไปใช้ในระบบ นอกเหนือจากนั้นเราจะนำเสนอกระบวนการวิเคราะห์เพื่อกำหนดระดับพลังงานสำรองที่เหมาะสมเมื่อพลังงานทดแทนถูกเพิ่มเข้าไปในระบบไฟฟ้าปกติ

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	วิทยาการคอมพิวเตอร์	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
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The renewable energy such as wind or solar power plays an important role in a modern power system. Due to low reliability of renewable energy source, uncertainty in a system is increasing. There are many models proposed for managing systems with renewable energy. However, these models are complicated and not computationally efficient when applied to large scale problems. In this work, we propose a stochastic model which incorporates uncertainty in renewable energy. A two-stage recourse model is used for our stochastic model with finite scenarios. Additionally, we increase a spinning reserve power of the system by adding a reserve from renewable energy. The additional reserve is computed from the expected value of renewable energy serving the system. Moreover we propose an analysis process to determine a suitable spinning reserve level once the renewable energy introduced to a conventional power system.

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INTRODUCTION

1.1 Motivation

A power system plays an important role in the national development, the economic development, and the quality of life development. The efficiency of power production comes from the accuracy of the amount of power output that satisfies the consumer demands for each time period. A problem of determining the optimal operation schedule for power generator units is called a unit commitment problem or a UC problem. A modern power system contains both conventional and renewable generators. Unfortunately, the power output from a renewable generator is random. Therefore, the conventional unit commitment problem would not provide a suitable solution for the renewable generators and the system. This is the reason that motivates us to study and improve the unit commitment problem in a power system with renewable energy.

1.2 Problem statement

Our problem in this research study is to determine an optimal unit status planning of each generator and its power output while satisfying the consumer demands under the system constraints as well as maintaining the reliability of the system through the spinning reserve. This problem is defined under the system with the renewable energy. The conventional unit commitment problem is used and transformed into a stochastic model to accommodate the uncertainty of the added renewable energy sources. A solution from this model can be used in the power production planning for such system.

1.3 Background knowledge

1.3.1 Conventional unit commitment model

The unit commitment problem is a scheduling problem aiming to find a suitable status for each generator and its power output in the power system. The objective of the problem is to minimize the production cost or to maximize the total profit under the system and generator constraints. This problem can be modeled as a mathematical linear program. Let us define notations that will be used in the model.

Parameters:

- T is the set of the planning time periods.
- G is the set of unit generators.
- L is the set of transmission lines in the system.
- M is the set of fuel types in the system.
- Z is the set of zones.
- L_j is the set of transmission lines connecting to zone j for each $j \in Z$.
- s_u is the startup cost of unit $u \in G$.
- $c_{m,u}$ is per unit fuel cost of unit $u \in G$ from fuel type $m \in M$.
- G_j is the set of unit generators in zone $j \in Z$.
- d_j^t is the demand of zone $j \in Z$ in the time period $t \in T$.
- $\underline{p}_u$ is the minimum generation of unit $u \in G$.
- $\overline{p}_u$ is the maximum generation of unit $u \in G$.
- α is the spinning reserve factor of the conventional energy ranging from 0 to 1.
- $\overline{TR}_l^t(i,j)$ is the maximum transmission power in line $l \in L$ that connects zone $i \in Z$ to zone $j \in Z$ in the time period $t \in T$.
- $intu_u$ is the initial condition number of unit $u \in G$.
- $intupu_u$ is the initial up time number of unit $u \in G$.
- $intdwu_u$ is the initial down time number of unit $u \in G$.

RU_u is the ramp up rate of unit $u \in G$.

RD_u is the ramp down rate of unit $u \in G$.

MU_u is the minimum up time of unit $u \in G$.

MD_u is the minimum down time of unit $u \in G$.

Decision variables:

p_u^t is the production power from unit $u \in G$ at the time period $t \in T$

$p_{m,u}^t$ is the production power from unit $u \in G$ at the time period $t \in T$ from fuel type $m \in M$.

$TR_l^t(i,j)$ is the transmission power in line $l \in L$ connecting zone $i \in Z$ to $j \in Z$ at the time period $t \in T$

$$y_u^t = \begin{cases} 1 & \text{if unit } u \in G \text{ is started up at the time period } t \in T, \\ 0 & \text{othewise.} \end{cases}$$

$$u_u^t = \begin{cases} 1 & \text{if unit } u \in G \text{ at the time period } t \in T \text{ is turned on,} \\ 0 & \text{if unit } u \in G \text{ at the time period } t \in T \text{ is turned off.} \end{cases}$$

$$z_u^t = \begin{cases} 1 & \text{if unit } u \in G \text{ is shut down at the time period } t \in T, \\ 0 & \text{othewise.} \end{cases}$$

A mathematical linear model for the unit commitment problem is explained below. The objective is to minimize the total cost that consists of the cost from starting up the generators, the cost of fuel for production and the cost of transmission power in the system.

Objective: Minimize

$$\sum_{t \in T} \sum_{u \in G} s_u y_u^t + \sum_{m \in M} \sum_{t \in T} \sum_{u \in G} c_{m,u} p_{m,u}^t + \sum_{i,j \in Z} \sum_{t \in T} \sum_{l \in L} TR_l^t(i,j), \tag{1.1}$$

We want to transmit the power from the cheap production power zone to others. Then, the unit cost of the transmission power is assumed to be one and fuel cost assume to be grater than 1.

Subject to the following constraints:

1. Power balance constraints: The constraint shows that for each zone and time period, the production power and the net total transmission power must be more than or equal to the power demand from consumers. The net total transmission power of each zone is the total transmission into this zone minus the total transmission out.

$$\sum_{u \in G_j} p_u^t + \sum_{i \in Z, i \neq j} \sum_{l \in L_j,} TR_l^t(i,j) - \sum_{i \in Z, i \neq j} \sum_{l \in L_j} TR_l^t(j,i) \geq d_j^t, \ \forall t \in T, j \in Z \quad (1.2)$$

2. Generator limits constraints: Each generator in the power system has different types and capacities of production. The power output of the unit that is online must lie between the maximum and minimum generation.

$$u_u^t \underline{p}_u \leq p_u^t \leq u_u^t \bar{p}_u, \quad \forall u \in G, \ t \in T \quad (1.3)$$

3. Spinning reserve constraints: The constraints of the unit commitment model must support not only the demand but also the reliability of the system. The number which indicates the reliability of the system is the amount of spinning reserve power. In situations where some generators are repaired or there is an outage in the system, the other generators must increase the production to support the demand from the consumers. Therefore, the spinning reserve is computed from the total difference between the current production and the maximum production of each generator in the system. This value must be at least a predetermined value which is equal to a constant factor times the total demand. The constant factor (α) is ranging from 0 to 1.

$$\sum_{u \in G} (\bar{p}_u u_u^t - p_u^t) \geq \alpha \sum_{j \in Z} d_j^t, \quad \forall t \in T \quad (1.4)$$

4. Transmission limits constraints: The power system consists of many zones of plants and consumers. The transmission lines are needed to transmit power between zones. The transmission must not exceed the maximum transmission capacity of each line.

Moreover, the total transmission into a zone must not exceed the production within the zone.

$$TR_l^t\,(i,j) \le \overline{TR}_l^t\,(i,j)\,, \quad \forall l \in L,\ t \in T,\ i,j \in Z \tag{1.5}$$

$$\sum_{i \in Z, i \neq j} \sum_{l \in L_j,} TR_l^t(i,j) \le \sum_{u \in G_j} p_u^t, \quad \forall j \in Z,\ t \in T \tag{1.6}$$

5. Unit status constrainst: A generator in the system has many statuses as it is changed from offline to online, and changed from online to offline. To determine the status of a generator, the relations between unit on-off status, startup status and shutdown status are formulated.

$$u_u^{t+1} - u_u^t \le y_u^{t+1}, \quad \forall u \in G,\ t \in T \tag{1.7}$$

$$z_u^{t+1} = y_u^{t+1} + u_u^t - u_u^{t+1}, \quad \forall u \in G,\ t \in T \tag{1.8}$$

In a case of $u_{t+1} = u_t = 1$, the value of y_{t+1} can be both 0 and 1. Since the objective is to minimizes y_{t+1}, the value of y_{t+1} is forced to be 0 and consequently $z_{t+1} = 0$ too.

6. Initial condition constraints: The status of a generator has the relations with not only the current plan but also the previous plan. The unit status of the previous plan is defined by the initial condition number of each generator. The initial condition number is binary and is used to determine the first period unit status of the current plan. If the initial condition number of a unit equals to 1, in the last period of the previous plan, this unit is online. Then, the startup status must be 0. On the other hand, if the initial condition is 0, the unit is offline in the last period of the previous plan and, therefore, the shutdown status must be 0.

$$\text{if } \ intu_u = 1 \ \text{ then } \ y_u^1 = 0 \ \text{ and } \ z_u^1 + u_u^1 = 1, \quad \forall u \in G \tag{1.9}$$

$$\text{if } \ intu_u = 0 \ \text{ then } \ z_u^1 = 0 \ \text{ and } \ y_u^1 = u_u^1, \quad \forall u \in G \tag{1.10}$$

7. Ramp up/down rate constraints: The change in the power output from a generator

must not exceed the bound of changing. If a generator increases the production, the increase in the power must not exceed the ramp up rate. Similarly, the decrease in the power within a time period must not exceed the ramp down rate.

$$p_u^{t+1} - p_u^t \le RU_u, \quad \forall u \in G,\ t \in T \tag{1.11}$$

$$p_u^t - p_u^{t+1} \le RD_u, \quad \forall u \in G,\ t \in T \tag{1.12}$$

8. Minimum uptime/downtime constraints: A generator u in the power system has the minimum length of time of being online or offline, which are given by the parameters MU_u and MD_u, respectively. If the generator u is started up, it has to remain up for at least MU_u time periods before it can be shutdown. Similarly, if the generator u is shutdown, it must remain down for at least MD_u time periods before it can be started up.

$$\text{if } \ intup_u > 0 \text{ and } \ intup_u < MU_u \text{then } \sum_{m=1}^{MU_u - intup_u} u_u^m = MU_u - intup_u, \quad \forall u \in G \tag{1.13}$$

$$\text{if } \ intdw_u > 0 \text{ and } \ intdw_u < MD_u \text{then } \sum_{m=1}^{MD_u - intdw_u} u_u^m = 0, \quad \forall u \in G \tag{1.14}$$

$$\sum_{m=t-MU_u+1}^{t} y_u^m \le u_u^t, \quad \forall u \in G,\ t > MU_u \tag{1.15}$$

$$\sum_{m=t-MD_u+1}^{t} z_u^m \le 1 - u_u^t, \quad \forall u \in G,\ t > MD_u \tag{1.16}$$

9. Fuel constraints: There are many types of generators in the power system which require different types of fuel. The relationship between the power output from each fuel type and the power output of each generator unit is shown in the following

constraints.

$$\sum_{m \in M} p_{m,u}^{t} = p_{u}^{t}, \quad \forall u \in G, \ t \in T \tag{1.17}$$

1.3.2 Renewable energy

The renewable energy is the energy from the renewable resources and the refining of biomass. There are many types of the renewable energy in Thailand's power system, such as wind, solar, biomass, biogas, co-generator and waste. The different types of the renewable energy have the different behavior of the power output. For example, the solar power can be obtained only when there is sunlight, while the biomass can be refined at any time of the day. The behavior of the power output for each type of renewable energy in 24 hours is shown in Figure 1.1 where each time period lasts 30 minutes. The data used to create the plot is obtained from Electricity Generating Authority of Thailand (EGAT).

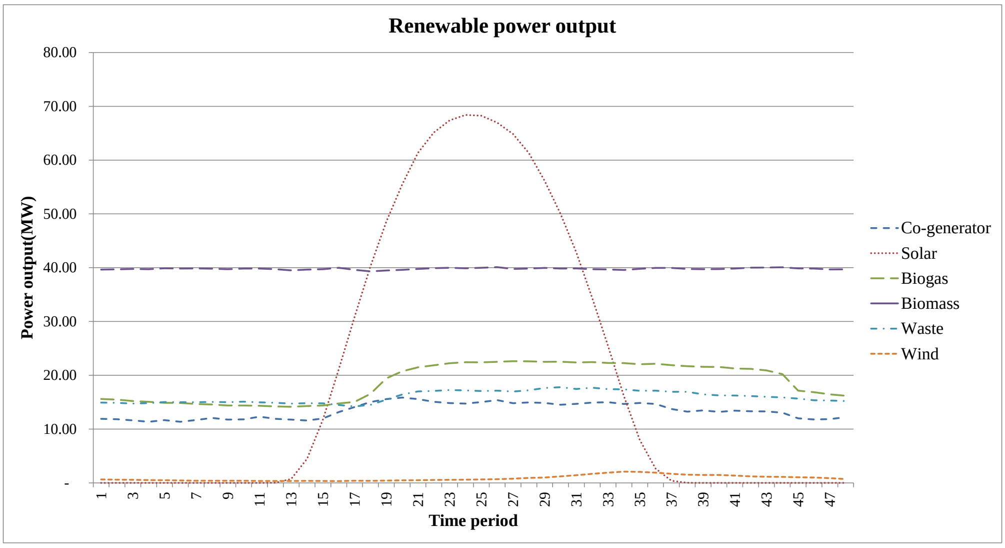


Figure 1.1**:** Behavior of renewable energy output.

Each type of the renewable generator is different. Some generator types have high reliability of production such as the waste generator and the co-generator but some generators have low reliability such as the solar generator and the wind generator. High-reliability generators are the generators which can reliably produce the power at full or almost full capacity of production. On the other hand, low-reliability generators are the generators which produce the power at less than full capacity of production most of the time. In Thailand's power system, the reliability is measured in terms of dependable percentage which is called dependable capacity factor (DCF). From power development plan (PDP) 2015, the value of DCF for each renewable type is shown in Table 1.1.

Type of renewable generator	Dependable capacity factor (%)
Solar	35
Wind	2
Biomass	36
Biogas	24
Waste	60
Co-generation	80

Table 1.1**:** Dependable capacity factor for each renewable generator type.

The DCF value of a power generator indicates a minimum percentage of its power production capacity that it can reliably generate. For example, suppose the solar generator has the generating capacity of 100 megawatts (MW) and the DCF value of solar is 35. This means the solar generator can surely produce at least 35 MW.

1.3.3 Stochastic expected recourse model

An optimization problem usually is solved with deterministic linear model where all coefficients are of certain values. Deterministic linear model are solved with a canonical method such as the simplex method. In a real problem, some parameters in the model are not certain. A stochastic model is applied to solve this situation.

A stochastic model is a model that some data in the model are imprecise or uncertain. Some parameters in a stochastic model are random variables with probability interpretation. A general form of a stochastic linear model is

$$\left.\begin{aligned} \min \quad & c^T x \\ \text{s.t.} \quad & \hat{A}x \geq \hat{b} \\ & Bx \geq d \\ & x \geq 0 \end{aligned}\right\} \tag{1.18}$$

where $\hat{A}$ and $\hat{b}$ contain uncertainty data.

One of the well-known stochastic models is a stochastic expected recourse model which transforms the uncertainty of the parameters into expectation of the recourse. To find an optimal solution of the stochastic model with imprecise data, a decision must be taken before the realization of those imprecise data is known. When the realization is known, if the decision did not satisfy the model requirements, recourse variables will appear to support the requirement. A recourse creates a penalty to the model. The stochastic expected recourse model aims to minimize the expected recourse and its penalty.

The stochastic expected recourse model can be explained as follows. From the general form of the stochastic model (1.18), the constraint $\hat{A}x \geq \hat{b}$ is the stochastic constraints. Suppose the random variables in $\hat{A}$ and $\hat{b}$ are $(\hat{a}_{11}, \hat{a}_{12}, \hat{a}_{13}, ..., \hat{a}_{mm})$ and $(\hat{b}_1, \hat{b}_2, \hat{b}_3, ..., \hat{b}_m)$ respectively. Suppose also the penalty price vector s is $(s_1, s_2, ..., s_m)^T$. The combination of realizations of random variables $\hat{A}$ and $\hat{b}$ is all realizations of the problem. The set of the realizations is the set of random vectors which are given by $\xi = \{\xi_i = (\hat{a}_{11i}, \hat{a}_{12i}, \hat{a}_{13i}, ..., \hat{a}_{mmi}, \hat{b}_{1i}, ..., \hat{b}_{mi}) | i = 1, 2, ..., t\}$, where ξ_i is the ith realization of $(\hat{a}_{11}, \hat{a}_{12}, \hat{a}_{13}, ..., \hat{a}_{mm}, \hat{b}_1, \hat{b}_2, \hat{b}_3, ..., \hat{b}_m)$ and t is the total number of realizations. From definition of the recourse variable which is appeared to support the requirements, the recourse variable will be zero when the first stage actions satisfy the requirements or will be the difference between the requirements and actions when the actions fail to satisfy the requirement. Therefore, the stochastic constraints can be transformed into $\hat{A}_i x + y(\xi_i) \geq \hat{b}_i$ and $y(\xi_i) \geq 0$ where $y(\xi_i)$ is the vector of recourse variables. Moreover, the aim of the stochastic expected model is to minimize the expected recourse and its penalty. Therefore, the stochastic expected recourse model has the following general form:

$$\begin{aligned} \min \quad & c^T x + E(s^T y(\xi)) \\ \text{s.t.} \quad & \hat{A}_i x + y(\xi_i) \geq \hat{b}_i \\ & Bx \geq d \\ & y(\xi_i), x \geq 0 \end{aligned}$$

The following small example illustrates how to transform a stochastic model to be a stochastic expected recourse model.

$$\begin{aligned} \min \quad & 2x_1 + 3x_2 \\ \text{s.t.} \quad & \hat{a}_1 x_1 + x_2 \geq \hat{b}_1 \\ & 3x_1 - x_2 \geq 6 \\ & x_1, x_2 \geq 0, \end{aligned}$$

where $\hat{a}_1 = \begin{cases} 1 & \text{with prob } 0.2, \\ 2 & \text{with prob } 0.8, \end{cases}$ and $\hat{b}_1 = \begin{cases} 5 & \text{with prob } 0.4, \\ 4 & \text{with prob } 0.6. \end{cases}$

Given the penalty be equal to 10.

The set of all realizations is $\xi = \{\xi_1 = (1,5), \xi_2 = (1,4), \xi_3 = (2,5), \xi_4 = (2,4)\}$ with probability $\{p_1 = 0.2 \times 0.4, p_2 = 0.2 \times 0.6, p_3 = 0.1 \times 0.4, p_4 = 0.1 \times 0.6\}$.

The constraint when the random variable $\hat{a}_1 = 1, \hat{b}_1 = 5$ in realization (1) is $y(\xi_1) \geq 5 - (1x_1 + x_2)$ and the constraint when the random vector $\hat{a}_1 = 1, \hat{b}_1 = 4$ in realization (2) is $y(\xi_2) \geq 4 - (1x_1 + x_2)$and so on. The expected value of the recourse variable is $0.08y(\xi_1) + 0.12y(\xi_2) + 0.32y(\xi_3) + 0.48y(\xi_4)$. Therefore, the stochastic expected recourse model for this example is

$$\begin{aligned}
\min \quad & 2x_1 + 3x_2 + 10[0.08y(\xi_1) + 0.12y(\xi_2) + 0.32y(\xi_3) + 0.48y(\xi_4)] \\
\text{s.t.} \quad & y(\xi_1) \geq 5 - (1x_1 + x_2) \\
& y(\xi_2) \geq 4 - (1x_1 + x_2) \\
& y(\xi_2) \geq 5 - (2x_1 + x_2) \\
& y(\xi_2) \geq 4 - (2x_1 + x_2) \\
& 3x_1 - x_2 \geq 6 \\
& x_1, x_2, y(\xi_1), y(\xi_2), y(\xi_3), y(\xi_4) \geq 0.
\end{aligned}$$

1.4 Research objectives

The objectives of the research study are to propose the stochastic model for the unit commitment with renewable energy and to propose the analysis process to determine a suitable spinning reserve level once the renewable energy is introduced to a conventional power system. The scope of this research study is shown as follows.

- An error on power demand is no more than 5%. Otherwise, the uncertainty of load demand is ignored.
- A reliability percentage of each type of the renewable energy is provided. Moreover, the production efficiency of all renewable energy generators in a power system follow their reliability percentage.
- All of the renewable energy types are considered as one group.
- All of the renewable energy output must be used in the power system.

1.5 Overview of thesis

This thesis consists of five chapters. Chapter 1 provides an introduction to the study which consists of motivation, problem statement, background knowledge and research objectives. The motivation and problem statement are proposed in this chapter to state the scope of the problem. The background knowledge has 3 sections; i.e., the unit commitment model, renewable energy, and stochastic expected recourse model. Lastly, the research objectives are proposed. Chapter 2 is the literature review, which is divided into 3 topics : a unit commitment, a stochastic model for a unit commitment problem and a renewable energy in the Thailand's power system. In Chapter 3, a deterministic and a stochastic recourse unit commitment model for a power system with a renewable energy are proposed. In Chapter 4, the parameterization study for each model and its results are proposed using Thailand's power system data. Conclusions of this research are presented in the last chapter.

CHAPTER II

LITERATURE REVIEW

2.1 Methods for solving unit commitment problems

Unit commitment problems can be solved by various methods which can be categorized into 3 groups as follows ([17] and [18]):

1. Conventional techniques: a unit commitment model is a linear model. In a small-scale problem, a unit commitment problem can be solved with exhaustive enumeration, a priority list and dynamic programming. In a large-scale problem, the previous methods are not efficient. The heuristic methods such as simulation annealing, lagrangian relaxation (LR) and tabu search is provided for solving such problem. Moreover, a large-scale unit commitment problem can be transformed into a mixed integer programming (MIP).

2. Non-conventional techniques: when the details of the problem were studied, the unit commitment problem may not be the linear model. The model of the problem is more complex from the uncertainty and non-linear functions. The expert systems such as artificial intelligent (AI), fuzzy system, and genetic algorithm are used for solving this situation.

3. The hybrid method: it is a combination between conventional and non-conventional techniques.

2.2 Stochastic model for unit commitment problem

In 1996, a stochastic model was first applied to the unit commitment problem for managing uncertainty in the power system by Takriti et al [1]. They studied the uncertainty in the load demand of the power system. The dynamic method and lagrangian relaxation were applied to solve their stochastic model. Their result showed that the operation cost of the stochastic model was better than the deterministic model. Since, their study has the size limitation, their stochastic model is not efficient in a large scale problem. Later, chance constraint stochastic models ([2] and [3]), two-stage stochastic models ([4] and [5]), and multistage stochastic models ([6] and [7]) were used in the unit commitment problem. A chance constraint stochastic model was applied to the problem which had uncertainty in the load demand. A two-stage model and a multistage model were compared in [8], and the result showed that the solutions of the two-stage model were not much different from the solutions of the multistage model. However, the two-stage model was easier to implement than the multistage model. Note that the uncertainty from the models above did not contain a renewable energy. When the spinning reserve of the system was considered, the spinning reserve of a system can be modeled in various ways, such as a fraction of the total demand in the system ([10] and [12]), and a production of the largest plant in the system [11].

2.3 The renewable energy in power system

The first renewable generator which is wind generator has been developed since 1900s [16]. The renewable energy was proposed to the power system at the beginning of the 2000s[16]. Since the number of renewable plants is increasing and a policy of using renewable power become more popular, there are many models proposed for managing systems with renewable energy. In [9], an optimal operation of a wind-thermal power system is provided by a stochastic model. The disadvantage of this model is the number of scenarios is too high which causes low efficiency in computation. This problem was managed by reducing the number of scenarios. A particle swarm optimization is used for reducing the number of scenarios that is not a part of a solution. The result of this model provides a better solution than the deterministic model and a better computational efficiency than the normal stochastic model. In [10], the stochastic unit commitment was applied to solar microgrid systems by a stochastic mixed integer program. Many scenarios of this model are generated from the forecast, and developed using a truncated normal distribution. In a spinning reserve constraint of the mathematical model, a percentage of the production from the solar power is a part of the spinning reserve. This spinning reserve constraint shows the relation between the amount of the renewable energy and the reliability of the system.

CHAPTER III

THE STOCHASTIC RECOURSE MODEL FOR POWER SYSTEM WITH RENEWABLE ENERGY

3.1 The deterministic unit commitment model for the power system with the renewable energy

When the renewable energy is integrated into the power system, the power from the conventional generators and the reliability of the system are changed. Assuming the renewable energy is deterministic, the load demand must be supported by both the conventional generator energy and the renewable energy. Therefore, the power balance constraint of the power system with the renewable energy is

$$\sum_{u\in G_j} p_u^t + \sum_{i\in Z, i\neq j}\sum_{l\in L_j,} TR_l^t(i,j) - \sum_{i\in Z, i\neq j}\sum_{l\in L_j} TR_l^t(j,i) + R_j^t \geq d_j^t, \quad \forall t\in T,\ j\in Z, \quad (3.1)$$

where R_j^t is the renewable energy that supports zone j in time period t.

The reliability of the system is changed when the renewable energy is integrated into the power system. Therefore, the spinning reserve constraint should be changed to maintain the reliability. The spinning reserve constraint of the system is changed by adding a fraction of the power output from the renewable energy serve to the system determined by the spinning reserve factor of the renewable energy. Hence, from the spinning reserve constraint in Equation (1.4),

$$\sum_{u\in G} (\bar{p}_u u_u^t - p_u^t) \geq \alpha \sum_{j\in Z} d_j^t, \quad \forall t\in T$$

is transformed into

$$\sum_{u \in G} (\bar{p}_u u_u^t - p_u^t) \geq \alpha \sum_{j \in Z} d_j^t + \nu \sum_{j \in Z} R_j^t, \quad \forall t \in T \tag{3.2}$$

where ν is the spinning reserve factor of the renewable energy ranging from 0 to 1.

The objective function of the power system will be transformed into minimizing

$$\sum_{t \in T} \sum_{u \in G} s_u y_u^t + \sum_{m \in M} \sum_{t \in T} \sum_{u \in G} c_{m,u} p_{m,u}^t + \sum_{i,j \in Z} \sum_{t \in T} \sum_{l \in L} TR_l^t(i,j) + \varphi \sum_{j \in Z, t \in T} R_j^t, \tag{3.3}$$

where φ is the cost of the renewable energy.

Therefore, the constraints of the deterministic unit commitment model for the power system with the renewable energy are shown in Equations (1.3), (1.5)-(1.17),(3.1)-(3.2).

3.2 The stochastic recourse model for the power system with the renewable energy

From the deterministic model, the power from renewable sources (R_j^t) are in fact uncertain. In process of preparing data for the stochastic expected recourse model, we generate scenarios of the stochastic expected recourse model by varying the power output from the renewable energy for zone j to be $R_{n,j}^t$ with the probability P_n^t for scenario n at time t as shown in Table 3.1.

	Renewable power output for zone j	Probability
1	The summation of the minimum level as indicated by the dependable capacity factor percentage from each source ($R_{1,j}^t$)	High (P_1^t)
2	The summation of the average between the full capacity and the minimum level from each source ($R_{2,j}^t$)	Medium (P_2^t)
3	The summation of the full capacity from each source ($R_{3,j}^t$)	Low (P_3^t)

Table 3.1: Scenarios of the stochastic expected recourse model.

Therefore, the power balance constraint of the stochastic constraint is

$$\sum_{u\in G_j} p_u^t + \sum_{i\in Z, i\neq j}\sum_{l\in L_j,} TR_l^t(i,j) - \sum_{i\in Z, i\neq j}\sum_{l\in L_j} TR_l^t(j,i) + R_{n,j}^t \geq d_j^t, \quad \forall t\in T,\ j\in Z,\ n\in N,$$

where $R_{n,j}^t$ is the realization of the renewable output for each zone and time period.

N is the set of the scenarios.

If the net total power does not satisfy the load demand, the recourse will be appear. On the other hand, if the power over the load demand, the recourse will be not appeared. Then, the recourse variable can be defined as

$$RE_{n,j}^t = max\left\{0, d_j^t - \left(\sum_{u\in G_j} p_u^t + \sum_{i\in Z, i\neq j}\sum_{l\in L_j,} TR_l^t(i,j) - \sum_{i\in Z, i\neq j}\sum_{l\in L_j} TR_l^t(j,i) + R_{n,j}^t\right)\right\}.$$

Since the production plaining considers 48 time periods and each period has 3 scenarios, the stochastic recourse model would have 3^{48} scenarios in total, which is too computationally expensive. For simplification, we assume the dependency of the renewable power output in each time period. Specifically, there are 3 scenarios across the 48 time periods, namely, the scenarios where the renewable power output is at the minimum, medium, and maximum level as explained in Table 3.1. The power balance constraint for the stochastic recourse model is written as

$$\begin{aligned}\sum_{u\in G_j} p_u^t + \sum_{i\in Z, i\neq j}\sum_{l\in L_j,} TR_l^t(i,j) - \sum_{i\in Z, i\neq j}\sum_{l\in L_j} TR_l^t(j,i) + R_{n,j}^t + RE_{n,j}^t \geq d_j^t,\\ \forall t\in T, j\in Z, n\in N,\end{aligned} \tag{3.4}$$

and

$$RE_{n,j}^t \geq 0, \tag{3.5}$$

Moreover, the spinning reserve constraint of the system is changed by adding the expected power output from the renewable energy multiplied by their spinning reserve factor. From the spinning reserve constraint of conventional unit commitment model, the spinning reserve constraint of the stochastic recourse model is transformed into

$$\sum_{u \in G} (\bar{p}_u u_u^t - p_u^t) \geq \alpha \sum_{j \in Z} d_j^t + \nu E(X^t), \quad \forall t \in T \tag{3.6}$$

where ν is the spinning reserve factor of the renewable energy ranging from 0 to 1,

X^t is the random variable representing the total renewable output from all zones at the time period t.

Hence,

$$E(X^t) = \sum_{n \in N} \sum_{j \in Z} (P_n^t) R_{n,j}^t$$

The objective function of the stochastic expected recourse unit commitment model is transformed into

$$\begin{aligned} \sum_{t \in T} \sum_{u \in G} s_u y_u^t + \sum_{m \in M} \sum_{t \in T} \sum_{u \in G} c_{m,u} p_{m,u}^t + \sum_{i,j \in Z} \sum_{t \in T} \sum_{l \in L} TR_l^t(i,j) + \varphi \sum_{j \in Z, t \in T} R_{n,j}^t \\ + \beta \sum_{z \in Z} \sum_{n \in N} \sum_{t \in T} RE_{z,n}^t P_n^t, \end{aligned} \tag{3.7}$$

where β is the penalty of the power balance constraint.

In summary, the stochastic expected recourse unit commitment model is given by

Minimize $\quad \sum_{t \in T} \sum_{u \in G} s_u y_u^t + \sum_{m \in M} \sum_{t \in T} \sum_{u \in G} c_{m,u} p_{m,u}^t + \sum_{i,j \in Z} \sum_{t \in T} \sum_{l \in L} TR_l^t(i,j) +$

$\varphi \sum_{j \in Z, t \in T} R_{n,j}^t + \beta \sum_{z \in Z} \sum_{n \in N} \sum_{t \in T} RE_{z,n}^t P_n^t,$

Subject to $\quad \sum_{u \in G_j} p_u^t + \sum_{i \in Z, i \neq j} \sum_{l \in L_j,} TR_l^t(i,j) - \sum_{i \in Z, i \neq j} \sum_{l \in L_j} TR_l^t(j,i) + R_{n,j}^t + RE_{n,j}^t \geq d_j^t,$

$\forall t \in T, j \in Z, n \in N,$

Subject to

$$u_u^t \underline{p}_u \leq p_u^t \leq u_u^t \bar{p}_u, \qquad \forall u \in G,\ t \in T,$$

$$\sum_{u \in G} (\bar{p}_u u_u^t - p_u^t) \geq \alpha \sum_{j \in Z} d_j^t + \nu \sum_{n \in N} \sum_{j \in Z} (P_n^t) R_{n,j}^t, \qquad \forall t \in T,$$

$$TR_l^t\,(i,j) \leq \overline{TR}_l^t\,(i,j)\,, \qquad \forall l \in L,\ t \in T,\ i,j \in Z,$$

$$\sum_{i \in Z, i \neq j} \sum_{l \in L_j,} TR_l^t(i,j) \leq \sum_{u \in G_j} p_u^t, \qquad \forall j \in Z,\ t \in T,$$

$$u_u^{t+1} - u_u^t \leq y_u^{t+1}, \qquad \forall u \in G,\ t \in T,$$

$$z_u^{t+1} = y_u^{t+1} + u_u^t - u_u^{t+1}, \qquad \forall u \in G,\ t \in T,$$

if $intup_u > 0$ and $intup_u < MU_u$ then $\sum_{m=1}^{MU_u - intup_u} u_u^m = MU_u - intup_u$, $\qquad \forall u \in G, t \leq MU_u$

if $intdw_u > 0$ and $intdw_u < MD_u$ then $\sum_{m=1}^{MD_u - intdw_u} u_u^m = 0$, $\qquad \forall u \in G, t \leq MD_u$

if $intu_u > 0$ then $y_u^1 = 0$ and $z_u^1 + u_u^1 = 1$, $\qquad \forall u \in G$,

if $intu_u = 0$ then $z_u^1 = 0$ and $y_u^1 = u_u^1$, $\qquad \forall u \in G$,

$$p_u^{t+1} - p_u^t \leq RU_u, \qquad \forall u \in G,\ t \in T,$$

$$p_u^t - p_u^{t+1} \leq RD_u, \qquad \forall u \in G,\ t \in T,$$

$$\sum_{m=t-MU_u+1}^{t} y_u^m \leq u_u^t, \qquad \forall u \in G,\ t > MU_u,$$

$$\sum_{m=t-MD_u+1}^{t} z_u^m \leq 1 - u_u^t, \qquad \forall u \in G,\ t > MD_u,$$

$$\sum_{m \in M} p_{m,u}^t \gamma_m = p_u^t, \qquad \forall u \in G,\ t \in T$$

$p_{m,u}^t$, $TR_l^t(i,j)$, $RE_{z,n}^t \geq 0$ and u_u^t, y_u^t, $z_u^t \in \{0,1\}$

The decision variables of the recourse model include decision variables from the deterministic model and recourse variables which are nonnegative. The recourse model has at least one feasible solution that corresponds to the constraints, which is all generators are online at their minimum capacity, and the recourse variables are some numbers large enough to support the load demand. Therefore, the proposed stochastic recourse model always is feasible.

CHAPTER IV

EXPERIMENTS AND RESULTS

We study the Thailand's power system that has 171 conventional generators, 5 zones and 6 types of renewable energy: co-generator power, solar power, biogas power, biomass power, waste power, and wind power. The zones of power consumer and production in Thailand's system include North, North-east, South, Central and Metro.

4.1 The deterministic unit commitment model for the power system with the renewable energy

To study the effect of the renewable energy to the power system, the deterministic unit commitment model is applied to the data on October 11, 2011 (Tuesday). This date is randomly chosen from the dates that have normal demand pattern. The demand in 48 half-hour time periods for each zone is shown in Figure 4.1.

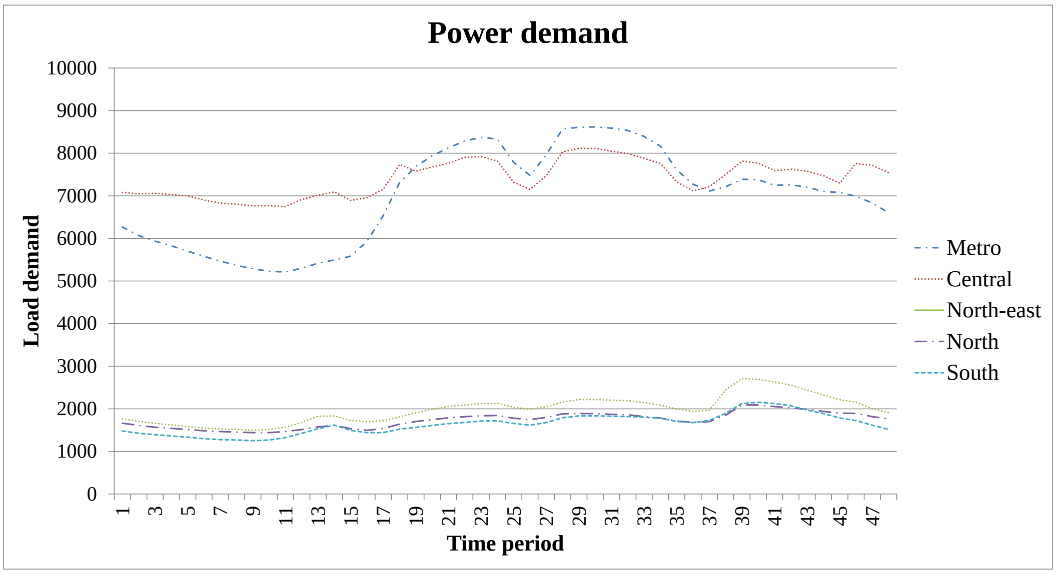


Figure 4.1**:** The power demand on October 11, 2011.

According to the assumptions, all power outputs from renewable energy must be used. Therefore, in the unit commitment model, the cost of renewable energy is supposed to be zero. The deterministic power output of the renewable energy in each time period is assumed to be the sum of the output of all renewable energy sources in the same time period as displayed in Figure 1.1. An optimal solution of the deterministic unit commitment model in the conventional generator and the system with the renewable energy is shown in Table 4.1.

	Conventional system	Conventional and renewable energy
Total cost	633629722.6	629941649.4
Conventional output	791325.0	786125.0
Renewable output	-	5199.98
Marginal cost	800.7	801.3
Total power output	791325.0	791325.0

Table 4.1**:** Solution of the deterministic conventional system and the conventional-renewable system.

The total cost and total power output are almost not much different because the power output from renewable energy is too small when compared with the demand of the system. For this reason, in the stochastic recourse model, not only parameters of the model but also the amount of the renewable are adjusted to study their effect on the model and the system.

4.2 The stochastic unit commitment model for the power system with the renewable energy

4.2.1 A scenario of the renewable power output

From the power output of the renewable energy and the generated scenarios, a scenario in each time period is determined based on their dependable capacity factor (DCF) value. For example, the waste generator has the dependable capacity factor of

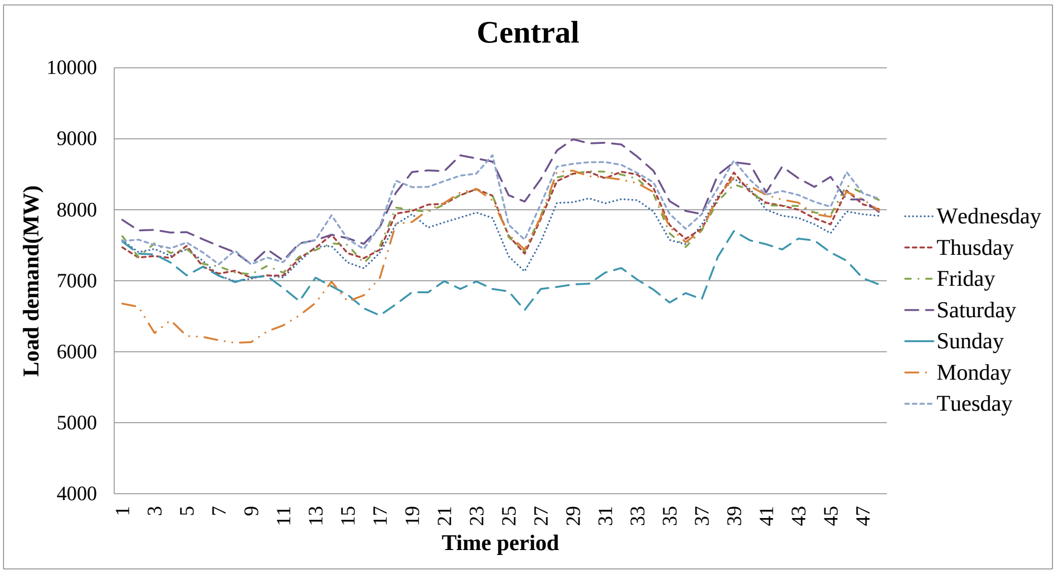
60%. At the first period, the prediction power output of the waste generator is 14.9 MW. Therefore, in the first scenario, power output at DCF is $14.9 \times 0.6 = 0.9$ MW. In the second scenario, power output at half of DCF and full capacity is $\frac{(0.9 + 14.9)}{2} = 11.9$ MW. In the third scenario, power output at full capacity is 14.9 MW. Therefore, the renewable energy output for each scenario can be calculated and shown in Table 4.2.

Renewable Type	Scenario	Time Period				
		1	2	3	···	48
Solar	1	0.0	0.0	0.0		0.0
	2	0.0	0.0	0.0	···	0.0
	3	0.0	0.0	0.0		0.0
Wind	1	0.0	0.2	0.1		0.0
	2	0.3	0.4	0.3	···	0.4
	3	0.6	0.6	0.6		0.7
Biomass	1	14.3	9.5	23.9		14.3
	2	27.0	24.6	31.8	···	27.0
	3	39.6	39.7	39.8		39.7
Biogas	1	3.7	9.3	12.2		3.9
	2	9.7	12.4	13.7	···	10.0
	3	15.6	15.5	15.2		16.2
Waste	1	9.0	8.9	8.8		9.1
	2	11.9	11.9	11.8	···	12.2
	3	14.9	14.9	14.7		15.2
Co-generation	1	6.0	5.8	5.9		6.0
	2	6.8	6.5	6.6	···	6.7
	3	7.5	7.3	7.3		7.5

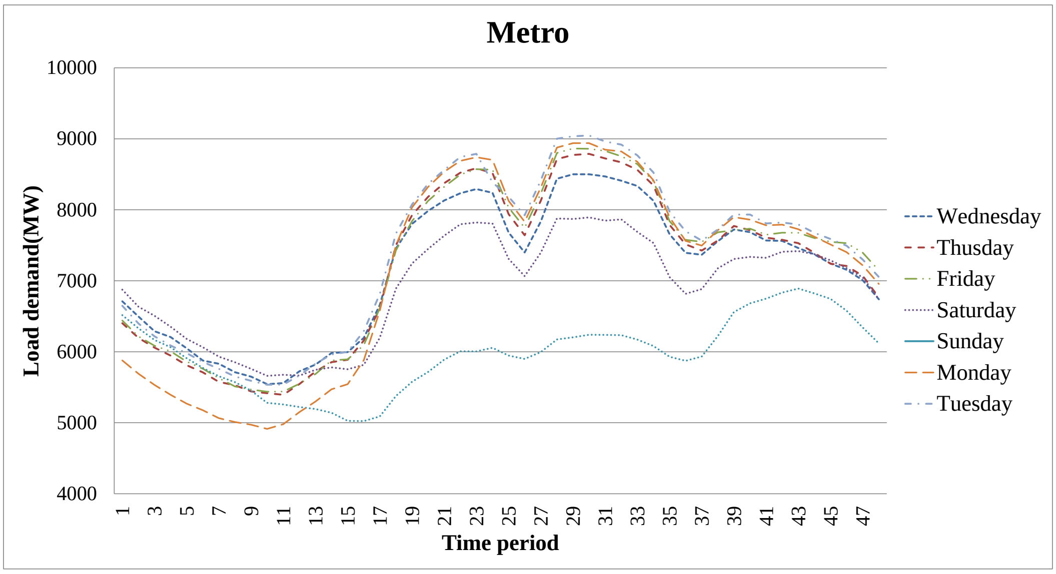
Table 4.2: Power output for each scenario of renewable type.

4.2.2 A case of load demand

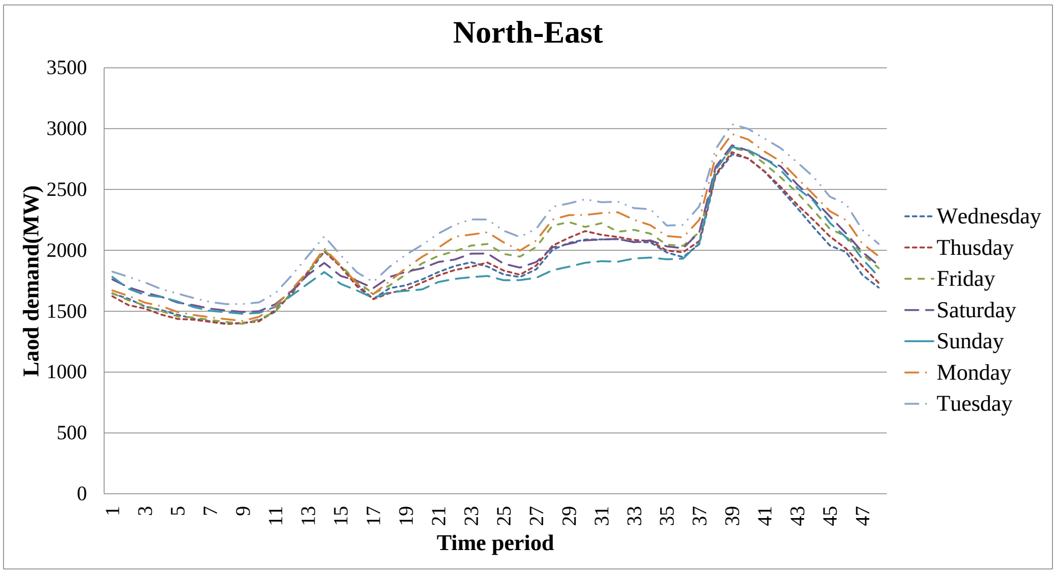
The behaviors of power load demand in each zone are different. Central zone and Metro zone have larger load demand than other zones. Metro zone has more fluctuation than Central zone. The on-peak periods of Central zone and Metro zone appear in midday. On-peak periods of North-east, North, and South appear during evening. The load demands in a week for each zone are shown in Figure 4.2. For each zone, when the power demands in each day of the week are considered, an on-peak periods and off-peak periods in the same zone are similar except for the weekend such as Sunday. The load demand on Sunday is significantly lower than other days in Central and Metro zone whereas in North, Northeastern, and South zone the Sunday load demand is slightly lower.



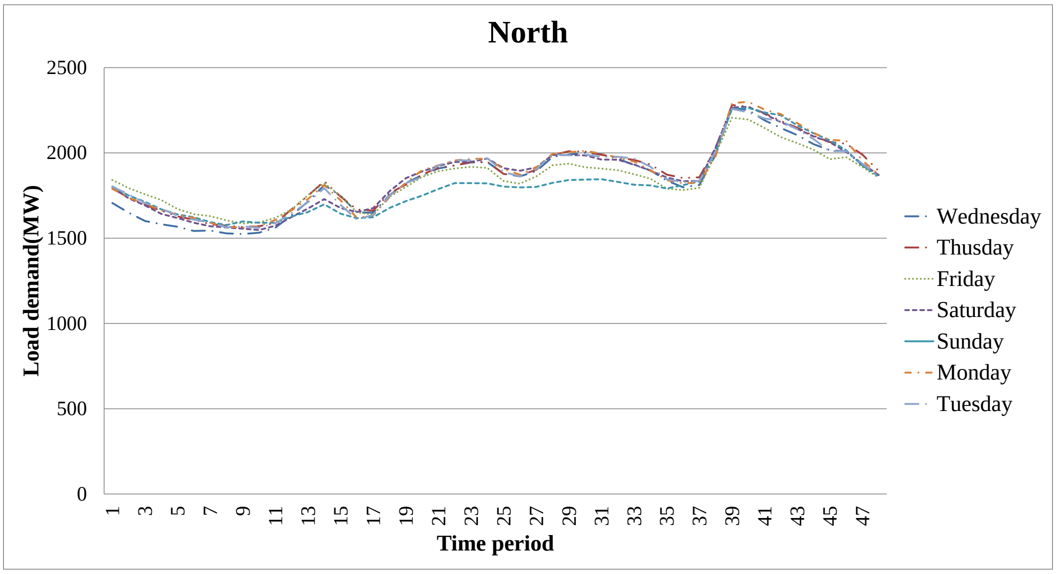
(a) Load demand in Central zone.



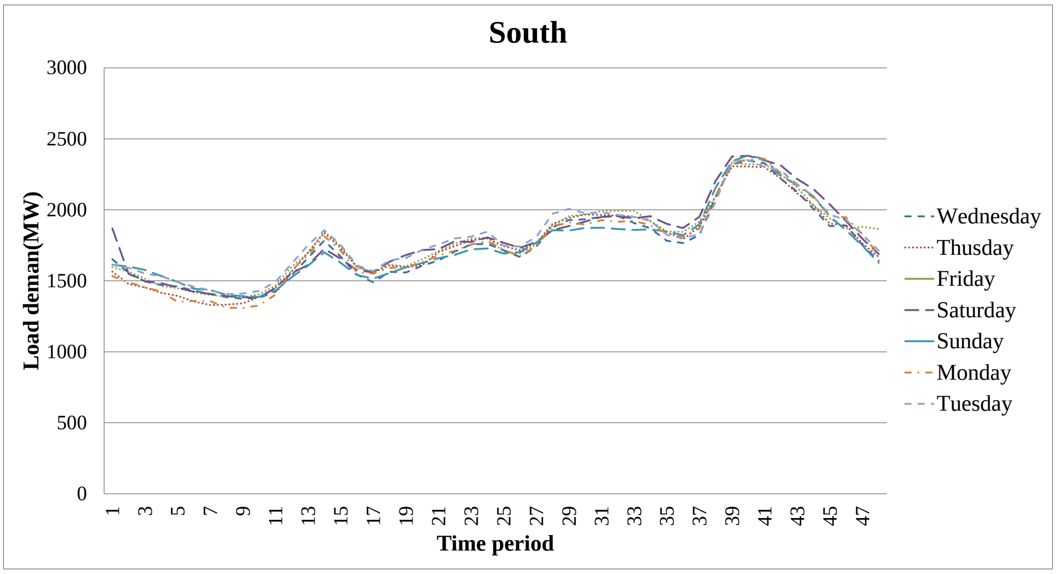
(b) Load demand in Metro zone.



(c) Load demand in North-east zone.



(d) Load demand in North zone.



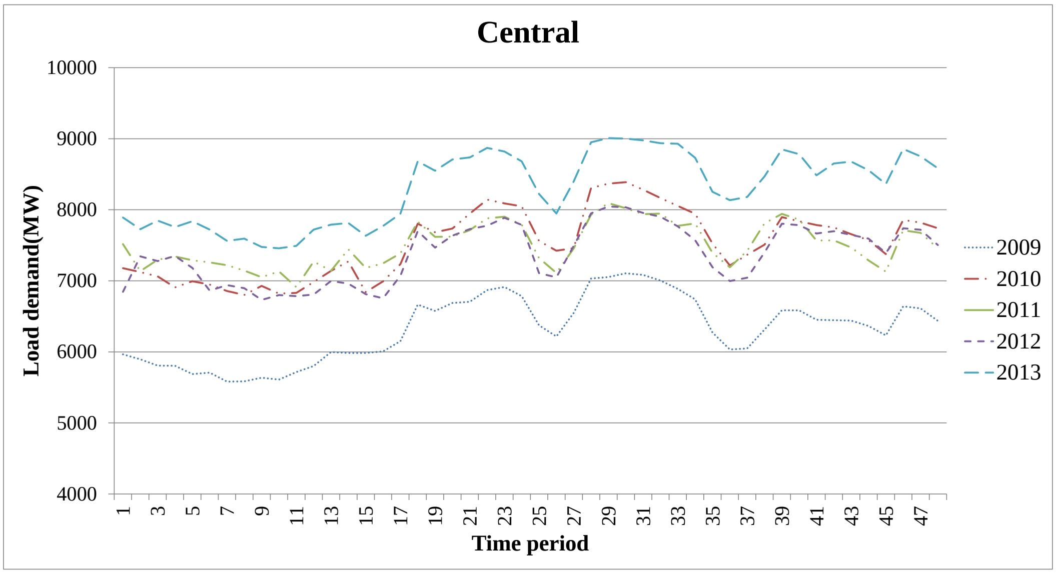
(e) Load demand in South zone.

Figure 4.2**:** Load demand in each zone of system.

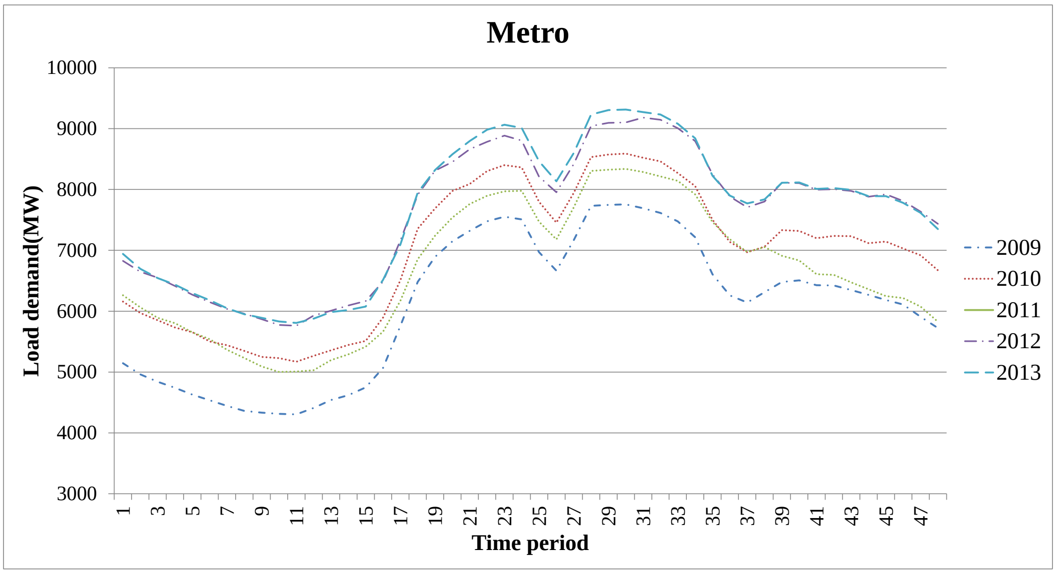
Therefore, we classify load demand into three groups.

- The first group is the load demand on a weekday. In a weekday, factories, malls, campuses and business centers are open during the day. So, the on-peak periods appear in the midday. The third Tuesday of March is used to represent load demand on a weekday.
- The second group is the load demand on a weekend day where factories and companies are closed. The main consumers are malls and houses. The second Sunday of March is used to represent load demand on a weekend day.
- The third group is the load demand on a holiday, which has different behavior from the first group and second group. The 1st of January is used to representing load demand on a holiday.

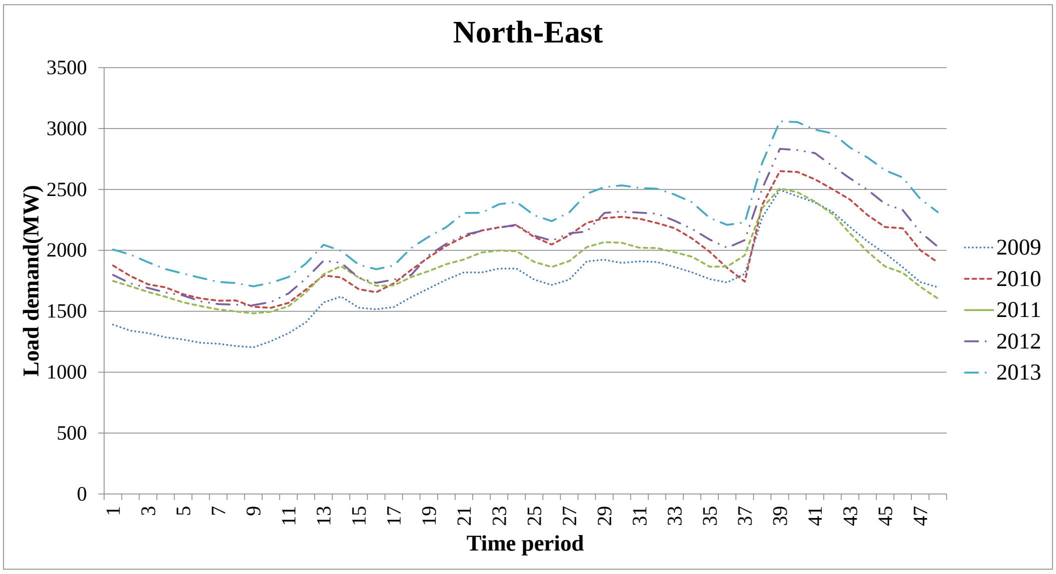
The history data from 2009-2013 of each group show that the off-peak and the on-peak pattern are similar in each year although the load demand significantly increases each year. The behavior of the load demand of a weekday, a weekend day and a holiday are shown in Figure 4.3 - 4.5, respectively.



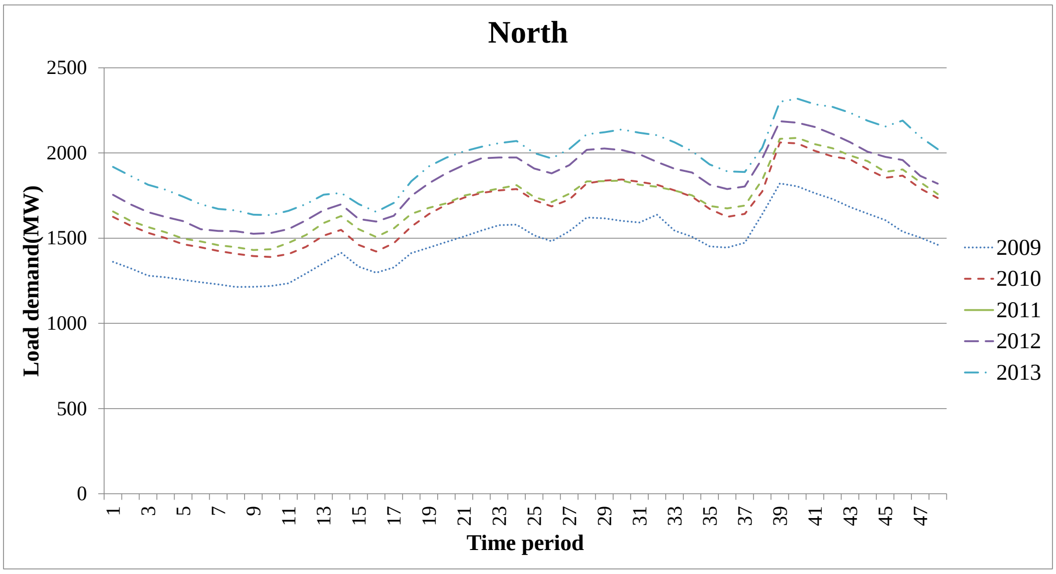
(a) Weekday load demand in Central zone.



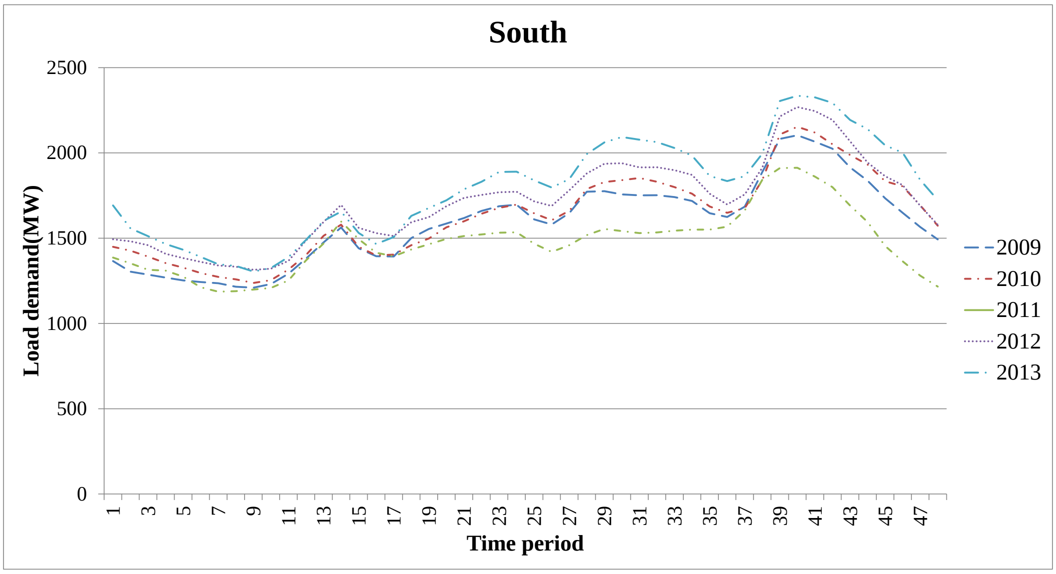
(b) Weekday load demand in Metro zone.



(c) Weekday load demand in Northeastern zone.

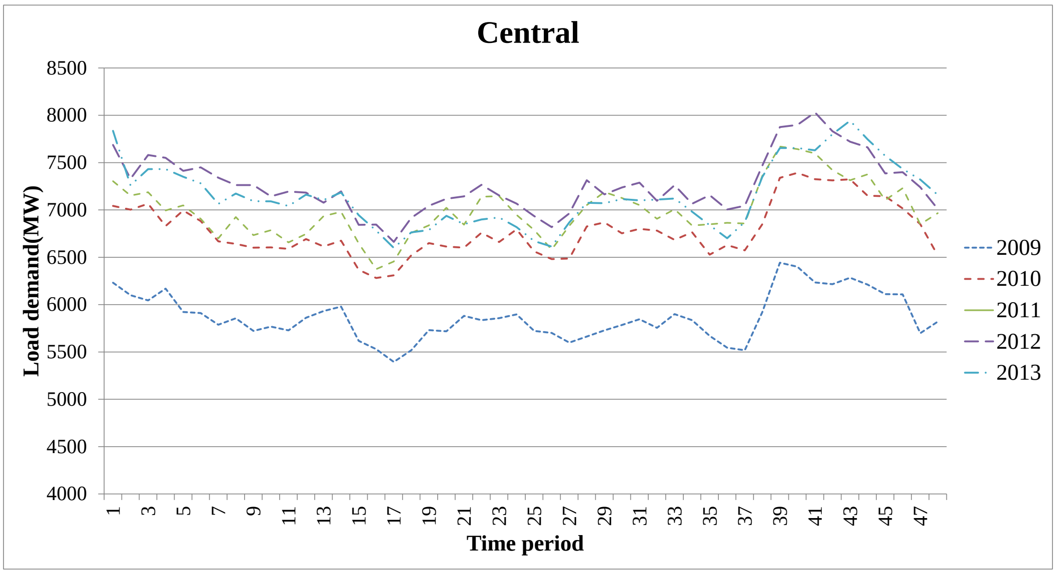


(d) Weekday load demand in North zone.

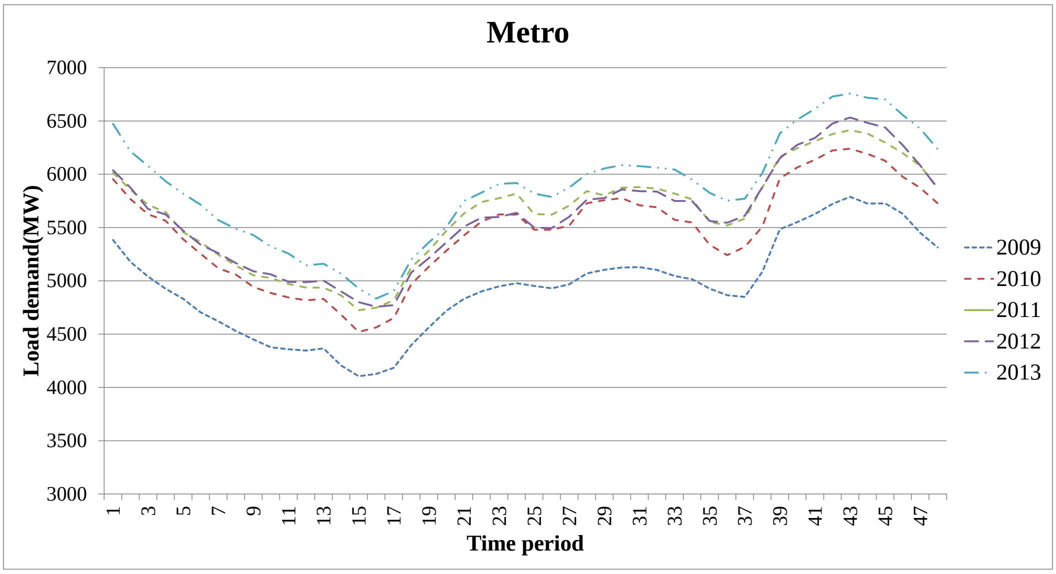


(e) Weekday load demand in South zone.

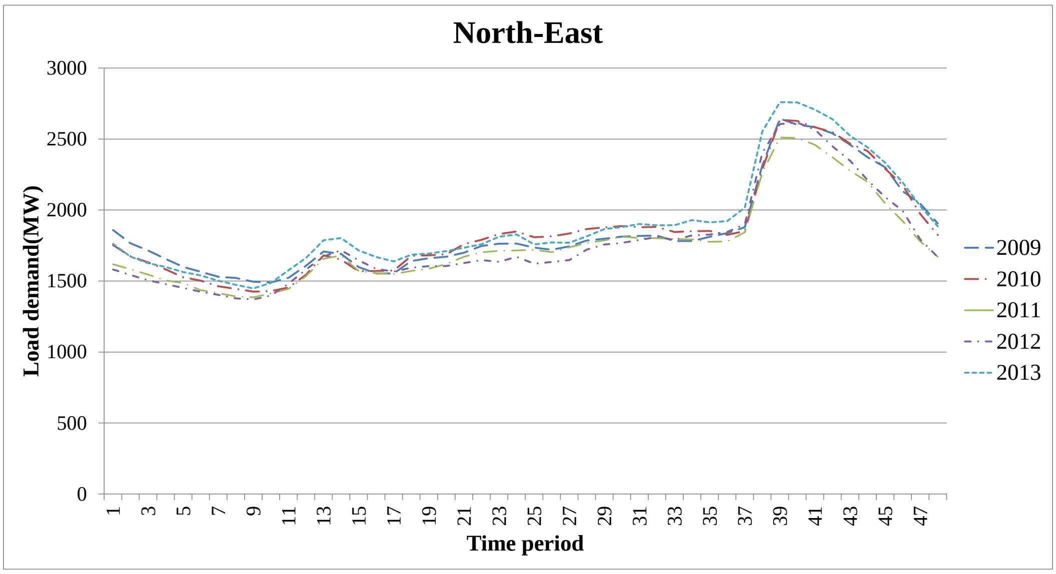
Figure 4.3: Weekday load demand in each zone of system.



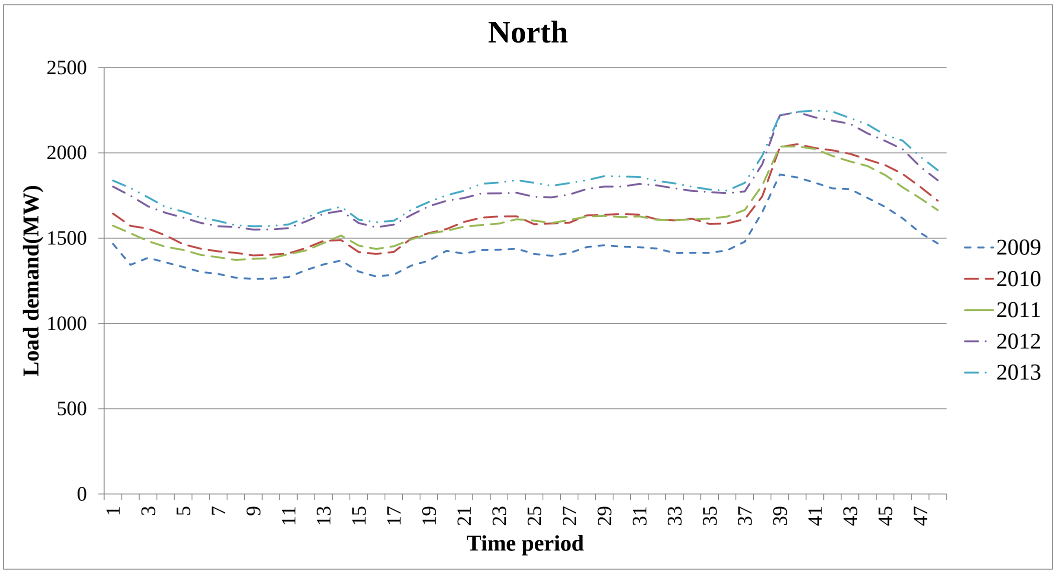
(a) Weekend load demand in Central zone.



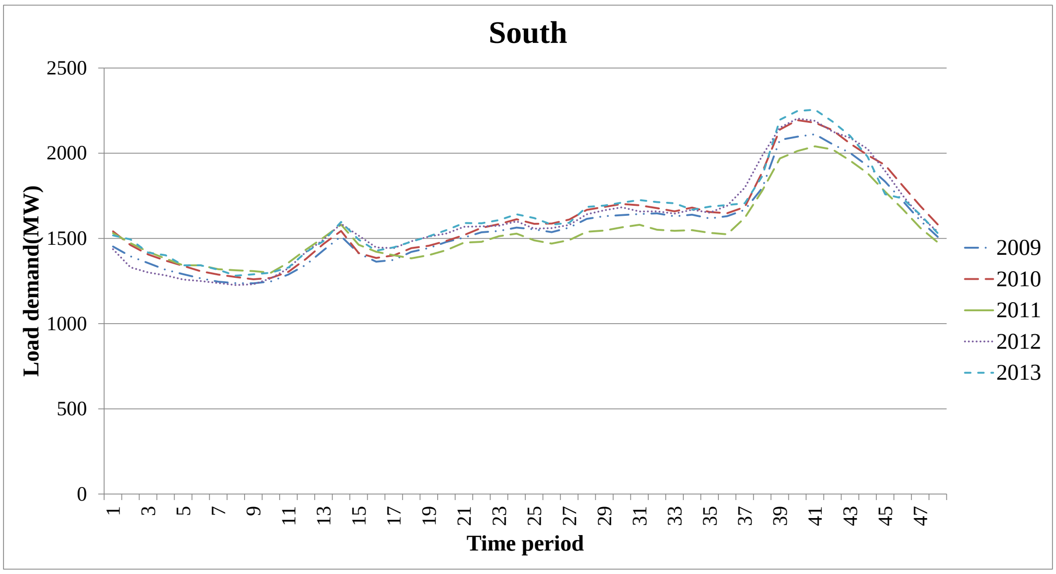
(b) Weekend load demand in Metro zone.



(c) Weekend load demand in North-east zone.

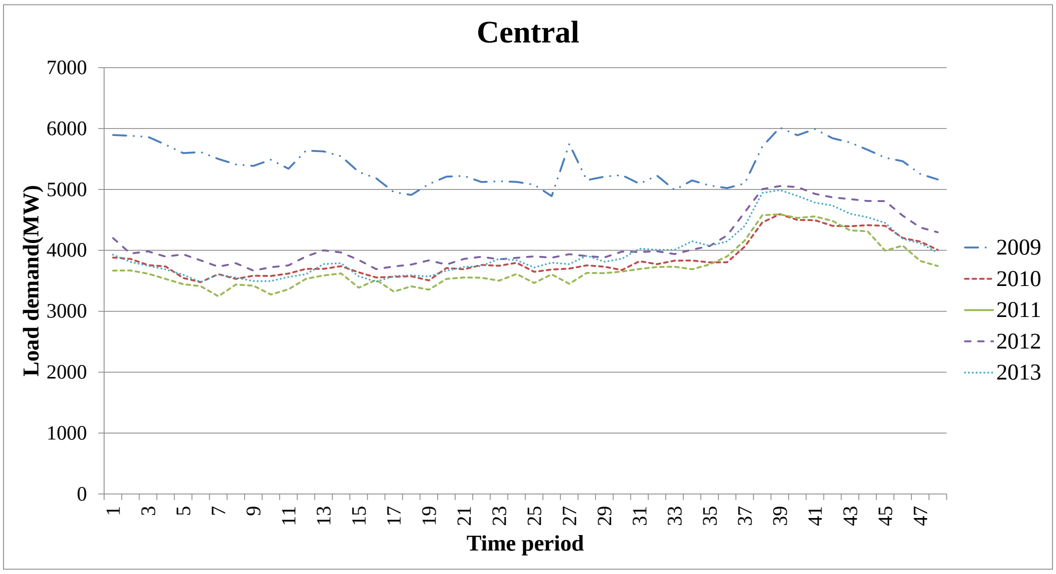


(d) Weekend load demand in North zone.

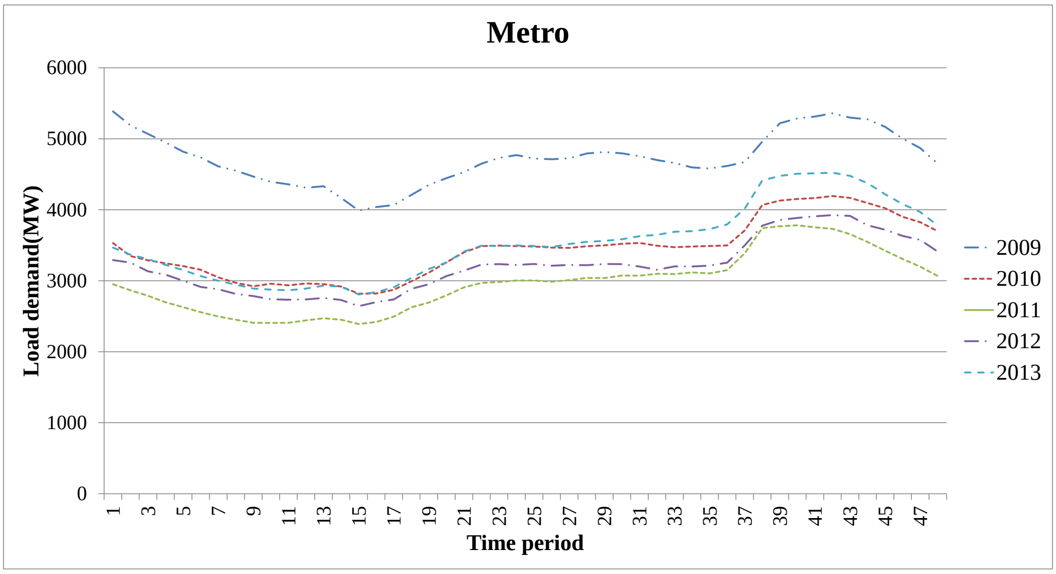


(e) Weekend load demand in South zone.

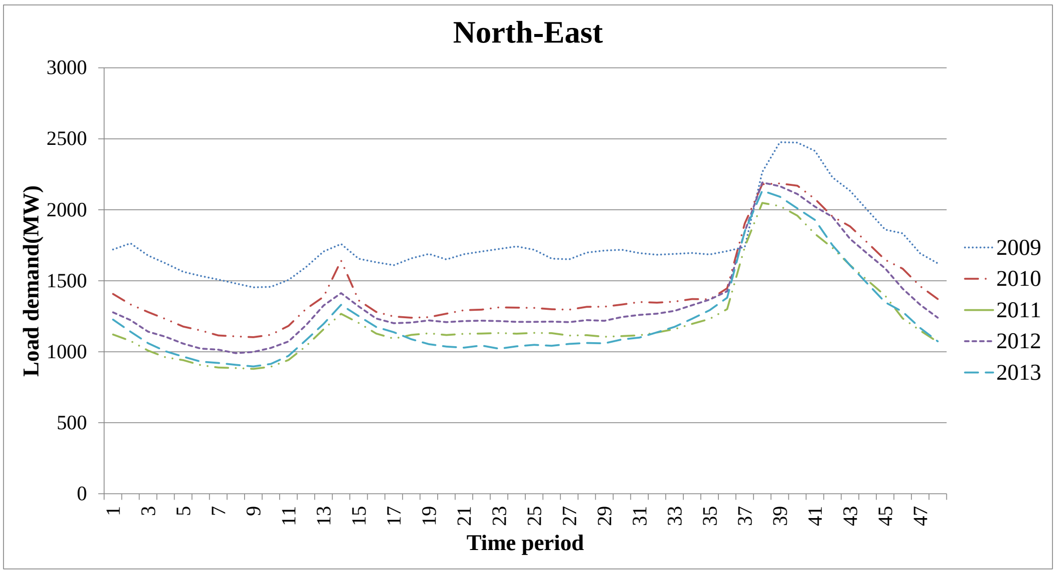
Figure 4.4: Weekend load demand in each zone of system.



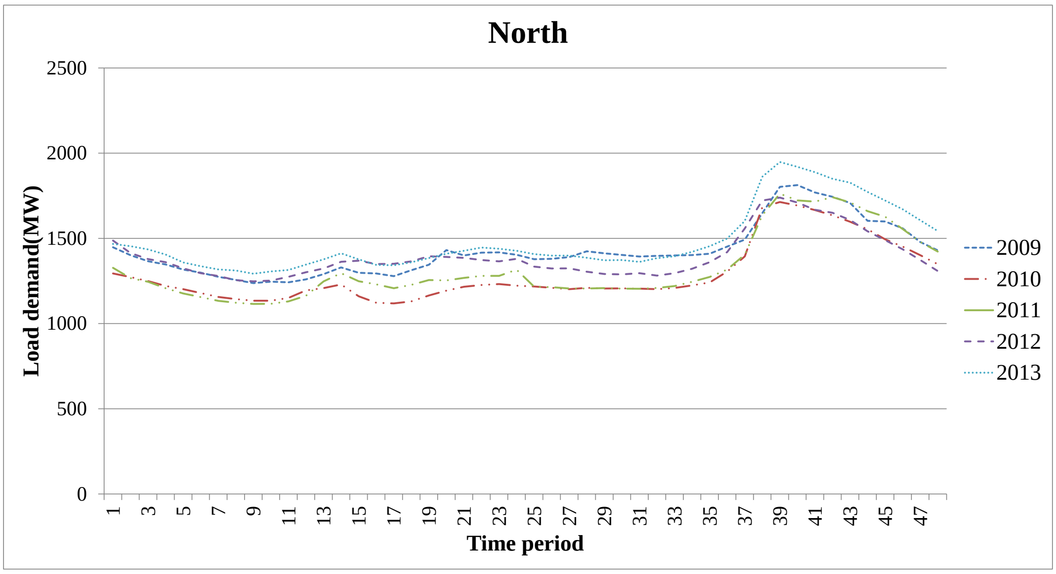
(a) Holiday load demand in Central zone.



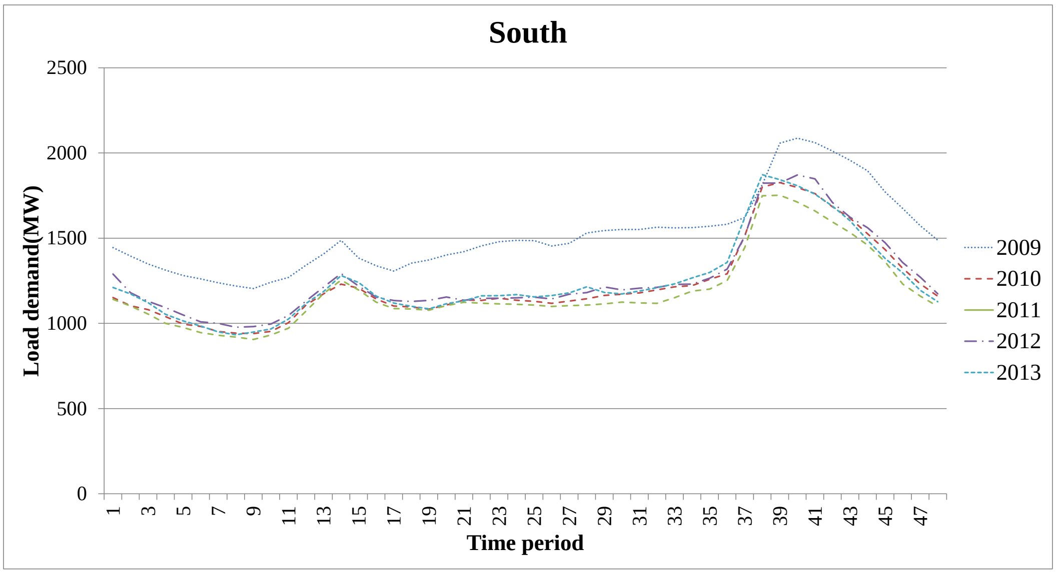
(b) Holiday load demand in Metro zone.



(c) Holiday load demand in North-east zone.



(d) Holiday load demand in North zone.



(e) Holiday load demand in South zone.

Figure 4.5**:** Holiday load demand in each zone of system.

To study the solution sensitivity of the parameters and the amount of additional renewable energy, the average load demand from the historical data is used to represent a load demand in each group. Therefore, a load demand of the first group, weekday, is shown in Figure 4.6. A load demand of the second group and third group are shown in Figure 4.7 and 4.8, respectively

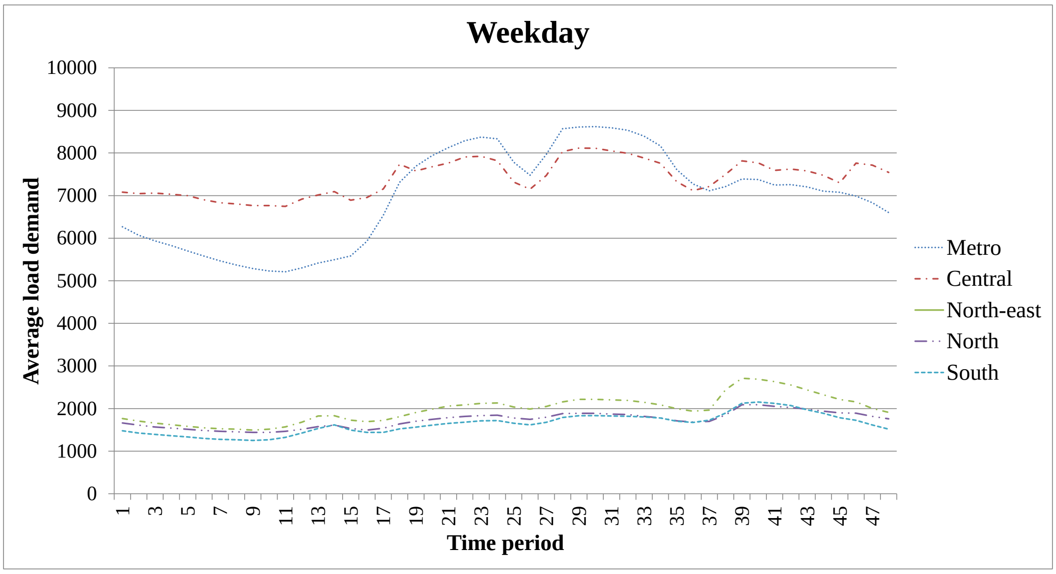


Figure 4.6: The average load demand on a weekday

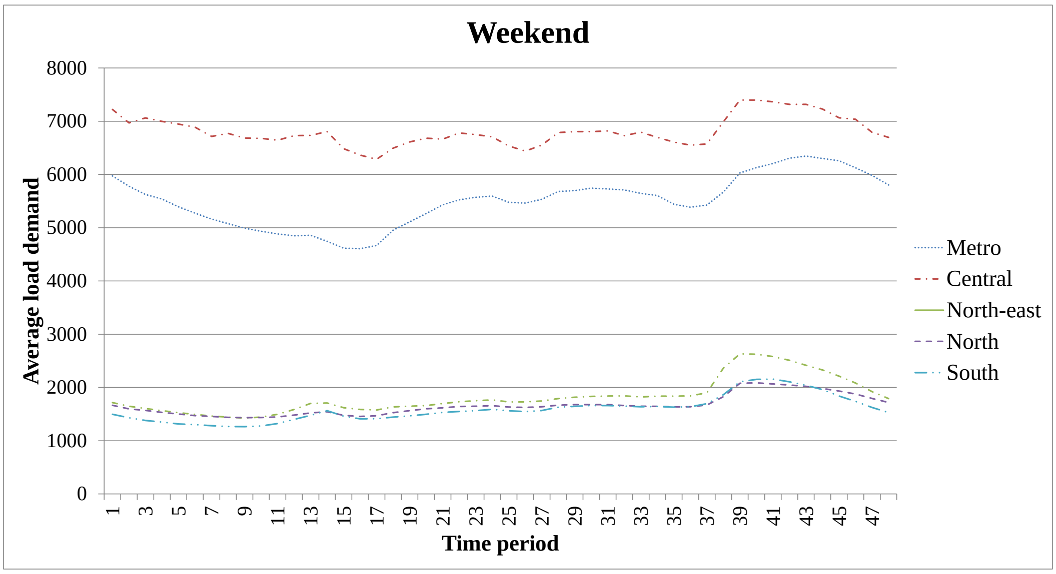


Figure 4.7: The average load demand on a weekend day

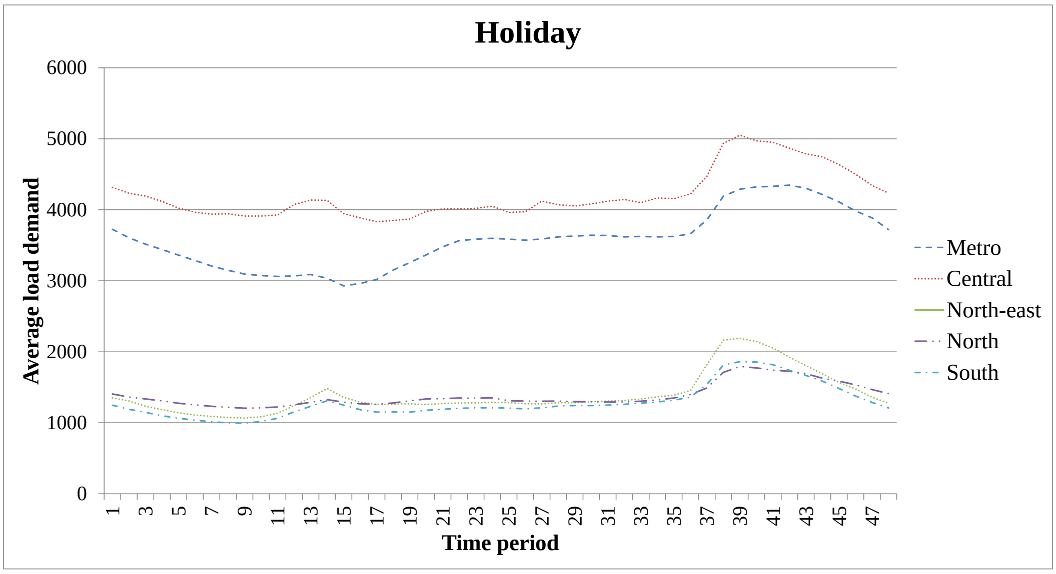


Figure 4.8**:** The average load demand on a holiday

4.2.3 The sensitivity of probability distribution

At first, the effect of probability distribution is studied. By the scenario generation, the power output of a renewable energy can appear in three scenarios. A probability of each scenario is defined as a simple discrete distribution. Their probability mass function are varied in the proportional $x : 0.75(1-x) : 0.25(1-x)$ where x represents the varying factor to agree with the high : medium : low probability proportion. The cost of the renewable energy is supposed to be zero with the same reason as the deterministic model. The results are shown is Figure 4.9 - 4.11.

In Figure 4.9, the expected total costs of the first group (weekday) for each probability mass function are almost the same. The expected total cost of a distribution 0.8:0.15:0.05 at penalty value 800 THBs is slightly different from other. Whereas, at penalty value 1,000 THBs, a distribution 0.5 : 0.375 : 0.125 and 0.6 : 0.3 : 0.1 are slightly greater than other.

In Figure 4.10, the expected total costs of the second group (weekend) for each probability mass function are similar. In general, the expected total cost of the weekend group is smaller than the expected total cost of weekday group.

In Figure 4.11, the expected total costs of the third group (holiday) for each probability mass function are fluctuating in small gap. A probability 0.6 : 0.3 : 0.1 is slightly greater than others when the penalty values are between 100 - 300.

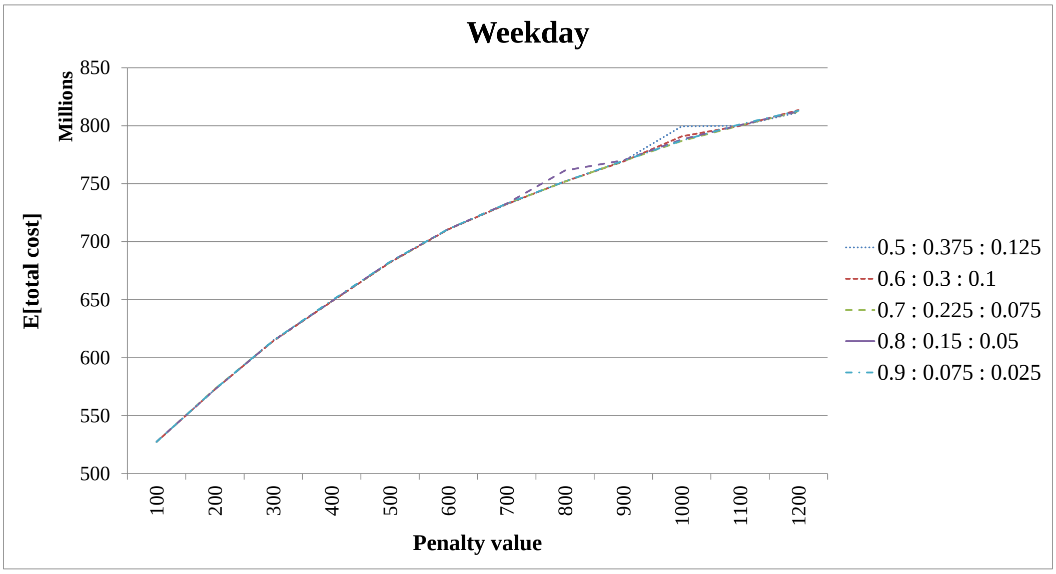


Figure 4.9**:** The expected total cost of weekday demand on each penalty value.

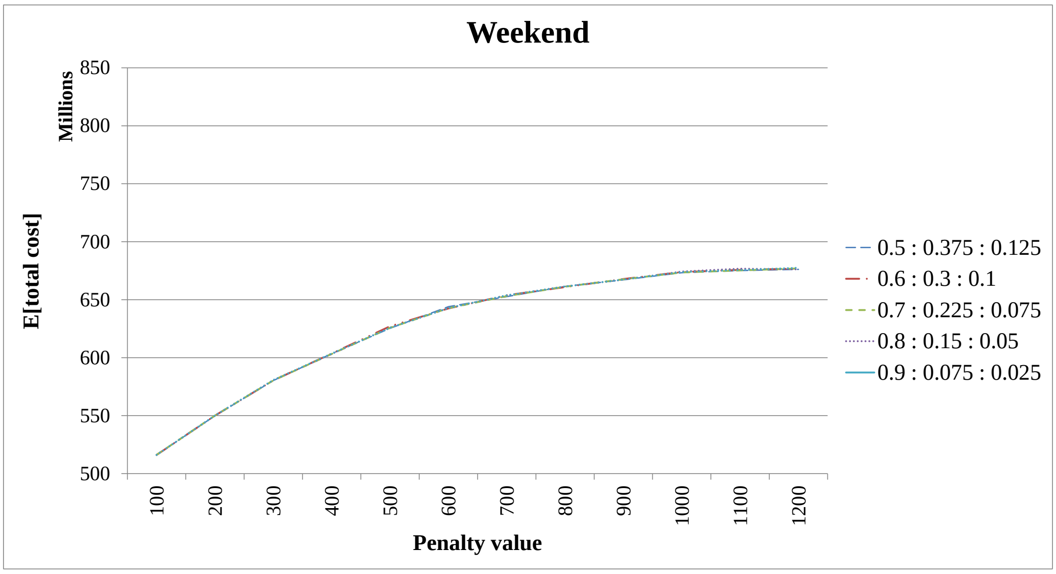


Figure 4.10**:** The expected total cost of weekend demand on each penalty value.

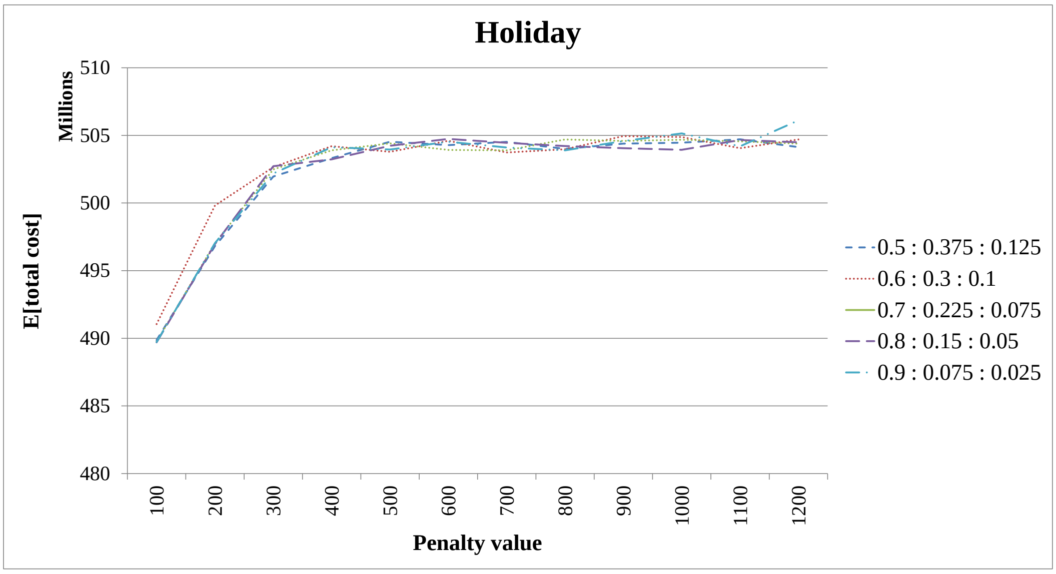


Figure 4.11**:** The expected total cost of holiday demand on each penalty value.

The result shows that each probability mass function does not affect too much on the optimal solution of the stochastic expected recourse unit commitment model. Thus, we choose only one probability mass function which is 0.6 : 0.3 : 0.1 to study a stochastic model with renewable energy. Therefore, the power output for each scenario and probability is shown in Table 4.3.

	Renewable power output for zone j	Probability
1	The summation of the minimum level as indicated by the dependable capacity factor percentage from each source ($R^t_{1,j}$)	High ($P^t_1 = 0.6$)
2	The summation of the average between the full capacity and the minimum level from each source ($R^t_{2,j}$)	Medium ($P^t_2 = 0.3$)
3	The summation of the full capacity from each source ($R^t_{3,j}$)	Low ($P^t_3 = 0.1$)

Table 4.3**:** The power output for each scenario of the renewable energy and their probability.

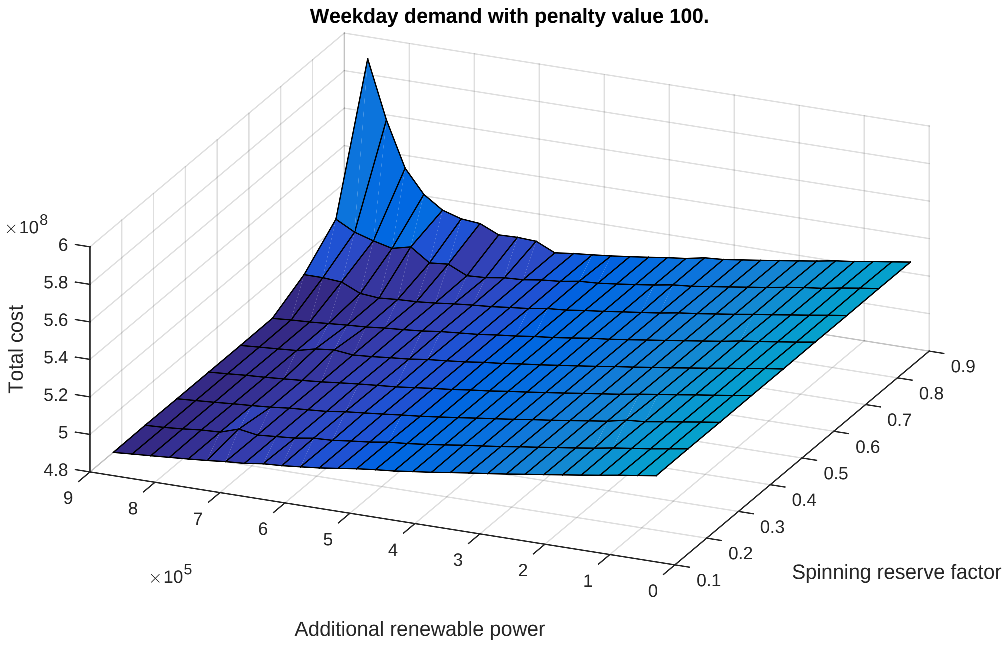
4.2.4 **Additional renewable energy analysis**

To study the effect of the amount of the renewable energy and the renewable spinning reserve factor to the total cost of the system, the parameters are varied. We increase the power output from renewable energy for each source type in the increment of 100 MW. Moreover, we increase the value of the renewable spinning reserve factor in the increment of 10 percent starting from 10 to 90 percent. The conventional spinning reserve factor is selected to be 0.05. We consider 6 values of penalty cost as follows: 100, 200, 400, 600, 800, and 1000. The results are shown in Figures 4.12 - 4.14.

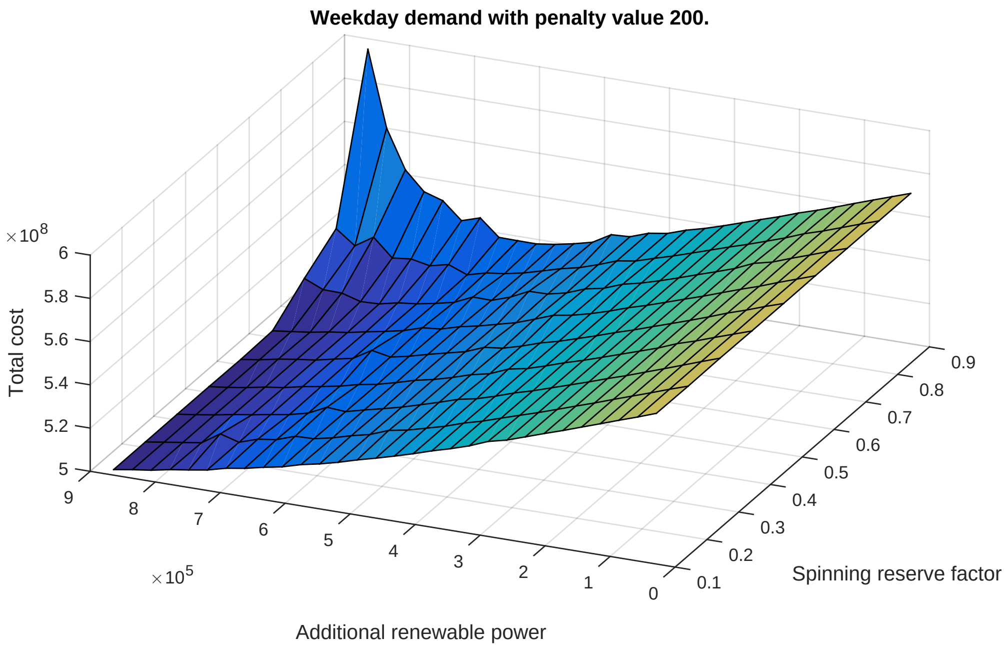
Figure 4.12 displays the result of each penalty cost for the weekday demand. When the additional renewable energy is increased, a total cost of the system decrease. When the reserve factor is increases, the total cost also increase. The change in the total cost is more prominent when the penalty cost is higher. However, when the additional renewable energy becomes too high, the total cost becomes increasing when the spinning reserve factor is high. The increase in total cost at penalty values 100-200 is significantly higher than others.

Figure 4.13 displays the result of each penalty cost for the weekend demand. The result of weekend demand is almost similar to the weekday. The total cost decreases when the amount of additional renewable energy is increased. The total cost increases when the reserve factor is increased. The change of total cost becomes greater when the penalty cost is higher.

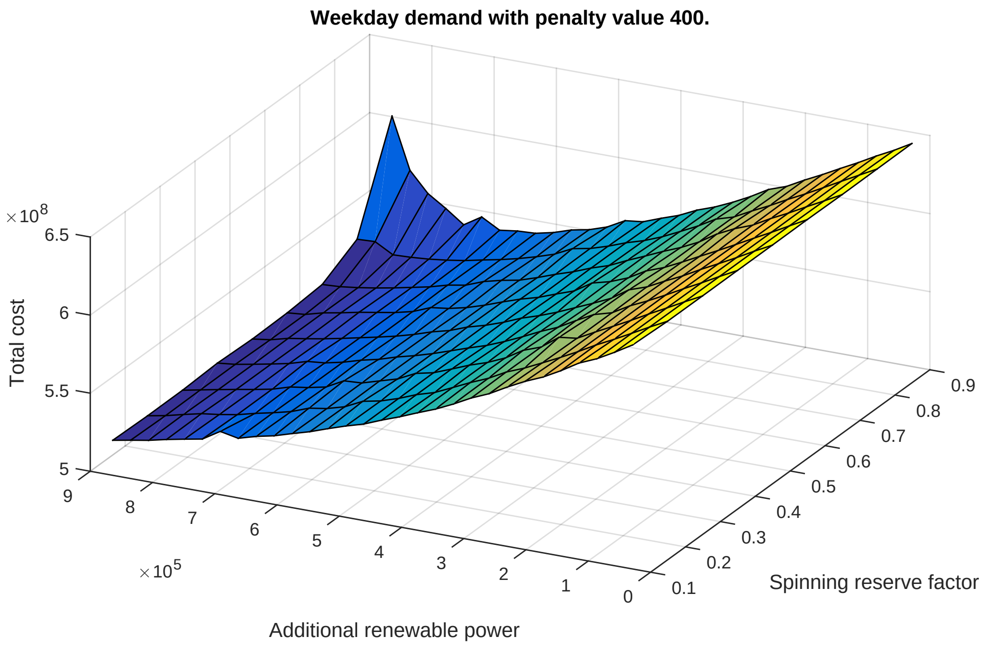
Figure 4.14 displays the result of each penalty cost for the holiday demand. A total cost of the system decreases as the additional renewable energy is increased but no more than 2000 MW. If the renewable energy is increased more than 2000 MW, the total cost is almost constant. When the value of additional renewable energy and spinning reserve factor are both high, the total cost is higher than others similar to the weekday demand and weekend demand.



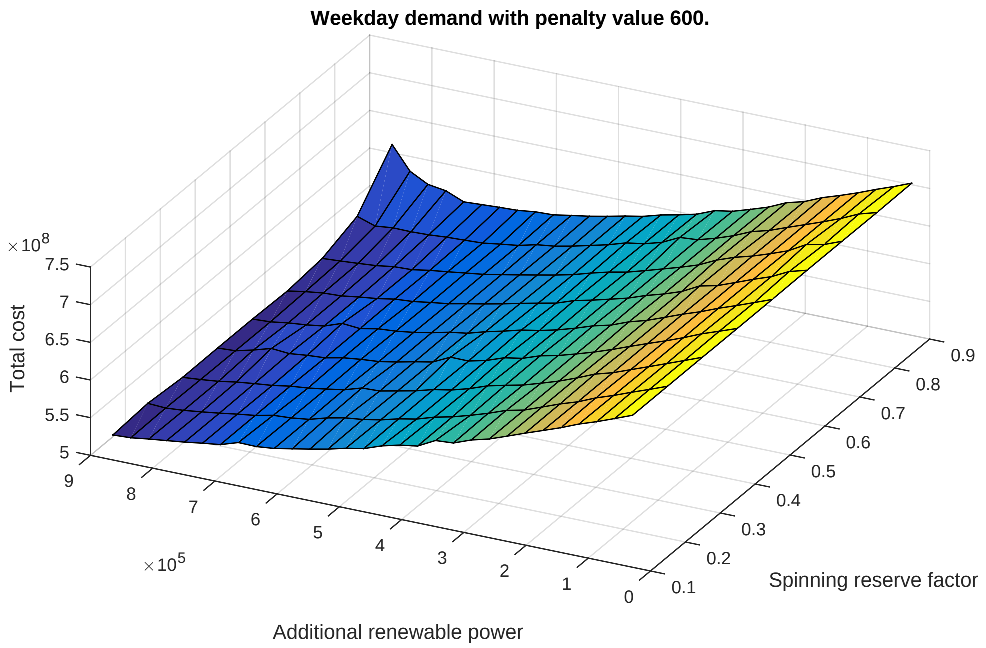
(a) Weekday load demand with penalty value 100.



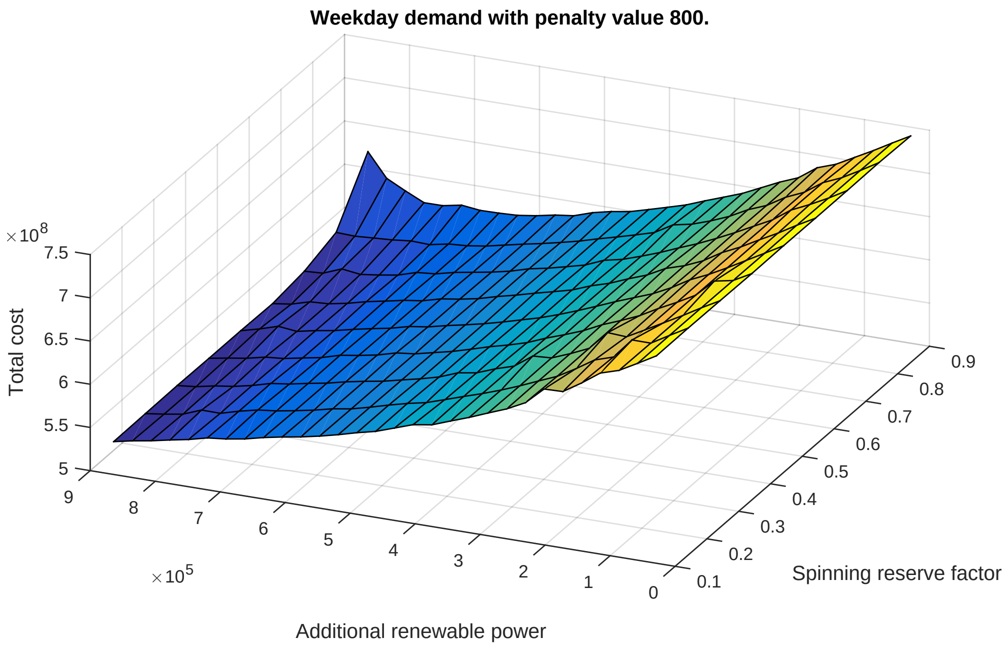
(b) Weekday load demand with penalty value 200.



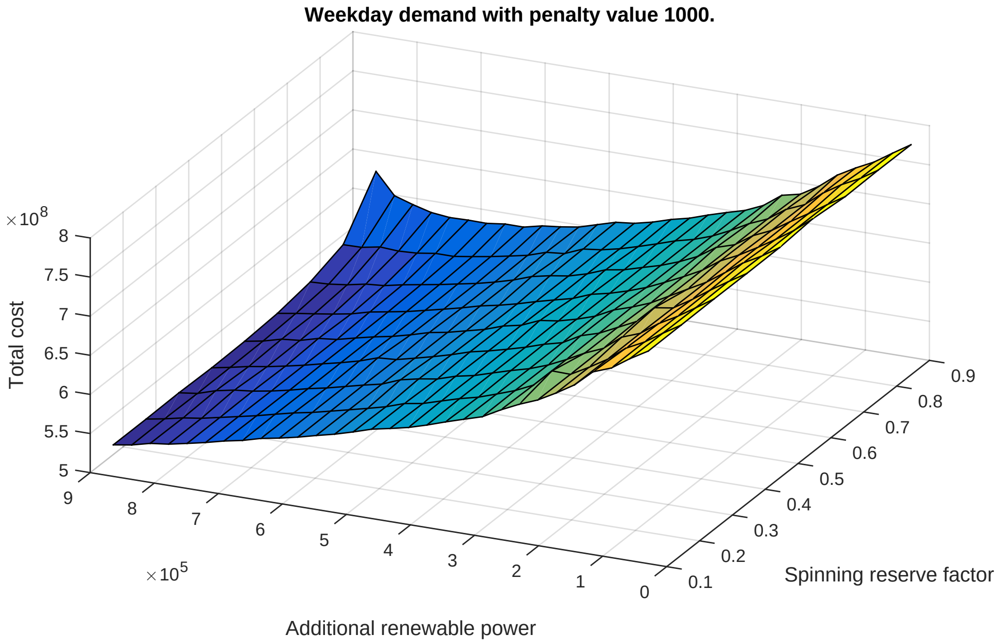
(c) Weekday load demand with penalty value 400.



(d) Weekday load demand with penalty value 600.

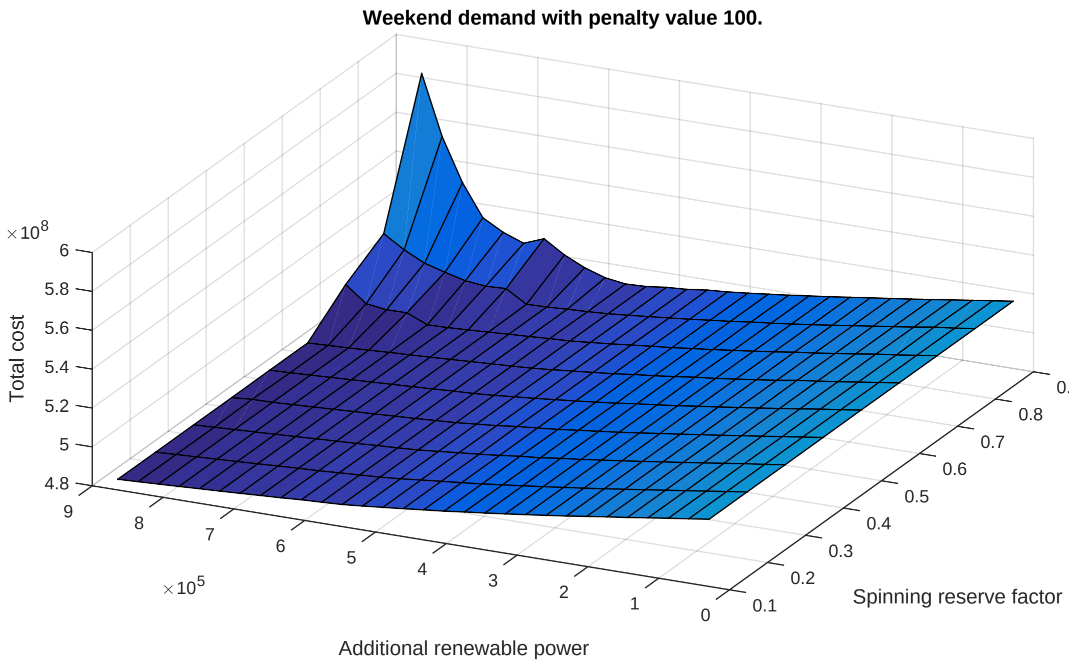


(e) Weekday load demand with penalty value 800.

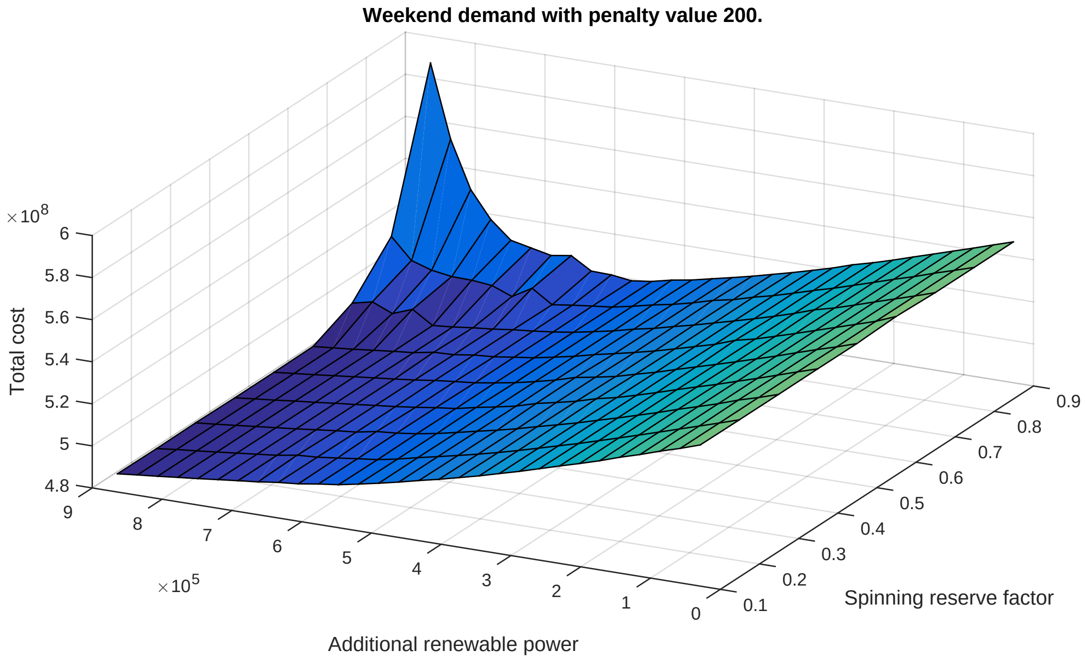


(f) Weekday load demand with penalty value 1000.

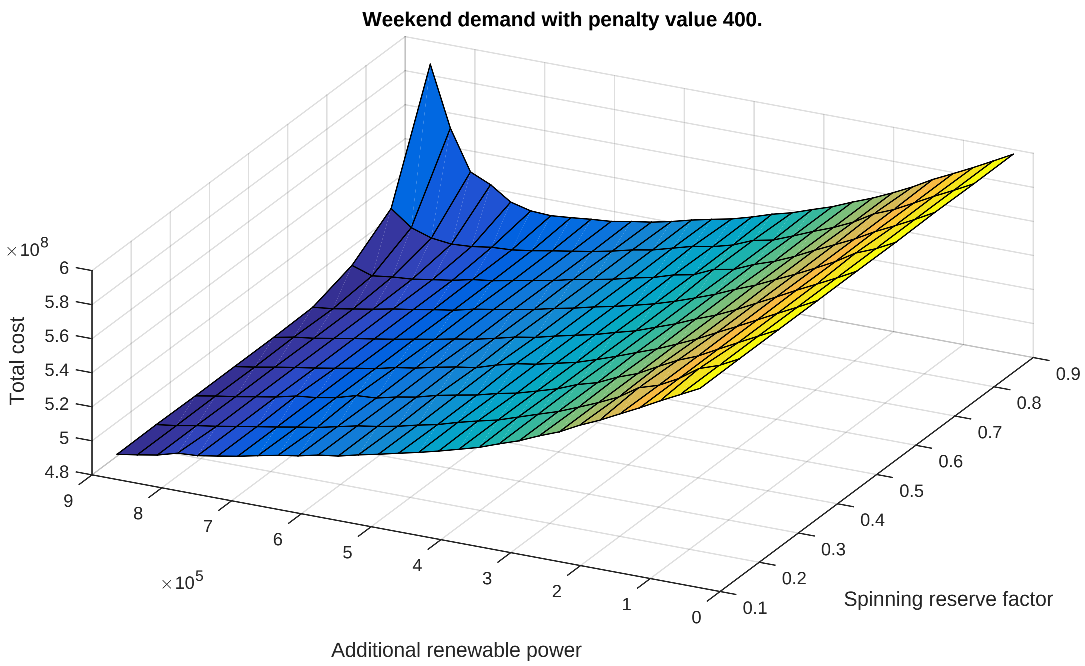
Figure 4.12: Total cost of each additional renewable energy and renewable spinning reserve factor on weekday load demand.



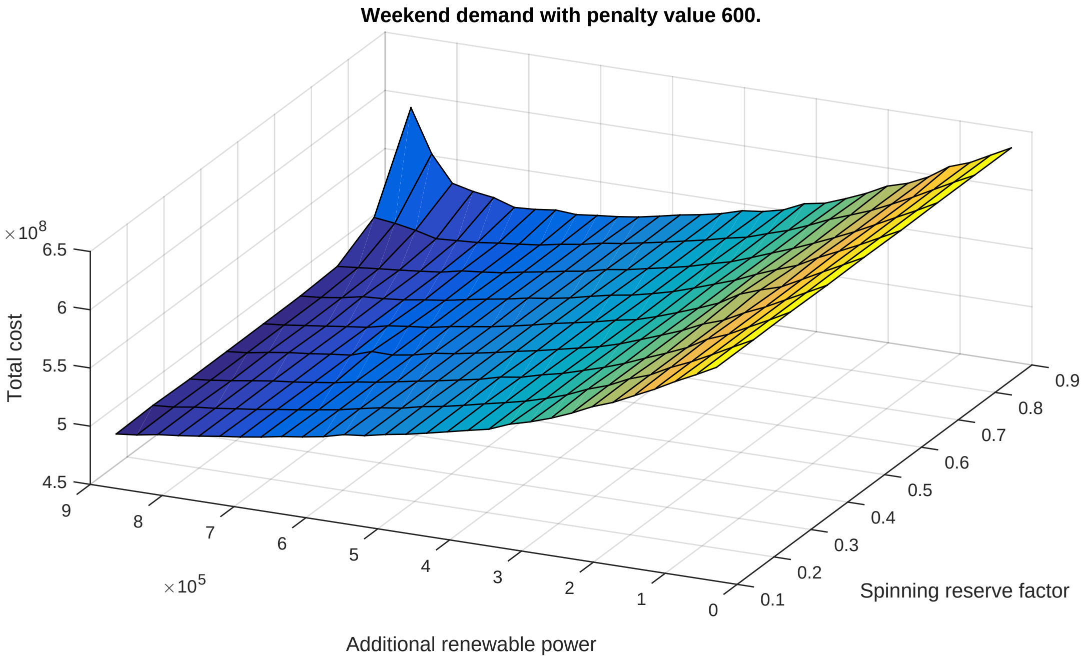
(a) Weekend load demand with penalty value 100.



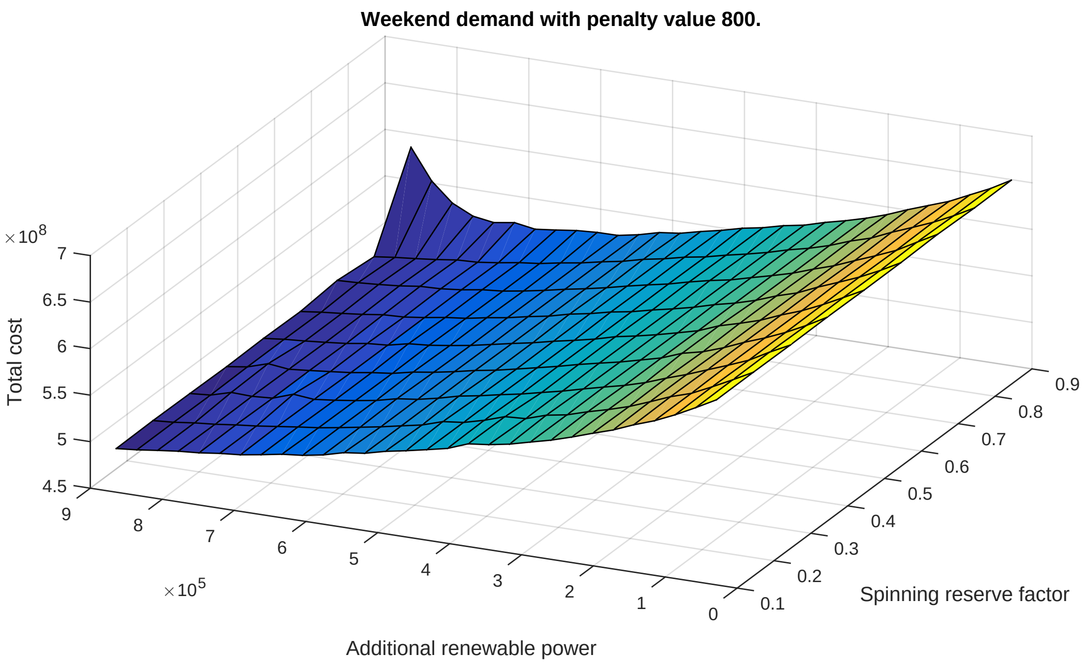
(b) Weekend load demand with penalty value 200.



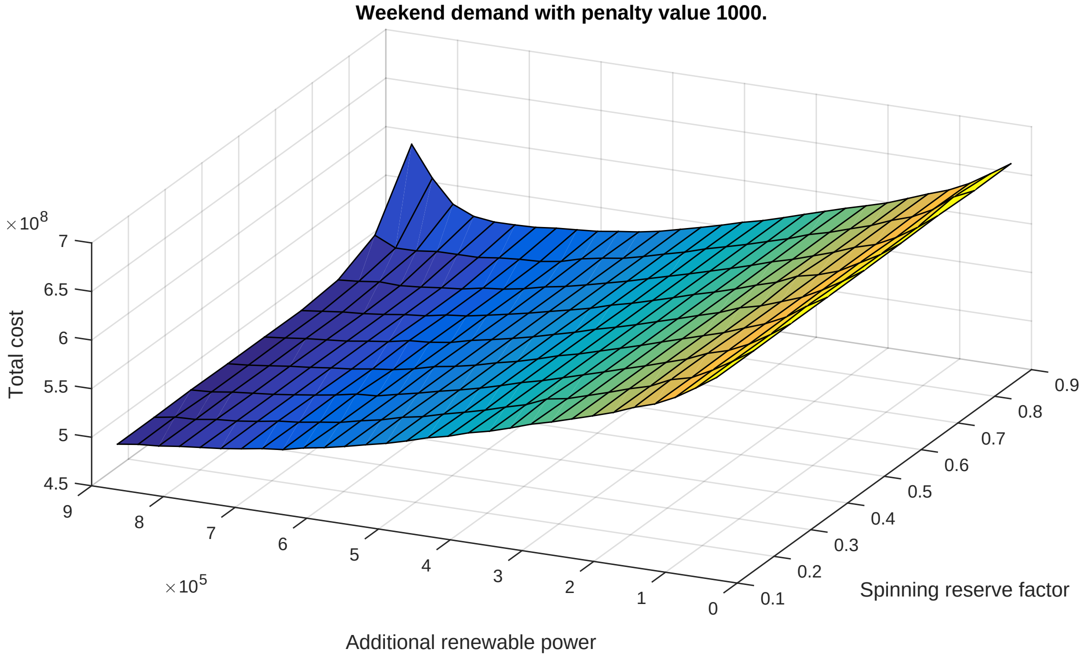
(c) Weekend load demand with penalty value 400.



(d) Weekend load demand with penalty value 600.

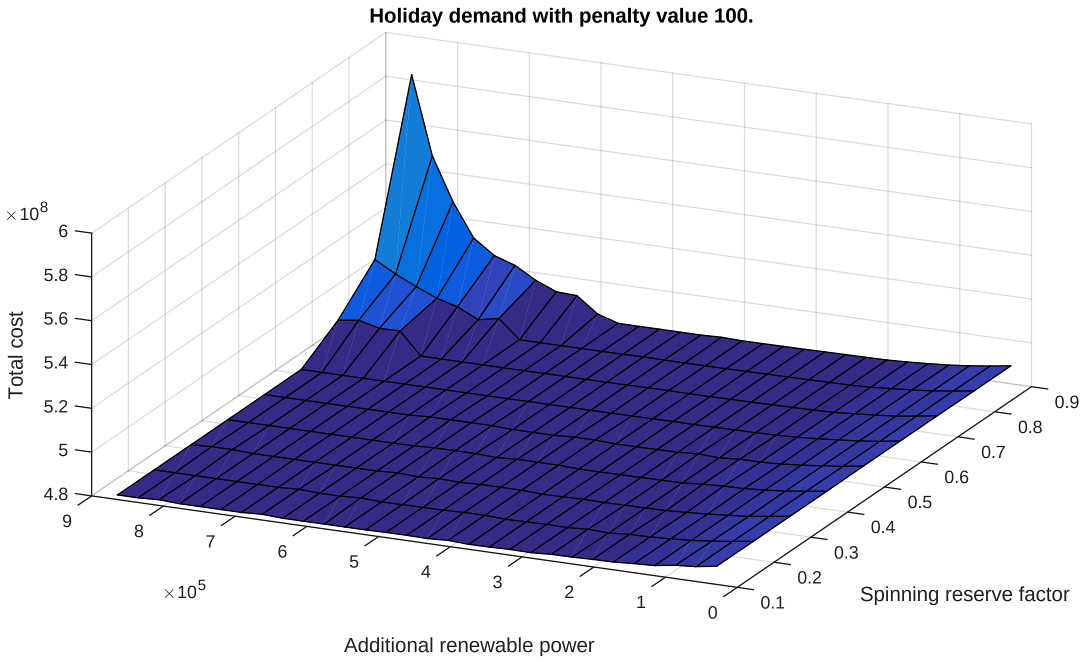


(e) Weekend load demand with penalty value 800.

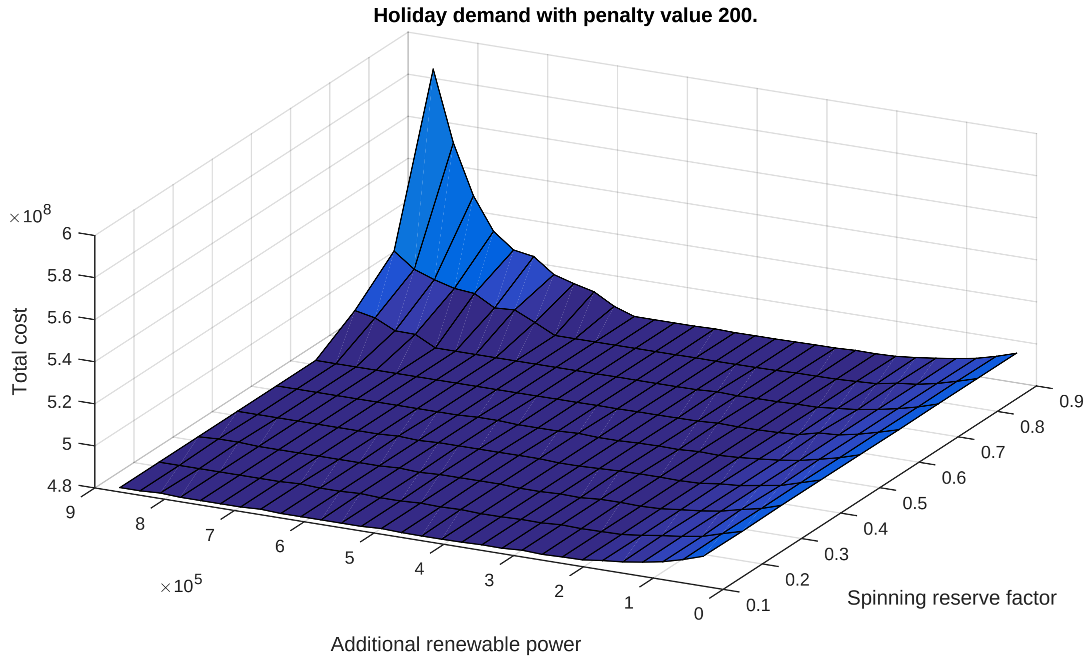


(f) Weekend load demand with penalty value 1000.

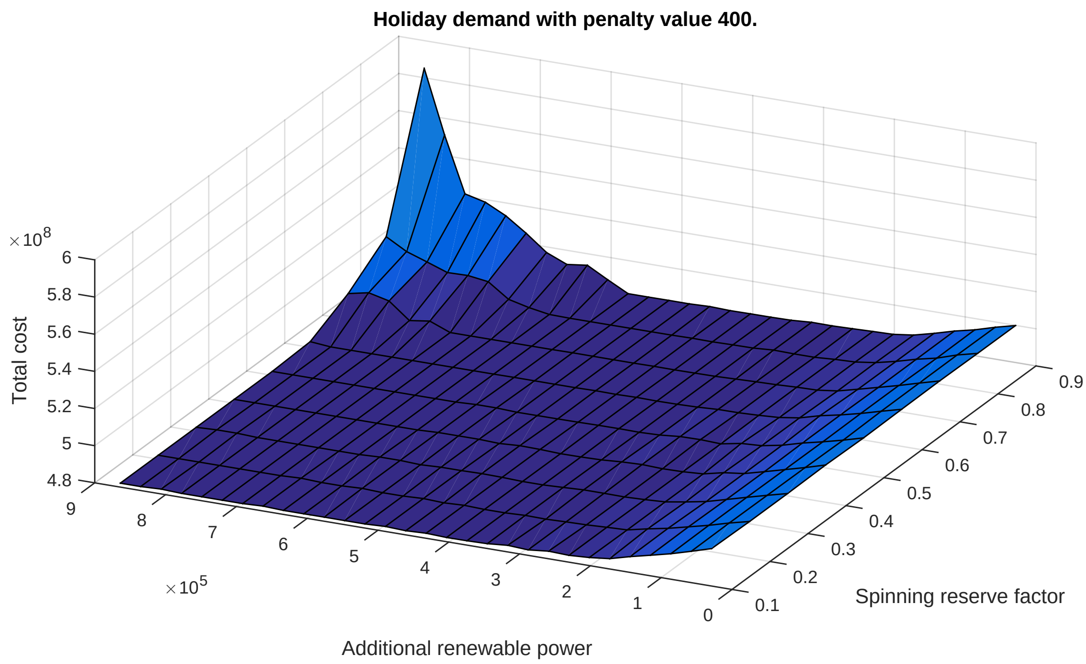
Figure 4.13: Total cost of each additional renewable energy and renewable spinning reserve factor on weekend load demand.



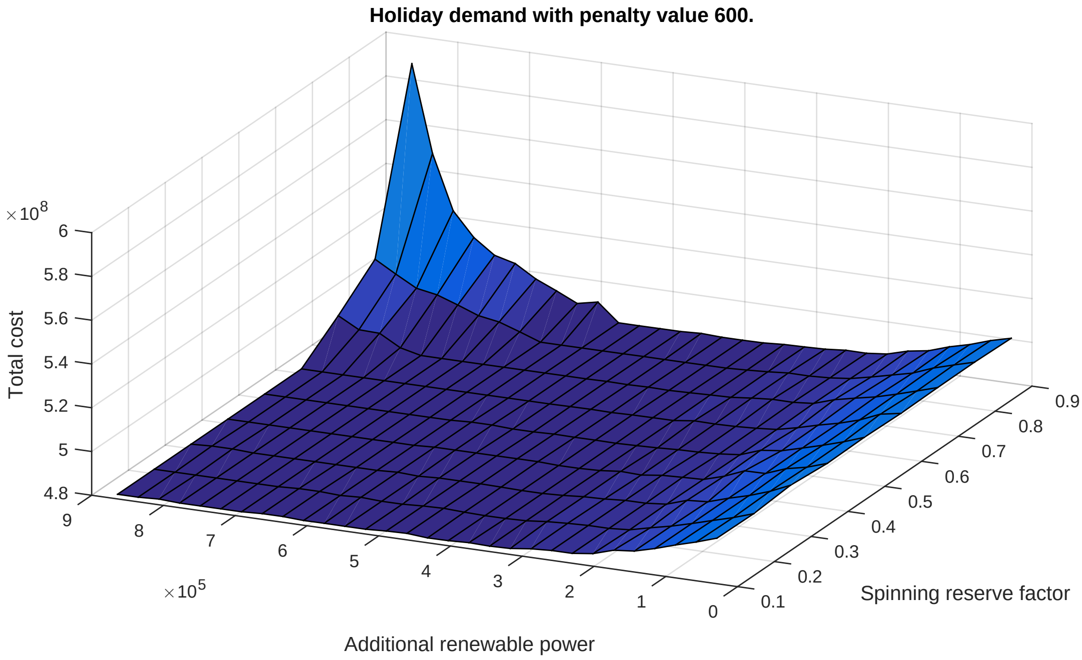
(a) Holiday load demand with penalty value 100.



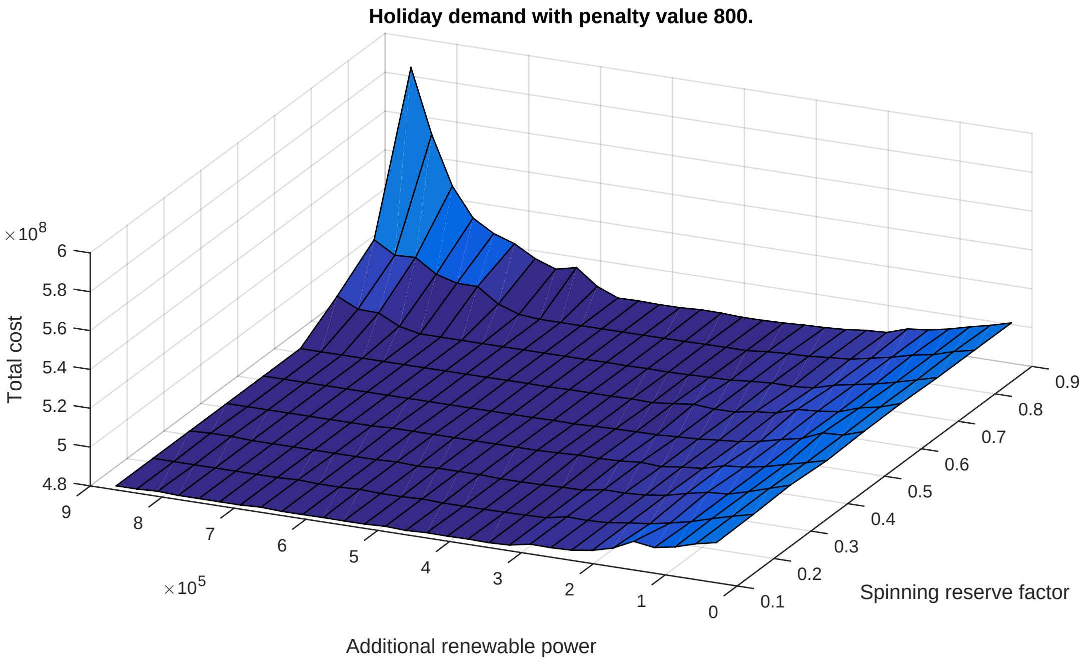
(b) Holiday load demand with penalty value 200.



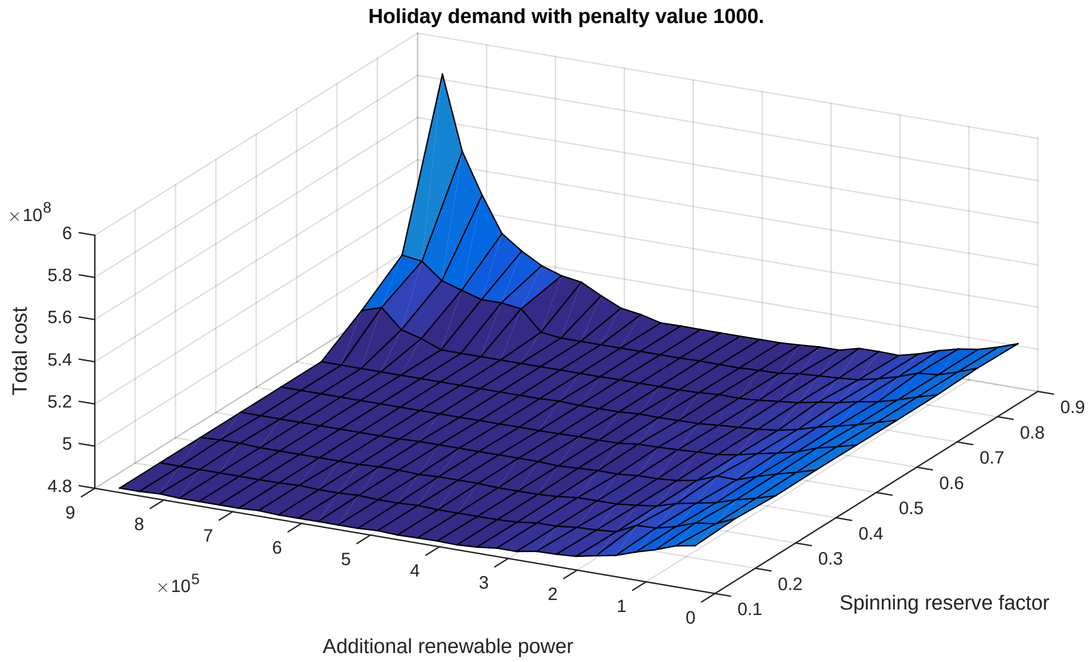
(c) Holiday load demand with penalty value 400.



(d) Holiday load demand with penalty value 600.



(e) Holiday load demand with penalty value 800.



(f) Holiday load demand with penalty value 1000.

Figure 4.14**:** Total cost of each additional renewable energy and renewable spinning reserve factor on holiday load demand.

CHAPTER V

CONCLUSIONS

5.1 Conclusion of this work

The stochastic expected recourse model is proposed to manage the power system with renewable energy which is the source of uncertainty. The higher portion of renewable energy in system implies the lower reliability of the system. Therefore, we increase the reliability by adding the expected renewable energy term to the spinning reserve constraint. As we increase the amount of renewable energy in the system, the total cost decreases. However, the total cost becomes indifferent after the renewable energy addition reaches 20000 MW in holiday demand and 80000 MW in weekday demand and weekend demand when the spinning reserve factor for the renewable energy is low. This value is related to total load demand power in each group. On the other hand, too much additional renewable energy provide the increasing total cost when the spinning reserve factor for the renewable energy is high since the more renewable energy in the system implies the more spinning reserve of the system. In such case, too much renewable energy will cause all generators in the system to be online for supporting the spinning reserve and consequently increase in the total cost.

5.2 Discussion and future works

The stochastic model can be further improved as follows.

1. The stochastic expected recourse unit commitment model does not consider other costs such as investment cost and capacity cost. Therefore, the renewable energy is significantly cheap. However, one should keep in mind that these costs for renewable energy are usually higher than the conventional power generation in reality. Incorporating these costs into the model would give more realistic results.

2. The model can be improved by considering the different of renewable energy type. The analyzed result will provide the effect of each type of the renewable energy on total cost.

3. Other details of problem should be considered such as the location and the renewable energy plant.

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APPENDICES

APPENDIX A : IBM ILOG OPL CPLEX code for import and export data.

```
/*** Parameters ***/
one = 1;
NumberOfPeriod = 48;
minuteperperiod = 30;
reservePercent = 0.05;
RenewreservePercent = 90;
/***vary parameter***/
Penalty = 200;
/*** External Data from Sheet ***/
SheetConnection filein("stochastic.xls");
DailyEGASUsage from SheetRead(filein, "DailyGas!B2"); //MBTU
DailyWGASUsage from SheetRead(filein, "DailyGas!B3"); //MBTU
/* Plants */
TherPlantSet from SheetRead(filein, "TherPlant!A2:I8");
GasPlantSet from SheetRead(filein, "GasPlant!A2:F6");
ComPlantSet from SheetRead(filein, "ComPlant!A2:I29");
HydroPlantSet from SheetRead(filein, "HydroPlant!A2:K12");
InitIntermediateReservoir from SheetRead(filein, "HydroPlant!E3");
/* Generators */
TherGenSet from SheetRead(filein, "TherGen!A2:W27");
GasGenSet from SheetRead(filein, "GasGen!A2:W17");
gtCombineGenSet from SheetRead(filein, "gtComGen!A2:AA63");
stCombineGenSet from SheetRead(filein, "stComGen!A2:O29");
HydroGenSet from SheetRead(filein, "HydroGen!A2:P40");
HydroPumpSet from SheetRead(filein, "HydroPump!A2:F6");
/* Demand */
Demand from SheetRead(filein, "Demand!B2:AW6");
/* RenewMW */
Renew from SheetRead(filein, "RenewGen!B2:AW7");
Renewbounded from SheetRead(filein, "RenewGen!B2:AW7");
RenewDCF from SheetRead(filein, "DCFrenew!B2:B7");
RenewPrice from SheetRead(filein, "DCFrenew!C2:C7");
```

```
/* MustRun MustShutDown */
MustRunGen from SheetRead(filein, "MustRun!A2:C54");
MustShutDownGen from SheetRead(filein, "MustShutDown!A2:C8");
/* Transmission Capacity Between Zones in MW */
TransCapacity from SheetRead(filein, "TransCapacity!A2:D13");
/*** Write Results ***/
SheetConnection fileout("stochastic_result.xls");
GeneratorSet to SheetWrite(fileout, "AllUnit!A2:O172");
Gen to SheetWrite(fileout, "Gen!B2:AW172");
status to SheetWrite(fileout, "Status!B2:AW172");
Trans to SheetWrite(fileout, "Trans!B2:AW13");
therfuel to SheetWrite(fileout, "Fuel!B2:AW27");
therfueluse to SheetWrite(fileout, "Fuel!B107:AW132");
gasturbine to SheetWrite(fileout, "Fuel!B28:AW43");
gasturbineuse to SheetWrite(fileout, "Fuel!B133:AW148");
gascombine to SheetWrite(fileout, "Fuel!B44:AW105");
gascombineuse to SheetWrite(fileout, "Fuel!B149:AW210");
PumpWater to SheetWrite(fileout, "Water!B3:AW7");
PumpPower to SheetWrite(fileout, "Water!B53:AW57");
AmountInUpperReservoir to SheetWrite(fileout, "Water!B11:AX21");
AmountInLowerReservoir to SheetWrite(fileout, "Water!B25:AX35");
IntermediateReservoir to SheetWrite(fileout, "Water!B22:AX22");
ReleasedWater to SheetWrite(fileout, "Water!B39:AW49");
Water to SheetWrite(fileout, "Water!B61:AW99");
nbTherOnline to SheetWrite(fileout, "Status!B174:AW174");
nbGasOnline to SheetWrite(fileout, "Status!B175:AW175");
nbgtCombineOnline to SheetWrite(fileout, "Status!B176:AW176");
nbHydroOnline to SheetWrite(fileout, "Status!B177:AW177");
utilizationOperating to SheetWrite(fileout, "KPI!B7:B149");
utilizationPhysical to SheetWrite(fileout, "KPI!C7:C149");
UpTime to SheetWrite(fileout, "Status!AX2:AX172");
DownTime to SheetWrite(fileout, "Status!AY2:AY172");
totalcost to SheetWrite(fileout, "KPI!D1");
StartUpCost to SheetWrite(fileout, "KPI!D2");
```

```
TransCost to SheetWrite(fileout, "KPI!D3");
SlackCost to SheetWrite(fileout, "KPI!D4");
thergencost to SheetWrite(fileout, "KPI!D7:D32");
gasgencost to SheetWrite(fileout, "KPI!D33:D48");
combinegencost to SheetWrite(fileout, "KPI!D49:D110");
totalproduction to SheetWrite(fileout, "KPI!E7:E149");
therfuelcost to SheetWrite(fileout, "Fuel!B212:AW237");
gasfuelcost to SheetWrite(fileout, "Fuel!B238:AW253");
combinefuelcost to SheetWrite(fileout, "Fuel!B254:AW315");
```

APPENDIX B : IBM ILOG OPL CPLEX code of stochastic expected recourse unit commitment model.

```
int one = ...;
int NumberOfPeriod = ...;
range Periods = one..NumberOfPeriod;
range Periods1 = one..NumberOfPeriod+1;
float minuteperperiod = ...;
float hourperperiod = minuteperperiod/60;
float LargeNumber = 1E10;
float reservePercent = ...;
float RenewreservePercent = ...;
float DailyEGASUsage = ...;
float DailyWGASUsage = ...;
float Penalty = ...;
{string} zones = {"CAC", "MAC", "NAC", "NEC", "SAC"};
{int} RenewType = {1,2,3,4,5,6} ;
{string} fuels = {"OIL", "EGAS", "LIGNITE", "KGAS", "HPPOIL", "WGAS"};
{string} gases = {"LGAS", "EGAS", "DIESEL"};
tuple Plant {
   key string name;
   string zone;
   float VOM;}
tuple TherPlant {
Plant plant;
float oil2Max;
float egasMax;
float ligniteMax;
float kgasMax;
float hppoilMax;
float wgasMax;}
tuple GasPlant {
Plant plant;
float egasMax;
```

```
float lgasMax;
float dieselMax;}
tuple ComPlant {
Plant plant;
float egasMax;
float jgasMax;
float kgasMax;
float wgasMax;
float ngasMax;
float dieselMax;}
tuple HydroPlant {
Plant plant;
float HydroPlantDailyRelease; // in MCM
float InitUpperReservoir; // in MCM
float InitLowerReservoir; // in MCM
float UpperReservoirCapacity; // in MCM
float LowerReservoirCapacity; // in MCM
float MinPumpLevel; // in MCM
float DailyWaterUse; // in MCM
float DailyWaterPump; // in MCM }
float InitIntermediateReservoir = ...;
{TherPlant} TherPlantSet = ...;
{GasPlant} GasPlantSet = ...;
{ComPlant} ComPlantSet = ...;
{HydroPlant} HydroPlantSet = ...;
tuple Fuel {
key string name;
float constantHeatRate; // MW
float linearHeatRate; // ratio of MW/MBTU
float cost;}
tuple Unit {
key string name;
string type;
string zone;
```

```
string plant;
float initProduct; // in MW
int initUpTime; // in Period
int initDownTime; // in Period
int minUpTime;  // in Period
int minDownTime; // in Period
float minGen;   // in MW
float maxGen;   // in MW
float operGen;  // in MW
float rampUp;   // in MW/min
float rampDown; // in MW/min
float startCost; // in Baht }
// Thermal Generator Data
tuple TherGen {
Unit unit;
Fuel fuelType1; // Fuel Option 1
Fuel fuelType2; // Fuel Option 2}
// Gas Turbine Generator Data
tuple GasGen {
Unit unit;
Fuel gas;
Fuel diesel;}
tuple GasCombineGen {
Unit unit;
Fuel gas;
Fuel diesel;
string SteamGenName;
float GasSteamRatio;
float HRSG;
int StartUpDelayTime;}
tuple SteamCombineGen {
Unit unit;}
// Hydro Generator Data
tuple HydroGen {
```

```
Unit unit;
float WaterPowerRate; // MCM/(GW hour)}
tuple HydroPump {
key string name;
string type;
string zone;
string plant;
float ConsumeRate; // MCM/GW
float ConsumeMW;  // MW/hour}
{TherGen} TherGenSet = ...;
{HydroGen} HydroGenSet = ...;
{HydroPump} HydroPumpSet = ...;
{GasGen} GasGenSet = ...;
{GasCombineGen} gtCombineGenSet = ...;
{SteamCombineGen} stCombineGenSet = ...;
// Set of All Generators
{Unit} GeneratorSet = {t.unit | t in TherGenSet} union
{g.unit | g in GasGenSet} union
{c.unit | c in gtCombineGenSet} union
{s.unit | s in stCombineGenSet} union
{h.unit | h in HydroGenSet};
{Unit} ExceptionSet = {s.unit | s in stCombineGenSet};
// Must Run/ShutDown
tuple Must_Run_Tuple {
string name;
int period1;
int period2;}
tuple Must_ShutDown_Tuple {
string name;
int period1;
int period2;}
{Must_Run_Tuple} MustRunGen with period1 in Periods, period2 in Periods
     = ...;
{Must_ShutDown_Tuple} MustShutDownGen with period1 in Periods, period2
```

```
    in Periods = ...;
float Demand[zones][Periods] = ...; // in MW
float Renew[RenewType][Periods]=...;
float Renewbounded[RenewType][Periods]=...;
float RenewDCF[RenewType]=...;
float RenewPrice[RenewType]=...;
// Transmission Capacity Between Zones
tuple Transmission {
key int ID;
string zone1;  // from zone
string zone2;  // to zone
float capacity; // in MW}
{Transmission} TransCapacity = ...;
/**********************
* Decision Variables *
**********************/
dvar float+ Gen[GeneratorSet][Periods]; // Production in MW
dvar boolean RunGen[GeneratorSet][Periods];
dvar boolean StartUpGen[GeneratorSet][Periods];
dvar boolean ShutDownGen[GeneratorSet][Periods];
dvar float+ SteamGen[gtCombineGenSet][Periods];
dvar boolean RunSteamGen[gtCombineGenSet][Periods];
dvar float+ Trans[TransCapacity][Periods]; // Transmission
dvar float+ TherFuel1[TherGenSet][Periods]; // amount of heat in MBTU
dvar float+ TherFuel2[TherGenSet][Periods]; // in MBTU
dvar boolean TherFuel1Use[TherGenSet][Periods]; // To use "Fuel Option 1" or not.
dvar boolean TherFuel2Use[TherGenSet][Periods];
dvar float+ GasTurbineGas[GasGenSet][Periods]; // in MBTU
dvar float+ GasTurbineDiesel[GasGenSet][Periods]; // in MBTU
dvar boolean GasTurbineGasUse[GasGenSet][Periods];
dvar boolean GasTurbineDieselUse[GasGenSet][Periods];
dvar float+ GasCombineGas[gtCombineGenSet][Periods]; // in MBTU
dvar float+ GasCombineDiesel[gtCombineGenSet][Periods]; // in MBTU
```

```
dvar boolean GasCombineGasUse[gtCombineGenSet][Periods];
dvar boolean GasCombineDieselUse[gtCombineGenSet][Periods];
dvar float+ Water[HydroGenSet][Periods]; // in MCM
dvar boolean RunPump[HydroPumpSet][Periods];
dvar float+ IntermediateReservoir[Periods1];
dvar float+ AmountInUpperReservoir[HydroPlantSet][Periods1]; // amount
    of water in the begining of period (MCM)
dvar float+ AmountInLowerReservoir[HydroPlantSet][Periods1];
dvar float+ ReleasedWater[HydroPlantSet][Periods];
dvar float+ s1[HydroPlantSet]; // slack for unmet water release
    constraint
dvar float+ recourse1[zones][Periods];
dvar float+ recourse2[zones][Periods];
dvar float+ recourse3[zones][Periods];
dexpr float PumpWater[i in HydroPumpSet][t in Periods] = RunPump[i][t]*
    i.ConsumeRate/1000*i.ConsumeMW*hourperperiod;
dexpr float PumpPower[i in HydroPumpSet][t in Periods] = RunPump[i][t]*
    i.ConsumeMW*hourperperiod;
execute{
cplex.epgap = 0.02;}
/*************
* Objectives *
**************/
// !!! Eqn. 1 !!!
dexpr float StartUpCost = sum (u in GeneratorSet : u not in
    ExceptionSet, t in Periods)
u.startCost*StartUpGen[u][t];
dexpr float TherFuelCost = sum (u in TherGenSet, t in Periods)
(u.fuelType1.cost*TherFuel1[u][t] +
u.fuelType2.cost*TherFuel2[u][t]);
dexpr float GasFuelCost = sum (u in GasGenSet, t in Periods)
(u.gas.cost*GasTurbineGas[u][t] +
u.diesel.cost*GasTurbineDiesel[u][t]);
dexpr float GasCombineFuelCost = sum (u in gtCombineGenSet, t in
```

```
Periods)
(u.gas.cost*GasCombineGas[u][t] +
u.diesel.cost*GasCombineDiesel[u][t]);
dexpr float TransCost = sum (l in TransCapacity, t in Periods) Trans[l][t];
dexpr float SlackCost = sum (p in HydroPlantSet) LargeNumber*s1[p];
dexpr float RecourseCost = sum(z in zones, t in Periods) (0.6*recourse1[z][t]+0.3*recourse2[z][t]+0.1*recourse3[z][t])*Penalty;
dexpr float totalGen = sum (g in GeneratorSet, t in Periods) Gen[g][t]-sum(j in HydroPumpSet, t in Periods) PumpPower[j][t];
dexpr float RenewGen = sum(r in RenewType, t in Periods) Renew[r][t];
minimize StartUpCost + TherFuelCost + GasFuelCost + GasCombineFuelCost + TransCost + SlackCost + RecourseCost ;
/**************
* Constraints *
***************/
subject to {
/*** Hard Constraints ***/
forall ( u in GeneratorSet: u.initProduct > 0) {
StartUpGen[u][1] == 0;
ShutDownGen[u][1] + RunGen[u][1] == 1;}
forall(u in GeneratorSet: u.initProduct == 0) {
ShutDownGen[u][1] == 0;
StartUpGen[u][1] == RunGen[u][1];}
forall(u in GeneratorSet) {
forall(t in 1..NumberOfPeriod-1) {
RunGen[u][t+1] - RunGen[u][t] <= StartUpGen[u][t+1];
ShutDownGen[u][t+1] == StartUpGen[u][t+1] + RunGen[u][t] - RunGen[u][t+1];}}
forall (u in gtCombineGenSet: u.unit.initProduct == 0) {sum(t in 1..u.StartUpDelayTime) RunSteamGen[u][t] == 0;}
/*** Relaxable Constraints ***/
forall(z in zones, t in Periods) {
meet_demand1: (Demand[z][t]-0.2*sum(r in RenewType) Renew[r][t]*
```

```
RenewDCF[r])-(sum(u in GeneratorSet : u.zone == z) Gen[u][t] + sum(l in TransCapacity : l.zone2 == z) Trans[l][t] - sum(l in TransCapacity : l.zone1 == z) Trans[l][t]- sum(j in HydroPumpSet: j.zone == z) PumpPower[j][t])<= recourse1[z][t] ; //power output on %realiability MW
meet_demand2:(Demand[z][t]-0.2*sum(r in RenewType)Renew[r][t]*((1+RenewDCF[r])/2))-(sum(u in GeneratorSet : u.zone == z) Gen[u][t] + sum(l in TransCapacity : l.zone2 == z) Trans[l][t] - sum(l in TransCapacity : l.zone1 == z) Trans[l][t]- sum(j in HydroPumpSet: j.zone == z) PumpPower[j][t])<= recourse2[z][t] ; // half output between full and %DCF
meet_demand3:(Demand[z][t]-0.2*sum(r in RenewType) Renew[r][t]*1)-(sum(u in GeneratorSet : u.zone == z) Gen[u][t] + sum(l in TransCapacity : l.zone2 == z) Trans[l][t] - sum(l in TransCapacity : l.zone1 == z) Trans[l][t]- sum(j in HydroPumpSet: j.zone == z) PumpPower[j][t])<= recourse3[z][t] ; // full capacities}
forall (l in TransCapacity, t in Periods) {max_trans: Trans[l][t] <= l.capacity;}
forall (z in zones, t in Periods) {sum(l in TransCapacity : l.zone1 == z) Trans[l][t] <= sum(u in GeneratorSet : u.zone == z) Gen[u][t];}
forall(u in GeneratorSet : u not in ExceptionSet, t in Periods) {
min_generation: Gen[u][t] >= RunGen[u][t]*u.minGen;
oper_max_generation: Gen[u][t] <= RunGen[u][t]*u.operGen;
max_generation: Gen[u][t] <= RunGen[u][t]*u.maxGen;}
forall(u in GeneratorSet : u not in ExceptionSet) {
init_ramp_up: Gen[u][1] - u.initProduct <= u.rampUp*minuteperperiod;
init_ramp_down: u.initProduct - Gen[u][1] <= u.rampDown*minuteperperiod;
forall(t in 1..NumberOfPeriod-1) {
ramp_up: Gen[u][t+1] - Gen[u][t] <= u.rampUp*minuteperperiod;
ramp_down: Gen[u][t] - Gen[u][t+1] <= u.rampDown*minuteperperiod;}}
forall(u in GeneratorSet : u not in ExceptionSet, t in Periods: t > u.minUpTime)
min_up: sum(i in t-u.minUpTime+1..t) StartUpGen[u][i] <= RunGen[u][t];
```

```
forall(u in GeneratorSet : u not in ExceptionSet, t in Periods: t >
    u.minDownTime)
min_down: sum(i in t-u.minDownTime+1..t) ShutDownGen[u][i] <= 1-RunGen[
    u][t];
forall(u in GeneratorSet : u not in ExceptionSet) {
if (u.initUpTime > 0 && u.initUpTime < u.minUpTime) {
init_up: sum(t in 1..u.minUpTime-u.initUpTime) RunGen[u][t] ==
    u.minUpTime - u.initUpTime;}
if (u.initDownTime > 0 && u.initDownTime < u.minDownTime) {
init_down: sum(t in 1..u.minDownTime-u.initDownTime) RunGen[u][t] ==
    0;}}
forall (u in TherGenSet, t in Periods) {
eqn_4:
TherFuel1[u][t]/hourperperiod*u.fuelType1.linearHeatRate +
    u.fuelType1.constantHeatRate*TherFuel1Use[u][t]
+TherFuel2[u][t]/hourperperiod*u.fuelType2.linearHeatRate +
    u.fuelType2.constantHeatRate*TherFuel2Use[u][t]
== Gen[u.unit][t];}
forall (u in GasGenSet, t in Periods) {
eqn_17:
GasTurbineGas[u][t]/hourperperiod*u.gas.linearHeatRate +
    u.gas.constantHeatRate*GasTurbineGasUse[u][t]
+GasTurbineDiesel[u][t]/hourperperiod*u.diesel.linearHeatRate +
    u.diesel.constantHeatRate*GasTurbineDieselUse[u][t]
== Gen[u.unit][t];}
forall (u in gtCombineGenSet, t in Periods) {
eqn_22:
GasCombineGas[u][t]/hourperperiod*u.gas.linearHeatRate +
    u.gas.constantHeatRate*GasCombineGasUse[u][t]
+GasCombineDiesel[u][t]/hourperperiod*u.diesel.linearHeatRate +
    u.diesel.constantHeatRate*GasCombineDieselUse[u][t]
== Gen[u.unit][t];}
forall (u in gtCombineGenSet, t in Periods : t > u.StartUpDelayTime) {
steam_delay:
```

```
sum (i in t-u.StartUpDelayTime..t-1) RunGen[u.unit][i] >= RunSteamGen[u][t]*u.StartUpDelayTime;}
forall (u in gtCombineGenSet, t in Periods) {
RunGen[u.unit][t] >= RunSteamGen[u][t];}
forall (u in gtCombineGenSet, t in Periods) {
steam_gen_1:
SteamGen[u][t] <= u.unit.maxGen*u.HRSG*u.GasSteamRatio*RunSteamGen[u][t];
steam_gen_2:
SteamGen[u][t] <= Gen[u.unit][t]*u.HRSG*u.GasSteamRatio;}
forall (u in stCombineGenSet, t in Periods) {
Gen[u.unit][t] == sum (v in gtCombineGenSet : v.SteamGenName == u.unit.name) SteamGen[v][t];}
forall (p in TherPlantSet) {
sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType1.name == "2%OIL") TherFuel1[u][t]
+ sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType2.name == "2%OIL") TherFuel2[u][t]
<= p.oil2Max;
sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType1.name == "EGAS") TherFuel1[u][t]
+ sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType2.name == "EGAS") TherFuel2[u][t]
<= p.egasMax;
sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType1.name == "LIGNITE") TherFuel1[u][t]
+ sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType2.name == "LIGNITE") TherFuel2[u][t]
<= p.ligniteMax;
sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType1.name == "KGAS") TherFuel1[u][t]
+ sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name && u.fuelType2.name == "KGAS") TherFuel2[u][t]
<= p.kgasMax;
```

```
sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.fuelType1.name == "HPPOIL") TherFuel1[u][t]
+ sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.fuelType2.name == "HPPOIL") TherFuel2[u][t]
<= p.hppoilMax;
sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.fuelType1.name == "WGAS") TherFuel1[u][t]
+ sum (u in TherGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.fuelType2.name == "WGAS") TherFuel2[u][t]
<= p.wgasMax;   }
forall (p in GasPlantSet) {
sum (u in GasGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.gas.name == "EGAS") GasTurbineGas[u][t]
+ sum (u in GasGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.diesel.name == "EGAS") GasTurbineDiesel[u][t]
<= p.egasMax;
sum (u in GasGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.gas.name == "LGAS") GasTurbineGas[u][t]
+ sum (u in GasGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.diesel.name == "LGAS") GasTurbineDiesel[u][t]
<= p.lgasMax;
sum (u in GasGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.gas.name == "DIESEL") GasTurbineGas[u][t]
+ sum (u in GasGenSet, t in Periods : u.unit.plant == p.plant.name &&
    u.diesel.name == "DIESEL") GasTurbineDiesel[u][t]
<= p.dieselMax;}
forall (p in ComPlantSet) {
sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name
    && u.gas.name == "EGAS")GasCombineGas[u][t]
+ sum (u in gtCombineGenSet, t in Periods : u.unit.plant ==
    p.plant.name && u.diesel.name == "EGAS") GasCombineDiesel[u][t]
<= p.egasMax;
sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name
    && u.gas.name == "JGAS") GasCombineGas[u][t]
```

```
+ sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.diesel.name == "JGAS") GasCombineDiesel[u][t]
<= p.jgasMax;
sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.gas.name == "KGAS") GasCombineGas[u][t]
+ sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.diesel.name == "KGAS") GasCombineDiesel[u][t]
<= p.kgasMax;
sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.gas.name == "WGAS") GasCombineGas[u][t]
+ sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.diesel.name == "WGAS") GasCombineDiesel[u][t]
<= p.wgasMax;
sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.gas.name == "NGAS") GasCombineGas[u][t]
+ sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.diesel.name == "NGAS") GasCombineDiesel[u][t]
<= p.ngasMax;
sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.gas.name == "DIESEL") GasCombineGas[u][t]
+ sum (u in gtCombineGenSet, t in Periods : u.unit.plant == p.plant.name && u.diesel.name == "DIESEL") GasCombineDiesel[u][t]
<= p.dieselMax; }
forall (u in TherGenSet, t in Periods)
TherFuel1Use[u][t] + TherFuel2Use[u][t] <= RunGen[u.unit][t];
forall (u in GasGenSet, t in Periods)
GasTurbineGasUse[u][t] + GasTurbineDieselUse[u][t] <= RunGen[u.unit][t];
forall (u in gtCombineGenSet, t in Periods)
GasCombineGasUse[u][t] + GasCombineDieselUse[u][t] <= RunGen[u.unit][t];
forall (u in TherGenSet, t in Periods) {
TherFuel1[u][t] <= LargeNumber*TherFuel1Use[u][t]; // zero or infinite
TherFuel2[u][t] <= LargeNumber*TherFuel2Use[u][t];}
```

```
forall (u in GasGenSet, t in Periods) {
GasTurbineGas[u][t] <= LargeNumber*GasTurbineGasUse[u][t];
GasTurbineDiesel[u][t] <= LargeNumber*GasTurbineDieselUse[u][t];}
forall (u in gtCombineGenSet, t in Periods) {
GasCombineGas[u][t] <= LargeNumber*GasCombineGasUse[u][t];
GasCombineDiesel[u][t] <= LargeNumber*GasCombineDieselUse[u][t];}
forall (u in HydroGenSet, t in Periods) {
Hydro_gen:
Gen[u.unit][t] == 1000*Water[u][t]/(u.WaterPowerRate*hourperperiod);}
forall (p in HydroPlantSet) {
AmountInUpperReservoir[p][1] == p.InitUpperReservoir;
AmountInLowerReservoir[p][1] == p.InitLowerReservoir;}
forall (p in HydroPlantSet: p.plant.name != "TN", t in Periods) {
upper_water:
AmountInUpperReservoir[p][t+1] == AmountInUpperReservoir[p][t]
- sum (u in HydroGenSet: u.unit.plant == p.plant.name) Water[u][t]
+ sum (u in HydroPumpSet: u.plant == p.plant.name) PumpWater[u][t];}
forall (p in HydroPlantSet: p.plant.name != "SNR" && p.plant.name != "
    TN", t in Periods) {
lower_water:
AmountInLowerReservoir[p][t+1] == AmountInLowerReservoir[p][t]
+ sum (u in HydroGenSet: u.unit.plant == p.plant.name) Water[u][t]
- sum (u in HydroPumpSet: u.plant == p.plant.name) PumpWater[u][t]
- ReleasedWater[p][t];}
IntermediateReservoir[1] == InitIntermediateReservoir;
forall (t in Periods) {
intermediate_water:
IntermediateReservoir[t+1] == IntermediateReservoir[t]
+ sum (u in HydroGenSet: u.unit.plant == "SNR") Water[u][t]
- sum (u in HydroGenSet: u.unit.plant == "TN") Water[u][t]
- sum (u in HydroPumpSet: u.plant == "SNR") PumpWater[u][t];}
forall (p in HydroPlantSet: p.plant.name == "TN", t in Periods)
sum (u in HydroGenSet: u.unit.plant == "TN") Water[u][t] ==
    ReleasedWater[p][t];
```

```
forall (p in HydroPlantSet, t in Periods1) {
upper_water_limit:
AmountInUpperReservoir[p][t] <= p.UpperReservoirCapacity;
lower_water_limit:
AmountInLowerReservoir[p][t] <= p.LowerReservoirCapacity;}
forall (p in HydroPlantSet: p.plant.name == "TN", t in Periods1) {
IntermediateReservoir[t] == AmountInUpperReservoir[p][t];}
forall (p in HydroPlantSet: p.plant.name == "SNR", t in Periods1) {
IntermediateReservoir[t] == AmountInLowerReservoir[p][t];}
forall (p in HydroPlantSet) {
daily_water_usage:
sum (u in HydroGenSet: u.unit.plant == p.plant.name) sum (t in Periods)
Water[u][t] <= p.DailyWaterUse;}
forall (p in HydroPlantSet)
water_release: // constraint for ¡ÃÁªÅ»ÃÐ·Ò¹
(sum (t in Periods) ReleasedWater[p][t]) + s1[p] ==
    p.HydroPlantDailyRelease;
forall (u in HydroGenSet, t in Periods)
100*(1 - RunGen[u.unit][t]) >= sum (v in HydroPumpSet: v.plant ==
    u.unit.plant) RunPump[v][t];
forall (v in HydroPumpSet, p in HydroPlantSet: p.plant.name == v.plant,
     t in Periods)
min_pump: AmountInLowerReservoir[p][t] >= RunPump[v][t]*p.MinPumpLevel;
sum (t in Periods) (
sum(w in TherGenSet: w.fuelType1.name == "EGAS" ) TherFuel1[w][t]
+sum(w in TherGenSet: w.fuelType2.name == "EGAS" ) TherFuel2[w][t]
+sum(u in GasGenSet: u.gas.name == "EGAS") GasTurbineGas[u][t]
+sum(u in GasGenSet: u.diesel.name == "EGAS") GasTurbineDiesel[u][t]
+sum(v in gtCombineGenSet: v.gas.name == "EGAS") GasCombineGas[v][t]
+sum(v in gtCombineGenSet: v.diesel.name == "EGAS") GasCombineDiesel[v
    ][t]
) <= DailyEGASUsage;
sum (t in Periods) (
sum(w in TherGenSet: w.fuelType1.name == "WGAS" ) TherFuel1[w][t]
```

```
+sum(w in TherGenSet: w.fuelType2.name == "WGAS" ) TherFuel2[w][t]
+sum(u in GasGenSet: u.gas.name == "WGAS") GasTurbineGas[u][t]
+sum(u in GasGenSet: u.diesel.name == "WGAS") GasTurbineDiesel[u][t]
+sum(v in gtCombineGenSet: v.gas.name == "WGAS") GasCombineGas[v][t]
+sum(v in gtCombineGenSet: v.diesel.name == "WGAS") GasCombineDiesel[v][t]
) <= DailyWGASUsage;
forall(r in MustRunGen)
must_run_rule: sum(t in r.period1..r.period2)
RunGen[<r.name>][t] == r.period2-r.period1+1;
forall(r in MustShutDownGen)
must_turn_off_rule: sum(t in r.period1..r.period2)
RunGen[<r.name>][t] == 0;
forall(t in Periods)
reserve_rule: sum(u in GeneratorSet : u not in ExceptionSet) (u.maxGen*RunGen[u][t]-Gen[u][t])
>= (reservePercent/100.0)*sum(z in zones) Demand[z][t]
+ (RenewreservePercent/100.0)*sum(r in RenewType) (0.6*Renew[r][t]*RenewDCF[r]+0.3*Renew[r][t]*((1+RenewDCF[r])/2)+0.1*Renew[r][t]) ;}
/*******
* KPIs *
********/
int nbGen = card(GeneratorSet);
int status[u in GeneratorSet][t in Periods] = StartUpGen[u][t] - ShutDownGen[u][t];
int UpTime[u in GeneratorSet];
int DownTime[u in GeneratorSet];
float finalProduct[u in GeneratorSet];
int nbTherOnline[t in Periods] = sum(u in TherGenSet)RunGen[u.unit][t];
int nbGasOnline[t in Periods] = sum(u in GasGenSet) RunGen[u.unit][t];
int nbgtCombineOnline[t in Periods] = sum(u in gtCombineGenSet) RunGen[u.unit][t];
int nbHydroOnline[t in Periods]=sum(u in HydroGenSet)RunGen[u.unit][t];
float utilizationOperating[u in GeneratorSet diff ExceptionSet] = sum(t
```

```
in Periods) Gen[u][t]/(NumberOfPeriod*u.operGen);
float utilizationPhysical[u in GeneratorSet diff ExceptionSet] = sum(t in Periods) Gen[u][t]/(NumberOfPeriod*u.maxGen);
float totalproduction[u in GeneratorSet diff ExceptionSet] = sum(t in Periods) Gen[u][t]*hourperperiod;
string therfueluse[u in TherGenSet][t in Periods];
string gasturbineuse[u in GasGenSet][t in Periods];
string gascombineuse[u in gtCombineGenSet][t in Periods];
float therfuel[u in TherGenSet][t in Periods] = TherFuel1[u][t] + TherFuel2[u][t];
float gasturbine[u in GasGenSet][t in Periods] = GasTurbineGas[u][t] + GasTurbineDiesel[u][t];
float gascombine[u in gtCombineGenSet][t in Periods] = GasCombineGas[u][t] + GasCombineDiesel[u][t];
float therfuelcost[u in TherGenSet][t in Periods] = (u.fuelType1.cost*TherFuel1[u][t] + u.fuelType2.cost*TherFuel2[u][t]);
float gasfuelcost[u in GasGenSet][t in Periods] = (u.gas.cost*GasTurbineGas[u][t] + u.diesel.cost*GasTurbineDiesel[u][t]);
float combinefuelcost[u in gtCombineGenSet][t in Periods] = (u.gas.cost*GasCombineGas[u][t] + u.diesel.cost*GasCombineDiesel[u][t]);
float thergencost[u in TherGenSet] = sum (t in Periods) therfuelcost[u][t];
float gasgencost[u in GasGenSet] = sum(t in Periods)gasfuelcost[u][t];
float combinegencost[u in gtCombineGenSet] = sum (t in Periods) combinefuelcost[u][t];
float totalcost = TherFuelCost + GasFuelCost + GasCombineFuelCost;
/******************
* Post Processing *
******************/
execute {
for (var u in GeneratorSet) {
finalProduct[u] = Gen[u][NumberOfPeriod];
for (var t = NumberOfPeriod; t >= one; t--) {
if (status[u][t] == -1) {
```

```
DownTime[u] = NumberOfPeriod-t+1;
UpTime[u] = 0;
break;} else if (status[u][t] == 1) {
DownTime[u] = 0;
UpTime[u] = NumberOfPeriod-t+1;
break;} }
if (t < one) {
if (RunGen[u][1] == 1) {DownTime[u] = 0;
UpTime[u] = NumberOfPeriod+1;}
else {DownTime[u] = NumberOfPeriod+1;
UpTime[u] = 0;}}}
for (u in TherGenSet) {
for (t in Periods) {
if (TherFuel1Use[u][t] == 1)
therfueluse[u][t] = u.fuelType1.name;
else if (TherFuel2Use[u][t] == 1)
therfueluse[u][t] = u.fuelType2.name;
else therfueluse[u][t] = "OFF";}}
for (u in GasGenSet) {
for (t in Periods) {
if (GasTurbineGasUse[u][t] == 1)
gasturbineuse[u][t] = u.gas.name;
else if (GasTurbineDieselUse[u][t] == 1)
gasturbineuse[u][t] = u.diesel.name;
else gasturbineuse[u][t] = "OFF";}}
for (u in gtCombineGenSet) {
for (t in Periods) {
if (GasCombineGasUse[u][t] == 1)
gascombineuse[u][t] = u.gas.name;
else if (GasCombineDieselUse[u][t] == 1)
gascombineuse[u][t] = u.diesel.name;
else gascombineuse[u][t] = "OFF";}}}
```

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