BACKUP CAPACITY COORDINATION BETWEEN RENEWABLE AND CONVENTIONAL POWER SUPPLIERS UNDER RENEWABLE PORTFOLIO STANDARD REGULATION

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Submitted to the Faculty of the
Graduate College of
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2015

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RENEWABLE AND CONVENTIONAL POWER SUPPLIERS

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ACKNOWLEDGEMENTS

I would like to offer my most sincere thanks to the following individuals who inspired, motivated, and supported me in many aspects during my doctorate research.

Dr. Tieming Liu, the dissertation committee chair, who served as my PhD advisor, mentor of academic research, and major facilitator of knowledge. I am extremely grateful for his valuable guidance and consistent encouragement I received throughout the PhD research. Dr. Liu has always been available to clarify my questions despite his tight schedules and I consider it as a great opportunity to do my doctoral program under his guidance and to learn from his research expertise.

Dr. Balabhaskar Balasundaram, Dr. Kevin Currier, Dr. Manjunath Kamath, and Dr. Chaoyue Zhao, the dissertation committee members, who helped me greatly in various aspects for my PhD research. The dissertation is related to the areas of optimization, economic analysis, energy market, game theory, and probability theory. Only with the guidance of all my committee members with their strong backgrounds in the above areas, it becomes possible for me to finish the dissertation with decent academic quality.

All the professors and staffs in the School of Industrial Engineering and Management, Oklahoma State University, who maintain a great environment with a lot of amazing curricular and extracurricular activities, for the growth of students in both academic and social skills.

My fellow colleagues in Oklahoma State University: Dahai Xing, Foad Mahdavi Pajouh, Juan Ma, Saeed Piri, Sandeep Srivathsan, Shareth Hariharan, Shuzhen Sun, Yanming Sun, and many other students who were my classmates or project teammates. They inspired me to expand my research horizons and to generate valuable research ideas.

Lastly and most importantly, I would like to express the greatest thanks to my parents, Leguo Zhou and Fanping Wu. During the past years of academic pursuing in U.S., I was very much indebted to them for not being able to spend more time with them in my hometown in China. My parents encouraged and helped me at every stage of my personal and academic life, and longed to see this achievement of receiving the doctorate degree come true for me.

Name: YINGJUE ZHOU

Date of Degree: MAY, 2015

Title of Study: BACKUP CAPACITY COORDINATION BETWEEN RENEWABLE AND CONVENTIONAL POWER SUPPLIERS UNDER RENEWABLE PORTFOLIO STANDARD REGULATION

Major Field: INDUSTRIAL ENGINEERING AND MANAGEMENT

Abstract:
This dissertation studies the impacts of renewable portfolio standard (RPS) regulation on regional electricity markets, and the backup capacity coordination mechanisms between renewable and conventional power suppliers with tradable green certificate (TGC) offering.

Firstly, we consider a regional market with renewable capacity and access to the TGC market. We establish a monopoly model and a duopoly model. We find that the green power output decreases when the RPS percentage increases in a regional market. When the TGC price increases, the green power output increases, and the total profit first decreases then increases. There exists an optimal RPS percentage to maximize the social welfare. By numerical analysis, we show that when the TGC price increases, the electricity outputs change slower in the duopoly market.

Secondly, we study a capacity coordination mechanism in a single region market. The intermittent nature of the renewable supplier results in random power shortage. Though a conventional supplier can prepare backup capacity to cover the shortage, there is no commitment that enough backup capacity will be prepared without any incentives to the conventional supplier. We design a coordination mechanism where the renewable supplier offers the conventional supplier free TGC proportional to the backup capacity. This mechanism coordinates the conventional supplier's decision on backup capacity and arbitrarily splits the system profit between the two suppliers by the wholesale price.

Thirdly, we design a coordination mechanism in a two-regional market with interregional transmission. The renewable suppliers offer TGC and pay transmission premium to encourage the conventional suppliers prepare enough backup capacities. The conventional suppliers decide the interregional transmission prices between them. This mechanism coordinates the system and achieves the global optimum. In contrast, an uncoordinated baseline case leads to under investment of backup capacity and the system profit is less than the global optimum. In the coordination model, when the transmission cost increases, the backup capacity in a region increases if this region is a net importer of backup power, or decreases if it is a net exporter.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

The increase of renewable penetration has been a significant trend in many regional electricity markets in U.S. (Mai et al. (2014)). Though the renewable (green) sources are more environmentally friendly, the generation costs are higher than the conventional (black) sources such as coal and natural gas. For example, Heal (2010) estimates that the capital cost of offshore wind power is $4000 per kilowatt while for coal it is from $1700 to $1900 per kilowatt.

To promote the growth of renewable energy generation, more than 30 states in the U.S. have established the renewable portfolio standard (RPS) regulations in their electricity markets. In a power market under the RPS regulation, a certain percentage of electricity must be from renewable sources, and such percentage may increase gradually per year. For example, Illinois sets a 25% target with mandatory RPS regulation to be reached by 2025, and New Mexico sets a 20% target to be reached by 2020 (Tamas et al. (2010)). Facing the RPS regulation, the power suppliers establish markets of tradable green certificate (TGC), which allow the renewable suppliers sell their extra TGC to the conventional suppliers, as the latter cannot meet the RPS requirement by their own generation.

The impacts of RPS regulation can be examined in both the strategic level and the tactic level. Strategic analysis focuses on the design and evaluation of RPS regulation mechanics, its influence on the power industry of a state, a nation or wider geographic area in long term. Tactic analysis focuses on the firms' behavior facing the RPS regulation, such as production quantity decision, pricing policy, coordination contract, and merging. We conduct our research at the tactic level, to study the impacts of RPS regulation on regional electricity markets in Chapter 4.

In addition, with the fast growth of renewable power, the intermittent nature of the renewable energy sources becomes a threat to the stability of the power gird. The power outputs from two major renewable sources, wind and solar power, are not as stable and controllable as the conventional sources (Sovacool (2009)). Therefore, in regional electricity markets with high renewable penetration, the risk of power shortage is significant.

To solve this problem, one option is to adopt energy storage service. Unfortunately, large scale installations of energy storage are still expensive based on the current technologies (Beaudin et al. (2010)), and thus it is unrealistic to rely on energy storage capacity to cover all the power shortage caused by intermittent renewable power outputs.

Another option is to buy backup power from the balancing markets (Vandezande et al. (2010)), which are operated by many regional independent system operators (ISO). The renewable suppliers predict and propose their demands (power shortages) for a future time period. The conventional suppliers bid to fulfill the demands, and their offers form a stairwise supply-price curve (Figure 1.1). These suppliers offering the lowest prices win the deal and provide the power up to their respective capacities. Though the above mechanism can help to mitigate the power shortage, it cannot be guaranteed that the balancing markets can always provide enough low-price power supply to fully cover the shortage, due to the uncertainty of both supply side and demand side. Therefore, many regional electricity markets still need dedicated backup capacities to buffer the renewable generation.

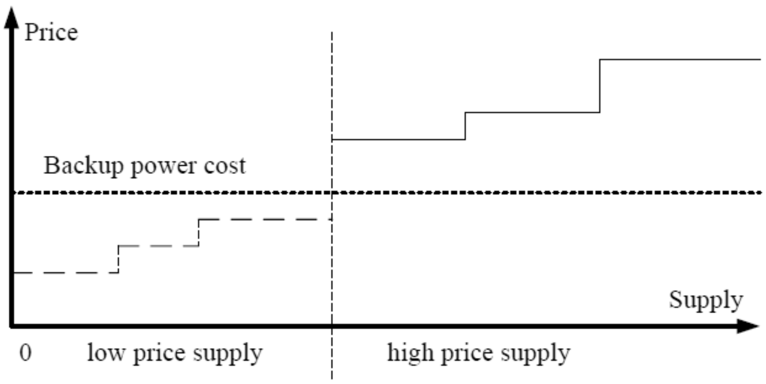

Figure 1.1: The Stairwise Supply-Price Curve in Balancing Market

Gas-fired power plants are suitable to serve as backup capacity, because they are fast ramping and relatively easy to be turned on and off. This buffering function of gas power for the renewable power has been well discussed by recent literature such as Hittinger et al. (2010) and Lee et al. (2012). Better thing is, the U.S. has ample resource of natural gas, including the rising trend of commercial production of shale gas (Krupnick et al. (2015)). In those regions with plenty of both renewable sources and gas sources such as Texas, gas-fired plants are built to firm the intermittent renewable generation. For example, the South Texas Electric Cooperative built up the Pearsall Power Plant (202.5 megawatt) to provide backup power for their customers in 65 counties where an increasing penetration of wind power brought challenges to the grid stability.[1]

Most renewable suppliers outsource the backup power capacity they need from conventional suppliers (Vandezande et al. (2010)), because of the difference in the generation technologies. However, when a renewable supplier and a conventional

[1]http://www.wartsila.com/en/gas-power-plant-to-south-texas-electric-cooperative

supplier operate independently, there is no economic incentive for the conventional supplier to build enough backup capacity for its competitor (Yang et al. (2012)). Facing high variability as backup power suppliers makes the fossil-fuel generators deviate from their optimal operating points where the generation efficiency is maximal, because they need respond to the electricity demand when the power shortage occurs. Thus the conventional suppliers' profits will be negatively affected.

Therefore, incentives are needed to encourage the conventional suppliers to build enough backup capacity to buffer the intermittent renewable power output (Lee et al. (2012)). In Chapter 5, we propose a coordination mechanism based on the TGC offering. The core idea is to let the renewable suppliers offer TGC in return for backup capacity committed by the conventional suppliers. The quantity of TGC is proportional to the backup capacities prepared by the conventional suppliers. In this way, the conventional suppliers will have incentives to prepare enough backup capacities to cover the renewable suppliers' power shortages.

In the context of regional power markets with RPS regulation, we highlight two advantages of offering TGC instead of paying money to facilitate the coordination. Firstly, the TGC is a reliable and convenient asset for trading between the renewable suppliers and the conventional suppliers, as the latter always need to outsource TGC from the former to meet the RPS requirement. By a direct offering of TGC, both parties save transaction cost charged by a third party broker (3% typically) when they buy of sell TGC in the national market. Secondly, it is more financially secure to transfer TGC than monetary payment for both parties. From the renewable suppliers' point of view, offering TGC eliminates the impact on their cash flows caused by paying money, as TGC is a by-product of its daily operation. From the conventional suppliers' point of view, the coordination mechanism provides a stable TGC source, which hedges the risk in the national TGC market due to the price uncertainty and the supply uncertainty (Klessmann et al. (2010)).

During the development of renewable power and implementation of RPS regulation, the interregional power transmission plays an important role, as many renewable energy sources are far from major power consumers (Munoz et al. (2013)). In Chapter 6, we examine the pooling effect, i.e., the power suppliers in different regions share their backup capacities. Given the power transmission is economical, if power shortage occurs in one region and it cannot be solely covered by the local backup capacity, the other regions' power suppliers can transmit their extra backup power to that region. And thus all the interconnected regions can benefit from such resource pooling practice.

In summary, our research can be categorized into three topics: impacts of the RPS regulation on regional electricity markets, firms' coordination contract based on tradable green certificate offering, and a capacity coordination mechanism taking interregional transmission into consideration. The following sections demonstrate overviews of the main results under the three topics.

1.2 Overview of Impacts of the Renewable Portfolio Standard on Regional Electricity Markets

In Chapter 4, we study a regional electricity market served by one or two suppliers. We analyze a monopoly market with one supplier and a duopoly market with two suppliers to study the impacts of TGC price and RPS percentage on the green/black energy outputs, the electricity price and the suppliers' profit.

We reveal the common properties of two structures. In a regional electricity market with TGC available from outside, the increase of local RPS percentage does not guarantee an increase of local green output. Our analytical results indicate that the green power output decreases when the RPS percentage increases in the regional electricity market if the TGC price in the national market remains unchanged. In contrast, a higher TGC price can effectively promote the local green power output. A collective effort of increasing RPS percentage by many regions increases the overall demand of TGC across the country, and the national TGC price will increase. In summary, we suggest the regional regulators to set up their RPS development plans carefully in a synchronized way.

We also compare the difference between two structures with numerical analysis. In the duopoly structure, the electricity price and suppliers' profits are lower, and the total electricity supply is higher than in the monopoly structure. The electricity outputs change slower when the TGC price increases in the duopoly structure than in the monopoly structure. The monopoly supplier only needs to pay attention to cost reduction and can respond rapidly; while the suppliers in the duopoly structure need to be concerned with both cost reduction and keeping their market shares. To maximize the social welfare, the optimal RPS percentage in the duopoly structure is higher than in the monopoly structure.

1.3 Overview of Coordination Contract in Regional Electricity Market Based on Tradable Green Certificate Offering

In Chapter 5, we study a coordination contract between a renewable supplier and a conventional supplier in a regional electricity market. The energy sources of the renewable suppliers are intermittent and lead to random power shortage. To encourage the conventional supplier to build backup capacity to cover the shortage, we design a coordination contract where the renewable supplier offers the conventional supplier free tradable green certificate proportional to the backup capacity. The renewable supplier decides the TGC offering rate and the wholesale price of backup power, and then the conventional supplier decides the quantity of backup capacity.

We prove the contract achieves the system coordination. The system profit can be arbitrarily allocated between the two suppliers by adjusting the wholesale price. We study a baseline case without coordination and prove the baseline case leads to under investment of the backup capacity. By comparing to the baseline case, we find the coordination model can achieve Pareto improvement for both suppliers.

Sensitivity analysis is conducted on the impacts of following market conditions. Firstly, when the fixed cost increases, the backup capacity decreases and the TGC offering rate increases. Both suppliers' profits decrease and the total profit decreases. Secondly, when the electricity price increases or the variable cost decreases, the backup capacity increases and the TGC offering rate decreases. Both suppliers' profits increase and the total profit increases. Lastly, when the shortage cost increases, the backup capacity increases and the TGC offering rate increases. The total profit decreases, the renewable supplier's profit decreases but the conventional supplier's profit increases.

Social welfare analysis is conducted, and we find that the social welfare of the coordination structure will be greater than of the baseline case unless the environmental damage of conventional power is extremely high.

1.4 Overview of Capacity Coordination in Regional Electricity Markets with Interregional Transmission

In Chapter 6, we study a capacity coordination mechanism between renewable suppliers and conventional suppliers in regional electricity markets with interregional power transmission. The renewable suppliers offer free tradable green certificates for backup capacity reservation and pay transmission premiums to encourage the conventional suppliers to prepare enough backup capacity. The renewable suppliers decide the TGC offering rates and the transmission premiums, and the conventional suppliers decide the power transmission prices and then the quantities of backup capacities.

We prove the above mechanism achieves the system coordination ,while the baseline case without coordination leads to under investment of the backup capacity. We show the coordination mechanism is robust, that if the TGC offering rate deviates from the optimal point, the system profit will not decrease significantly. Comparing to the single region scenario without transmission in Chapter 5, the backup capacity in a certain region will increase if that region is more possible to export backup power, or decrease if it is more possible to import.

We conduct sensitivity analysis to find the impacts of following market conditions. Firstly, when the electricity price increases, both the total capacity and the TGC offering rate increase. All suppliers' profits and the system profit increase. Secondly, when the shortage cost increases, both the total capacity and the TGC offering rate increase. The system profit and the renewable suppliers' profits decrease, but the conventional suppliers' profits increase. Thirdly, when the fixed cost increases, the capacity in each region decreases while the TGC offering rate keeps the same. All suppliers' profits and the system profit decrease. Fourthly, when the variable cost increases, the total capacity decreases while the TGC offering rate increases. All suppliers' profits and the system profit decrease. Lastly, When the transmission cost increases, the TGC offering rate keeps the same. The capacity in a region increases (decreases) if this region is more possible to import (export) backup power. All suppliers' profits and the system profit decrease.

CHAPTER 2

LITERATURE REVIEW

Our research studies the impacts of RPS regulation on regional electricity markets, firms' coordination contract based on TGC offering, and a capacity coordination mechanism considering interregional transmission. In the following sections, we review the three streams of literature related to our research.

2.1 Impacts of the Renewable Portfolio Standard on Electricity Markets

The RPS regulation attracts increasing attention from both practitioners and scholars because it is reshaping the electricity industry fundamentally. The impacts of RPS regulation on electricity markets are widely investigated by recent literature. Kydes (2007) analyzes the impacts of imposing a 20% federal RPS policy on the US energy markets by 2020. Such policy may be effective in promoting the adoption of renewable generation technologies and reducing emissions. The electricity prices are expected to rise about 3 percent since the generation costs are higher. Singh (2009) proposes a national tradable renewable energy credits scheme in India, and they suggest it would reduce the cost of compliance to a renewable portfolio obligation, and encourage efficient resource utilizations and investments in appropriate technologies. Verbruggen (2009) establishes a general framework of criteria to evaluate the performance of renewable energy support policies and tests the framework with the data from Flemish TGC support system. Wiser et al. (2011) study the design of and experience with state level RPS programs in the U.S. aimed to encourage a wider diversity of renewable energy technologies, and solar energy in particular.

These papers focus on the impacts of RPS regulation on the national-scale markets, while our research studies firms' decisions in a regional market under the RPS regulation.

The research interest on firms' decisions in power markets with renewable penetration, is increasing in recent years. Tamas et al. (2010) compare the oligopoly firm decisions between feed-in-tariff and TGC schemes, and perform numerical analysis using the UK data. Zhou and Tamas (2010) show that the RPS regulation may induce mergers between the black and green generators. Such mergers enable the integrated firms to extend market power from the TGC market to the electricity market. Fischer (2010) analyzes price-taking firms in both electricity and TGC markets under perfect competition. Amundsen and Bergman (2012) examine two scenarios on the Nordic electricity market. In the first scenario, both firms are Cournot oligopoly players in electricity markets and price takers in TGC markets; in the second, both firms are Cournot oligopoly players in the two markets. Tanaka and Chen (2013) model dominant-fringe firms in a Stackelberg game to examine market power in both electricity and TGC markets.

The above literature address a national electricity market or an international market without external TGC supply, and the TGC trade is internalized between suppliers. Our research differs from existing work by considering a regional electricity market where the TGC trade is external.

In summary, the investigation of the impacts of RPS in regional electricity markets with external TGC trade is still limited. Our research in Chapter 4 will fill the gap in this area.

2.2 Firms' Coordination Mechanisms in Electricity Markets with Renewable Energy Penetration

Firms' coordination behavior in the electricity markets have been studied for a long time. The recent rising of renewable power entices more research in this area, because the intermittence nature of renewable energy sources requires more coordination between power suppliers. Andersen and Lund (2007) study how to integrate fluctuating renewable power supplies into power systems by using combined heat and power plants as backup. They focus on the methodologies and computer tools necessary to optimize the participants' market decisions. Klessmann et al. (2010) discuss three coordination mechanisms, including transferring of TGC between regions, to assist the European states to achieve the EU-wide RPS target of reaching 20% in 2020. Milligan et al. (2010) evaluate the important factors to improve the power systems' ability to absorb renewable generation. By studying the Eastern Interconnection electricity markets of U.S., they show how large, responsive energy markets can help the integration of renewable electricity. Vandezande et al. (2010) discuss the market structure for backup power. They suggest a two-part payment, one for backup capacity and one for backup power, is appropriate to achieve a well-functioning market. Lee et al. (2012) explore potential synergies of natural gas and renewable energy in the U.S. electric power sector, and discuss market design issues that could benefit from collaborative engagement. Klinge Jacobsen et al. (2014) study the coordination mechanisms such as joint support schemes to achieve the EU renewable targets. They show that by cost sharing and interregional transferring of green credits, the renewable investment will become more efficient.

Though the above literature have discussed many aspects of coordination between power suppliers, the investigation on coordination between renewable suppliers and conventional suppliers based on TGC offering is still limited. In Chapter 5, we analyze such coordination mechanism and provide insights to fill this void.

2.3 Renewable Power Transmission and General Goods Transshipment Problems

Our research in Chapter 6 is related to the literature on power transmission problem with renewable penetration. Schaber et al. (2012) show that in a regional electricity market with high renewable penetration, the transmission grid expansion alleviates the competition between the renewable and conventional suppliers and benefits both parties. Munoz et al. (2013) study the cost-effective investment policy for power transmission infrastructure to meet the RPS regulation of many U.S. states. Rodriguez et al. (2014) estimate that in a fully renewable Europe electricity market, a well interconnected power transmission grid can reduce the backup capacity requirement from 24% of total demand down to 15%. These papers do not consider the coordination mechanisms between power suppliers, which is the focus of our research.

The research in Chapter 6 is also related to the classical transshipment literature, methodologically. Rudi et al. (2001) study a two-region model with transshipment where each region makes its ordering decision independently. They find there exists a pair of coordinating transshipment prices which lead to the global optimal inventory decisions and maximize the joint-profit. Dong and Rudi (2004) examine a two-echelon model and find that the transshipment generally benefits the manufacturer while hurts the retailers. When the correlation between the retailers' demands decreases or the number of retailers increases, the transshipment incurs better pooling effect. The research of Shao et al. (2011) on a two-echelon model shows that the manufacturer prefers a high transshipment price, while the retailers prefers a low price. If the transshipment price is low, the manufacturer prefers a centralized retailer rather than multiple decentralized retailers. System coordination mechanism design is not studied in that paper. Though the above papers have covered a wide range of market structures, the coordination mechanisms for a two-echelon model with transshipment are not analyzed. In contrast, our research in Chapter 6 proposes a coordination contract for four independent players in a two-echelon market with interregional power transmission.

In summary, though the above papers discuss many aspects of the renewable power transmission problem and the general commodity transshipment problem, the coordination mechanism in a two-echelon renewable power market with interregional transmission is not fully discussed yet. To fill the gap, we study this type of market and propose a coordination mechanism based on TGC offering and transmission premium, to drive the system performance to global optimum.

CHAPTER 3

PROBLEM STATEMENT, RESEARCH OBJECTIVES AND CONTRIBUTIONS

3.1 Problem Statement

There are two major research problems in this dissertation. The first is to study the impacts of RPS regulation on regional electricity markets. Many states and countries have set mandatory RPS regulation which requires a certain percentage of power supply must be from renewable resources. A national TGC market is fast developing associated with the RPS regulation, and the interregional TGC trade encourages renewable power to be produced from low cost regions. Because of different natural environment in different regions, the fixed cost of building renewable capacity and the variable cost to generate renewable power vary greatly. Moreover, the market structure could be monopoly or have multiple competing firms. Thus the impacts of RPS regulation have significant heterogeneity in different regional markets, and an analytical investigation is needed for them.

The second problem is to study the coordination mechanism facing renewable energy penetration. With the fast growth of renewable power, the intermittent nature of the renewable energy sources becomes a threat to the stability of the power gird. The power outputs from two major renewable sources, wind and solar power, are not as stable and controllable as the conventional sources, which incurs random power shortage in the renewable suppliers' outputs. Though the renewable suppliers can outsource backup power from the conventional suppliers, there is no guarantee that enough backup capacity will be prepared. Therefore, there is a need of economical incentives to encourage the conventional suppliers prepare enough backup capacities to buffer the intermittent renewable power outputs.

3.2 Research Objectives

The objectives of this research are listed as follows.

- **Objective 1.** Study the impacts of RPS on regional electricity markets in different market structures.

  Objective 1.1 Build analytical models for a monopoly market and a duopoly market. Obtain the close form solutions for the models.

  Objective 1.2 Analyze the properties of the models by sensitivity analysis and numerical analysis.

  Objective 1.3 Compare between the models to find the similarity of and difference between them.

- **Objective 2.** Study the firms' coordination behavior in a single region market

  Objective 2.1 Build analytical models for a centralized market, a decentralized market (baseline case), and a coordination contract based on TGC offering. Obtain the close form solutions for the models.

  Objective 2.2 Compare between the models to prove that the coordination model can achieve the global optimum and outperform the baseline case.

  Objective 2.3 Analyze the properties of coordination model by sensitivity analysis and numerical analysis.

- **Objective 3.** Study the firms' coordination behavior in a two-region market with interregional transmission

Objective 3.1 Build analytical models for a centralized market, a horizontally decentralized market, a fully decentralized market (baseline case), and a coordination contract based on TGC offering and transmission premium. Analyze the properties of the global optimal solutions of the models.

Objective 3.2 Compare between the models to prove that the coordination model can achieve the global optimum and outperform the baseline case.

Objective 3.3 Analyze the properties of coordination model by sensitivity analysis and numerical analysis.

3.3 Research Contributions

The rapid growth of renewable power in electricity markets introduces many new research questions on firms' decision makings and system coordination mechanism design. In literature published so far, the detailed analysis on firms' decisions facing RPS regulation in regional electricity markets, especially their coordination behavior, are not sufficient. Our research is among the first batch of works to study in this area.

The main contributions of this research are listed as follows.

- We establish analytical models to describe the power suppliers' decision problems facing the RPS regulation in regional electricity markets with external TGC markets.
- We analyze the firms' decisions in a monopoly structure and a duopoly structure, and compare between the two structures.
- We propose coordination mechanisms based on TGC offering to tackle the random power shortage for renewable suppliers. Both a single region structure and a two-region structure with interregional transmission are considered.

- We analyze the properties of the coordination mechanisms, prove they can achieve system coordination and are robust.

CHAPTER 4

IMPACTS OF THE RENEWABLE PORTFOLIO STANDARD ON REGIONAL ELECTRICITY MARKETS

In this chapter we examine the impacts of the renewable portfolio standard (RPS) regulation on regional electricity markets. We consider a regional market with one or two power suppliers with the capacity to generate renewable energy and access to the tradable green certificate (TGC) market. We establish a monopoly model and a Nash game duopoly model to study the impacts of TGC price and RPS percentage. Our analytical results indicate that the green power output may decrease when the RPS percentage increases in a regional market. Our analytical results also show that, when the TGC price increases, the green power output increases, and the total profit first decreases then increases. Under both regional market structures, there exists an optimal RPS percentage to maximize the social welfare. We also compare the difference between two models with numerical analysis. When the TGC price increases, the electricity outputs change slower in the duopoly market than in the monopoly market. The optimal RPS percentage to maximize the social welfare in the duopoly market is higher than in the monopoly market.

4.1 Models

In this section we establish two models to analyze the regional suppliers' decisions in the monopoly and duopoly market structures. In the first structure, a monopoly supplier generates both green and black power; in the second structure, a black power supplier and a green power supplier compete with each other.

4.1.1 Assumptions and Notations

We study a regional electricity market where a group of rational customers are served by one or two rational suppliers. The suppliers own the generators, and also have access to the TGC market. The utility function of consuming electricity follows the classic definition in Microeconomics, $U(D) = \alpha D/\beta - D^2/(2\beta) - pD$, where D is the demand, $p > 0$ is the retail price, $\alpha > 0$ is the base demand and $\beta > 0$ is the price sensitivity. The first term is the benefit of consuming D quantity of electricity; the second term reflects the cost of equipment and labor to utilize the electricity; the last term is the monetary payment to buy electricity.

For customers who try to maximize the utility, there exists a unique optimal order quantity in the linear form $D = \alpha - \beta p$. Newbery (1998) explains that though in reality the price bidding offered by competitive power suppliers is stair-wise, the average demand curve faced by a single supplier can be simplified as a linear form without heavy loss of accuracy. This linear demand function for electricity is also used in Tamas et al. (2010) and Zhou and Tamas (2010).

We assume the feasible region of black output S_B is $S_B \geq 0$, and the feasible region of green output S_G is $S_G \geq 0$. The total output satisfies the supply-demand balance $S_B + S_G = D = \alpha - \beta p$. We assume the black and green power cost functions, $c_B(S_B)$ and $c_G(S_G)$, are positive, monotonically increasing and twice differentiable everywhere in $S_B \geq 0$ or $S_G \geq 0$. We assume $c''_B(S_B) > 0$ and $c''_G(S_G) > 0$ everywhere in $S_B \geq 0$ or $S_G \geq 0$. It is because in this research, we highlight the scarcity nature of cheap energy resources in a certain regional power market, both black and green. Such that to increase either type of power output will lead to an upward sloping curve of electricity generation cost. This strict convexity of cost function is also applied in Fischer (2010), Tanaka and Chen (2013) and other papers in this field. Lastly, we assume parameter values for $c_B(S_B)$ and $c_G(S_G)$ to ensure that the global optimum is in the interior of $S_B \geq 0$ and $S_G \geq 0$. In Section 4.2 we introduce the quadratic cost functions and explain the economical meanings of the bounds of parameter values which lead to the interior solution.

We assume the unit TGC price of $c_T > 0$ is exogenous in the national TGC market, and the national TGC market has an unlimited capacity for the supplier to buy or sell. This assumption holds when the regional supplier is small and its impact on the national market is marginal. Let $0 \leq \lambda \leq 1$ denote the RPS percentage. According to recent data, most states have the RPS percentage between 10% and 35% (Tamas et al. (2010)).

4.1.2 Market Structures

According to Nagurney and Matsypura (2007), a regional electricity market can be described with four layers: generator, supplier, transmission service provider and customers, from top to bottom. The left part of Figure 4.1 illustrates the four-layer market. We simplify the market structure into two layers based on the following considerations. The electricity prices facing final customers are regulated in most states. Therefore the layer of transmission service provider is not a decision maker. We let the transmission layer serve as representative for the customer layer.

Among several groups of electricity market structures categorized by Belyaev (2011), we focus on the vertical-integrated structure, which is used in many regional markets. In such structure, one region is served by one or several suppliers, and the generators belong to the supplier (similar to "single buyer model" in Belyaev (2011)). The right part of Figure 4.1 shows a typical single region vertical-integrated structure prior to RPS regulation, where a single supplier integrated with a black generator serves the regional customers.

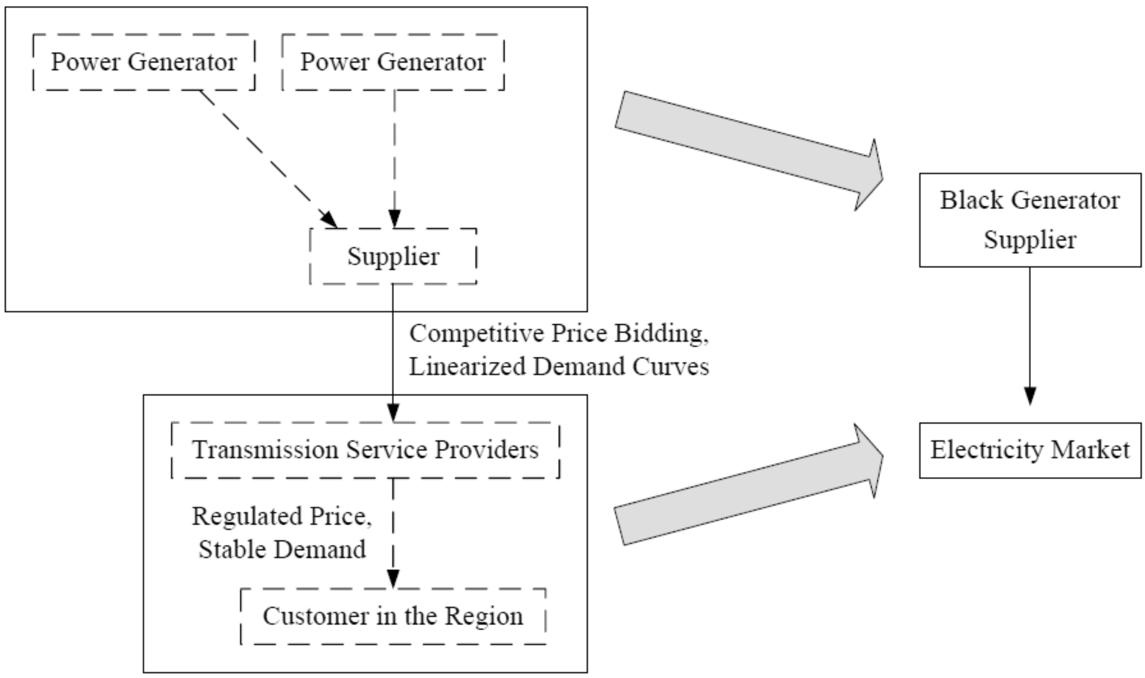

Figure 4.1: A Regional Electricity Market with a Monopoly Supplier

To meet the RPS regulation, besides building new green generators, another way is to access the national TGC market. Though not fully grown, the framework of national TGC market is under development in several nations including the U.S. In the western and the northern regions of Europe, the TGC market is expanding internationally. With access to the TGC market, the supplier can sell excess TGC if it generates more green power than the RPS requirement, or buy TGC if less than required.

Though in a national market there generally exists multiple electricity suppliers competing with each other, the electricity markets on the regional level are more concentrated, and the number of suppliers serving one particular region is small. For instance, most counties in Oklahoma are served by Oklahoma Gas & Electric Company only, and many counties in Kentucky are served by Kentucky Utilities Company only. Besides such monopoly scenario, we also consider the regional markets served by a black supplier and a green supplier. For example, in the regions with large wind farms nearby, although the customers have convenient access to the green power, they still need a steady black power source to provide cushion due to the intermittency nature of wind power. We model the monopoly market and the duopoly market as follows.

Monopoly model

Firstly we establish the monopoly model shown in Figure 4.2. The supplier decides the black output S_B and the green output S_G. Notice the retail price p is implicitly decided because of the supply-demand balance $S_B + S_G = D = \alpha - \beta p$. The supplier sells excess TGC if $S_G > D * \lambda$, or buys TGC if $S_G < D\lambda$.

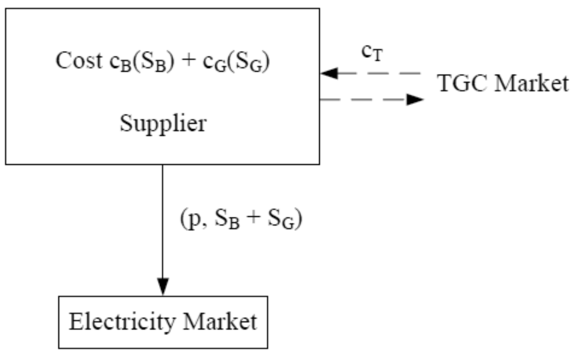

Figure 4.2: Monopoly Structure

The supplier maximizes its profit function as follows, with the feasibility constraints $S_B \geq 0$ and $S_G \geq 0$.

$$\begin{cases} \text{Max} \quad \Pi(S_B, S_G) = [\frac{\alpha - S_B - S_G}{\beta}(S_B + S_G)] - [c_B(S_B) + \lambda c_T S_B] - [c_G(S_G) + (\lambda - 1)c_T S_G] \\ S_B \geq 0, S_G \geq 0 \end{cases} \tag{4.1}$$

Lemma 4.1 $\Pi(S_B, S_G)$ *is strictly concave on* (S_B, S_G).

Please see appendix for the proof. Then given the assumption that the parameter values ensure an interior solution of $\{S_B, S_G\}$, there exists a unique optimal solution of (S_B, S_G) to maximize the monopoly supplier's profit.

Duopoly model

Secondly we establish the duopoly model shown in Figure 4.3. We assume neither supplier has significant market power over another. The black supplier decides S_B and the green supplier decides S_G simultaneously in the Nash game.

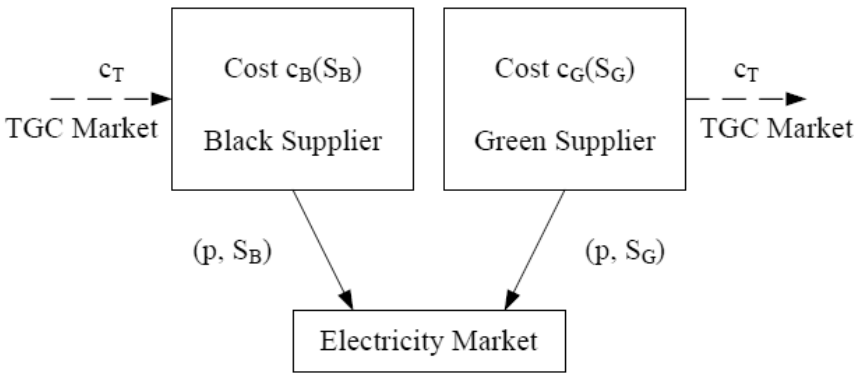

Figure 4.3: Duopoly Structure

The black supplier maximizes its profit function as follows, with the feasibility constraints $S_B \geq 0$.

$$\begin{cases} \text{Max} \quad \Pi_B(S_B) = \dfrac{\alpha - S_B - S_G}{\beta} S_B - c_B(S_B) - \lambda c_T S_B \\ S_B \geq 0 \end{cases} \tag{4.2}$$

And the green supplier maximizes its profit function as follows, with the feasibility constraints $S_G \geq 0$.

$$\begin{cases} \text{Max} \quad \Pi_G(S_G) = \dfrac{\alpha - S_B - S_G}{\beta} S_G - c_G(S_G) + (1-\lambda) c_T S_G \\ S_G \geq 0 \end{cases} \tag{4.3}$$

Lemma 4.2 *$\Pi_B(S_B)$ and $\Pi_G(S_G)$ are diagonally strictly concave on (S_B, S_G).*

Please see appendix for the proof. Given the assumption that the parameter values ensure an interior solution of $\{S_B, S_G\}$, there exists a unique Nash equilibrium of (S_B, S_G) for the black and the green suppliers.

4.2 Analytical Results

In this section, we focus on the common properties of the two structures. To acquire the close-form solution of suppliers' decisions and its property, a specific cost function is needed. We adopt a quadratic form as follows.

$$\begin{cases} c_B(S_B) = b_2 S_B^2 + b_1 S_B + b_0 \\ c_G(S_G) = g_2 S_G^2 + g_1 S_G + g_0 \\ b_2, g_2, b_1, g_1 > 0; b_0, g_0 \geq 0 \end{cases}$$

For the economical meanings of the parameters, $b_0 \geq 0$ and $g_0 \geq 0$ are the fixed cost (zero fixed cost means the generating facility has been built and free to use). $b_1 > 0$ and $g_1 > 0$ are the variable cost; $b_2 > 0$ and $g_2 > 0$ reflect the scarcity nature of cheap energy resources (both black and green) in this regional market, such that to increase either type of power output leads to an upward sloping curve of electricity generation cost.

In the monopoly structure, the close-form solution of monopoly supplier's optimal decision derived by first order condition is as follows.

$$\begin{cases} S_B = \dfrac{g_1 + \alpha g_2 - b_1(1+\beta g_2) - c_T(1+\beta\lambda g_2)}{2(g_2 + b_2(1+\beta g_2))} \\ S_G = \dfrac{b_1 + c_T - g_1 + b_2(\alpha + (\beta - \beta\lambda)c_T - \beta g_1)}{2(g_2 + b_2(1+\beta g_2))} \end{cases} \tag{4.4}$$

Now we analyze the conditions to ensure an interior solution. For $S_B > 0$, we need

$$b_1 < \bar{b}_1^M = \frac{-\beta g_2 \lambda c_T - c_T + \alpha g_2 + g_1}{\beta g_2 + 1}$$

and

$$c_T < \bar{c}_T^M = \frac{-\beta b_1 g_2 - b_1 + \alpha g_2 + g_1}{\beta g_2 \lambda + 1}.$$

It means the variable cost of black power and the TGC price cannot be too high, else generating black power is unprofitable. For $S_G > 0$, we need

$$g_1 < \bar{g}_1^M = \frac{\alpha b_2 - \beta b_2 \lambda c_T + \beta b_2 c_T + b_1 + c_T}{\beta b_2 + 1},$$

which means the variable cost of green power cannot be too high, else generating green power is unprofitable.

Given equation (4.4), the electricity price p can be derived from the assumption of supply-demand balance ($S_B + S_G = D = \alpha - \beta p$). The monopoly supplier's profit Π can be derived from the profit function (Equation 4.1).

In the duopoly structure, the close-form solution of duopoly suppliers' Nash equilibrium derived by first order condition is as follows.

$$\begin{cases} S_B = \dfrac{\alpha + \beta g_1 + 2\alpha\beta g_2 - 2\beta b_1(1+\beta g_2) - \beta c_T(1+\lambda+2\beta\lambda g_2)}{3 + 4\beta g_2 + 4\beta b_2(1+\beta g_2)} \\ S_G = \dfrac{\alpha + \beta b_1 + 2\beta c_T - \beta\lambda c_T - 2\beta g_1 + 2\beta b_2(\alpha + (\beta - \beta\lambda)c_T - \beta g_1)}{3 + 4\beta g_2 + 4\beta b_2(1+\beta g_2)} \end{cases} \tag{4.5}$$

To ensure an interior solution, similar to the monopoly model, we need upper bounds of black variable cost, TGC price, and green variable cost as follows.

$$\begin{cases} b_1 < \bar{b}_1^P = \dfrac{\alpha - 2\beta^2 g_2 \lambda c_T - \beta\lambda c_T - \beta c_T + 2\alpha\beta g_2 + \beta g_1}{2\beta\left(\beta g_2 + 1\right)} \\ c_T < \bar{c}_T^P = \dfrac{\alpha - 2b_1\beta - 2b_1\beta^2 g_2 + 2\alpha\beta g_2 + \beta g_1}{\beta\left(2\beta g_2 \lambda + \lambda + 1\right)} \\ g_1 < \bar{g}_1^P = \dfrac{\alpha + 2\alpha b_2\beta + b_1\beta - 2b_2\beta^2\lambda c_T + 2b_2\beta^2 c_T - \beta\lambda c_T + 2\beta c_T}{2\beta\left(\beta b_2 + 1\right)} \end{cases}$$

Given equation (4.5), the electricity price p can be derived from the assumption of supply-demand balance ($S_B + S_G = D = \alpha - \beta p$). The suppliers' profits Π_B and Π_G can be derived from their profit functions (Equations 4.2 and 4.3).

The impacts of market conditions on the black/green outputs, electricity price, suppliers' profits and social welfare are analyzed as follows.

Impacts of RPS percentage

Proposition 4.1 *In both market structures, when the RPS percentage increases:*

- *both the black and green output decrease;*
- *the electricity price increases;*
- *the suppliers' profits decrease.*

The first result reveals an important difference between our regional market model and the national market models. In a national electricity market where TGC is traded within the market, higher RPS percentage generally leads to higher green power output and lower black power output. Whereas, in a regional electricity market with TGC available from outside, the increase of RPS percentage does not guarantee an increase of green output. A recent empirical study by Yin and Powers (2010) supports our finding, and it points out that allowing free trade of TGC can significantly weaken the effect of RPS aiming for promoting local green power. This result implies that if the TGC price in the national market is unchanged, increasing the RPS percentage in a individual region can not push the local supplier to produce more green power because it will incur higher production cost.

Alternatively, many states set a step-by-step schedule to increase their RPS percentages gradually. For example, Oklahoma starts from a 10% in 2010, increases 1% per year and will reach 15% in 2015. When many regions increase their RPS percentages simultaneously, the overall demand of TGC across the country increases and the national TGC price may increase. The regional supplier will increase the local green output in response to higher TGC price, as shown in the Proposition 4.2.

The second and third results are due to higher RPS percentage incurs extra cost to the regional suppliers in both structures. For the black supplier in the duopoly structure, it means more TGC must be purchased and submitted to the regional regulator. For the green supplier in the duopoly structure, similarly more TGC must be reserved and submitted for itself, and then less TGC for sale. For the monopoly supplier both effects exist. In all scenarios, the suppliers' costs increase and therefore the profits decrease.

Impacts of TGC Price

Proposition 4.2 *In both market structures, when the TGC price increases:*

- *the green output increases and the black output decreases;*
- *the total profit in the monopoly market first decreases then increases; in the duopoly structure, the green supplier's profit increases and the black supplier's profit decreases;*

- *the impact on the electricity price depends on the RPS percentage. When the RPS percentage is low, the electricity price decreases when the TGC price increases; when the RPS percentage is high, the trend reverses.*

The first result is easy to understand. When the TGC becomes more expensive, the suppliers tend to generate more green output and less black output, in order to reduce the amount of TGC purchased or increase the amount of TGC sold. The second result implies in the duopoly market, higher TGC price naturally leads to higher profit for the green supplier and lower profit for black supplier. In the monopoly structure, when the TGC price is very low, the supplier will buy TGC from the national market and reduce the green output to save cost, and the higher the TGC price, the less the saving; when the TGC price is very high, the supplier will become a TGC seller. It generates more green power and thus more TGC as the TGC price increases. The third result shows the electricity price does not always increase with the TGC price. When the RPS percentage is low, the supplier is a TGC seller, and higher TGC price brings more revenue to compensate the green generation cost, which leads to a reduction of the electricity price. When the RPS percentage is high, the supplier becomes a TGC buyer, and the effect of TGC price on the electricity price reverses. In the next section, we compare the difference of the black/green outputs, electricity price and the suppliers' profits between two market structures.

Social Welfare Analysis

An important purpose of RPS is to increase the social welfare (W) whose definition in Microeconomics is as follows (Tamas et al. (2010)):

social welfare = customer utility - production cost - environmental damage

To quantitatively measure the social welfare, we adopt the following form:

$$W = [\alpha(S_B + S_G)/\beta - (S_B + S_G)^2/(2\beta)] - (g_2 S_G^2 + g_1 S_G + g_0) - (\gamma_B b_2 S_B^2 + b_1 S_B + b_0)$$

The first term is the utility function defined in Section 6.2, the second term is the green power production cost, and the third term is the black power production cost and its environmental damage, which is assumed to be quadratic to black power output S_B and then reflected in the coefficient $\gamma_B > 1$.

Proposition 4.3 *In both market structures, there exists a unique RPS percentage to maximize the social welfare.*

This result shows the regulator could achieve the goal of social welfare maximization by setting RPS percentage accordingly. In the next section, we compare the difference of the optimal RPS percentage between two market structures.

4.3 Numerical Analysis

In this section we demonstrate several interesting insights by comparison between the monopoly structure and the duopoly structure. The following parameter values are adopted in most cases: $\alpha = 100, \beta = 1, b_0 = 0, b_1 = 15, b_2 = 0.1, g_0 = 20, g_1 = 40, g_2 = 1$. Any change from these values and other necessary parameter values are demonstrated on the graph.

Comparison of Black and Green Outputs

As analyzed in previous section, when the TGC price increases, the black output decreases and the green output increases. Figure 4.4 shows that as the TGC price increases, the adjustments of black and green outputs are slower in the duopoly structure than in the monopoly structure.

The reason behind the slower change of black/green outputs of the duopoly sup-

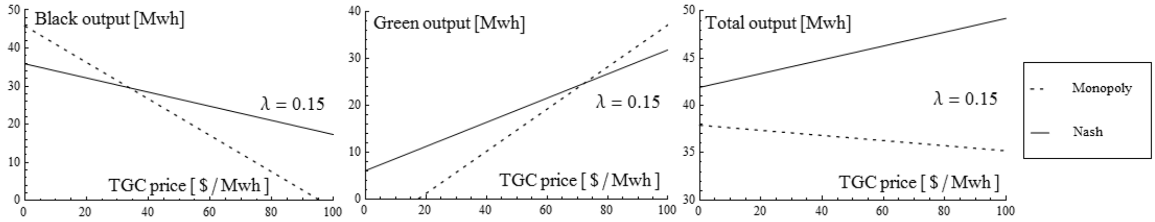

Figure 4.4: Comparison of Electricity Output on the Impact of TGC Price

pliers is as follows. When facing an increase of the TGC price, the monopoly supplier only needs to concern with cost reduction, and then decreases the black output and increases the green output accordingly. While in the duopoly structure, the suppliers need to consider both cost reduction and maintaining their market shares. When the TGC price increases, the black supplier will not decrease the output as fast as in the monopoly structure, because that will yield the market share to the green supplier. The green supplier will not increase its output significantly due to concern of driving down the electricity price. In the next section we analyze the total output since it is linear to the electricity price.

Comparison of Electricity Price and Suppliers' Profits

In Section 4 we have pointed out when the TGC price increases, the electricity price decreases if the RPS percentage is low, and increases if the RPS percentage is high. Interestingly, at certain range the electricity prices in the two structures respond oppositely to the increase of RPS percentage, as shown in Figure 4.5. When $\lambda = 0.15$ in the second graph, the duopoly market's electricity price keeps decreasing when the TGC price increases, but the monopoly supplier is able to drive the electricity price up with the increased TGC price.

The phenomenon can be explained by the third graph of Figure 4.4. As discussed previously, when the TGC price increases in the monopoly structure, the monopoly

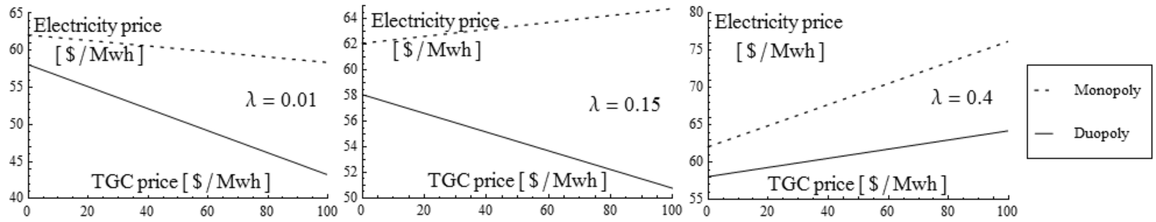

Figure 4.5: Comparison of Electricity Price on the Impact of TGC Price

supplier is not as concerned of the market share as in the duopoly structure, and then the total output decreases and the electricity price increases. In the duopoly structure, the black supplier is unwilling to yield that much market share to the green supplier, and the black output decreases slower. Though the green output also increases slower, the total output still increases and then the electricity price decreases.

We also observe that the electricity price in the monopoly structure is higher than in the duopoly structure, for the lack of competition gives the monopoly supplier more market power to set a higher price.

We compare the suppliers' profits between the two structures in Figure 4.6. Not surprisingly, the total profit in the monopoly structure is higher than in the duopoly structure, which implies a merger between the black and green suppliers may be desirable, as also pointed out by Zhou and Tamas (2010).

Comparison of Social Welfare

We plot the social welfare of two market structures in Figure 4.7. Noticeably there exists an optimal RPS percentage for both structures, as mentioned in Proposition 4.3. Though the maximum social welfare values of the two structures are close, the duopoly structure's optimal RPS percentage is 61%, much higher than the monopoly structure's optimal percentage 13%. Intuitively, these is competition between suppli-

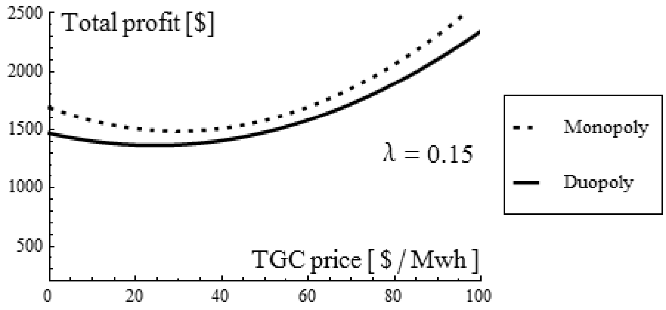

Figure 4.6: Comparison of Suppliers' Profits on the Impact of TGC Price

ers in the duopoly structure, and the electricity price is lower than in the monopoly structure as shown in Figure 4.5. Due to the cheaper electricity price, the customers in the duopoly structure can support more aggressive plan of green power development.

At the optimal point of monopoly structure, the electricity price is high and power output is low, and then both the utility of consuming electricity and the environmental damage are at low level. At the optimal point of duopoly structure, the electricity price is low and total electricity output is high. Both the utility of consuming electricity and the environmental damage are higher in the duopoly structure than in the monopoly structure. In summary, the duopoly structure is beneficial to keep a high RPS percentage without hurting the social welfare.

4.4 Summary of Chapter 4

This chapter examines the impacts of the renewable portfolio standard regulation on a regional electricity market. Both a monopoly market and a Nash game duopoly market are analyzed. In the monopoly market, a single supplier decides both the black and green power outputs. In the duopoly market, a black supplier and a green

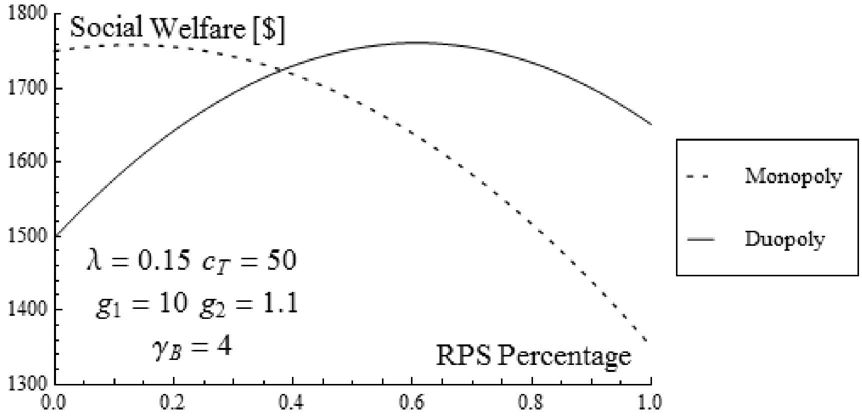

Figure 4.7: Comparison of Social Welfare

supplier decide their outputs simultaneously. The electricity price is determined by the total output with a linear demand function. The suppliers have access to the national tradable green certificate market.

We find the close-form solutions and analyze the impacts of the TGC price and the RPS percentage on the black/green outputs, the electricity price and the suppliers' profits under the two structures. We find in a regional electricity market with TGC available from outside, the increase of local RPS percentage does not guarantee an increase of local green output. The green power output decreases when the RPS percentage increases in the regional electricity market if the TGC price in the national market remains unchanged, because the supplier has the option to buy TGC from outside instead of self-production which incurs high product cost. In contrast, a higher TGC price can effectively promote the local green power output.

From a policy implementation point of view, we suggest the regional regulators collectively and gradually increase their RPS percentages to push up the overall demand of TGC across the country, which will increase the national TGC price. As the national TGC becomes more expensive, the regional suppliers will have the incentive to increase the local green outputs.

The impact of TGC price on the electricity price depends on the RPS percentage. When the RPS percentage is low, the supplier is a TGC seller, and higher TGC price brings more revenue to compensate the green generation cost, which leads to a reduction of the electricity price. When the RPS percentage is high, the supplier becomes a TGC buyer, and the effect of TGC price on the electricity price reverses. When the TGC price increases, the total profit first decreases then increases. When the TGC price is very low, the supplier will buy TGC from the national market and reduce the green output to save cost, and the higher the TGC price, the less the saving; when the TGC price is very high, the supplier will become a TGC seller. It generates more green power and thus more TGC as the TGC price increases.

By comparing the two structures with numerical analysis we have the following insights. In the duopoly market, the electricity price and suppliers' profit are lower, and the total electricity supply is higher. The electricity outputs change slower in the duopoly structure than in the monopoly structure when the TGC price increases. It is because the monopoly supplier only needs to pay attention to cost reduction and can respond rapidly; while the suppliers in the duopoly structure need to be concerned with both cost reduction and keeping their market shares. We find there exists an optimal RPS percentage to maximize the social welfare in each structure, respectively. To maximize the social welfare, the optimal RPS percentage in the duopoly market is higher than in the monopoly market.

CHAPTER 5

Capacity Coordination in Regional Electricity Market Based on Tradable Green Certificate Offering

In this chapter we study a coordination mechanism between a renewable supplier and a conventional supplier in a regional electricity market. The intermittent nature of the renewable supplier results in random power shortage. Though the renewable supplier can buy backup power from a conventional supplier who prepares backup capacity to cover the shortage, there is no commitment that enough backup capacity will be prepared without any incentives to the conventional supplier. We design a coordination mechanism where the renewable supplier offers the conventional supplier free tradable green certificate (TGC) proportional to the backup capacity. We prove that this mechanism coordinates the conventional supplier's decision on backup capacity and arbitrarily splits the system profit between the two suppliers by the wholesale price. Our analytical results show that when the shortage cost increases, the backup capacity increases, the TGC offering rate increases, the total profit decreases, the renewable supplier's profit decreases but the conventional supplier's profit increases. We also show analytically that the social welfare under this mechanism is higher than in the baseline case unless the environmental damage of conventional power is extremely high. By numerical analysis, we show that the coordination mechanism is robust.

5.1 Models

In this section we firstly introduce the assumptions and notations, and then describe a centralized model, a decentralized model (baseline case), and a coordination model.

5.1.1 Assumptions and Notations

We study a regional electricity market served by a renewable supplier (G). G utilizes intermittent energy sources which cause random power shortage. We assume there is not enough low-price power available in the balancing market to cover the shortage, and then an adjacent conventional supplier (B) prepares S units of backup capacity dedicated to buffer G's demand. Notice the participants of the regional market can be a single supplier or a coalition of suppliers acting as a single decision maker (Andersen and Lund (2007)). For simplicity, we treat the latter also as a single supplier.

To represent the intermittency nature of the renewable energy sources, let a series of non-negative random variables, x_t, $t = 1, ..., m$, denote the shortage faced by G at period t. The p.d.f. of x_t is $f_t(.)$, which is continuous and defined on $x_t \geq 0$. We assume for at least one period t, $f_t(.)$ is not always zero when $x_t > 0$, to avoid the trivial scenario of zero shortage. For simplicity we assume the overall shortage cost is linear to the shortage quantity. Though B provides backup capacity to cover the shortage, if in some periods the shortage exceeds the backup capacity ($x_t > S$), the shortage cost incurred on G will be $c_u \sum_{t=1}^{m} \max(0, x_t - S)$, where $c_u > 0$ is the unit cost of power shortage, including using the expensive ancillary services or buying power from the balancing market at a higher price, paying fine to the regional ISO due to demand cutting, losing reputation among the customers, etc.

To prepare the backup capacity, we assume B incurs a capacity cost that is linear to the backup capacity quantity as $c_f S$. We also assume the variable cost is linear to the power output quantity as $c_v \sum_{t=1}^{m} \min(x_t, S)$, where c_v represents the unit variable cost related to power generation and transmission, including the fuel cost, operation and maintenance, transmission loss, etc. The overall cost function of B is $c_f S + c_v \sum_{t=1}^{m} \min(x_t, S)$. To ensure the investment on the backup capacity is profitable, we assume $c_v < r$, the variable cost is less than the electricity price; and m is large enough such that $(r + c_u - c_v) \sum_{t=1}^{m} \min(x_t, S) > c_f S$, the overall revenue plus saving of shortage cost during m periods of operation is greater than the capacity cost. Lastly, after meeting G's demand, B can sell the residue capacity on the balancing market if it is profitable. In this research, we normalize this residue value to zero, and it does not change our main results.

5.1.2 Centralized Model

The centralized model (C) describes a market structure where G and B merge as one firm. The centralized firm decides the backup capacity S to maximize its total profit as follows, with the feasibility constraint $S \geq 0$.

$$\Pi_C(S) = R - c_u \bar{D} + (r - c_v + c_u) Y(S) - c_f S, \tag{5.1}$$

where R is a constant denoting the basic revenue that G collects from the regional market. r is the unit price of backup power. $\bar{D} = \sum_{t=1}^{m} \int_0^{\infty} x_t f_t(x_t) dx_t$, is a constant denoting the expected demand (shortage). $Y(S) = \sum_{t=1}^{m} [\int_0^S x_t f_t(x_t) dx_t + \int_S^{+\infty} S f_t(x_t) dx_t]$, is the expected amount of backup power delivered to G. $Y(S)$ takes the standard form of Newsvendor model, and it is easy to prove $Y(S)$ is a monotonically increasing and concave function of S by using Leibniz's rule to obtain the first and second derivatives (Khouja (1999)).

By using the first order condition $\partial \Pi_C / \partial S = 0$, we have:

$$\bar{F}(S_C) = m - c_f / (r - c_v + c_u), \tag{5.2}$$

where $\bar{F}(.) = \sum_{t=1}^{m} F_t(.)$ is the sum of c.d.f. of the random demands in m periods. It is the expected number of periods that the shortage is completely covered by the backup capacity. Notice $(r + c_u - c_v)mS \geq (r + c_u - c_v)\sum_{t=1}^{m} \min(x_t, S) > c_f S$, such that $m - c_f/(r - c_v + c_u) > 0$. Also it is easy to verify that $\bar{F}(0) = 0$ and $\bar{F}(S)$ monotonically increases on S. Then $S_C > 0$ is an interior solution.

By using the second order condition , we have $\partial^2 \Pi_C/\partial S^2 = -(r+c_u-c_v)\sum_{t=1}^{m} f_t(.) < 0$. Such that Π_C is strictly concave and the first order condition (Equation (5.2)) defines the unique global optimal solution of backup capacity S_C.

5.1.3 Decentralized Model

The decentralized model (D) serves as a baseline case that the two suppliers operate independently. B sells backup power to G at a wholesale price w. We assume all suppliers' margins are positive, that is $r > w > c_v$. G decides w and its profit is

$$\Pi_G^D = R - c_u \bar{D} + (r + c_u - w)Y(S).$$

B decides to prepare S units of backup capacity to maximize its profit as follows, with the feasibility constraint $S \geq 0$.

$$\Pi_B^D(S) = (w - c_v)Y(S) - c_f S.$$

The system profit of decentralized model takes the same form as in the centralized model shown in Equation 5.1.

By using the first order condition $\partial \Pi_B^D/\partial S = 0$, we have:

$$\bar{F}(S_D) = m - c_f/(w - c_v).$$

By using the second order condition , we have $\partial^2 \Pi_B^D/\partial S^2 = -(w - c_v)\sum_{t=1}^{m} f_t(.) < 0$. Such that Π_B^D is strictly concave and the first order condition defines the unique global optimal solution of backup capacity S_D. Similar to the Model C, to ensure an interior solution of $S_D > 0$, we need the parameter values that $m - c_f/(w - c_v) > 0$, or equivalently $w > c_f/m + c_v$. The economical meaning of this condition is straightforward: only when the wholesale price is greater than of per period capacity cost plus the variable cost, B is willing to build backup capacity.

It is easy to see the investment in the baseline case is less than the global optimum shown in Equation (5.2), $\bar{F}(S_D) < \bar{F}(S_C) = m - \dfrac{c_f}{r - c_v + c_u}$. Then the system profit in the baseline case is less than in the coordination model. It is because in the decentralized model B only concerns its own profit without considering G's shortage cost. On the other hand, G does not offer any incentive to B and then does not share the risk of investing on the backup capacity with B, which leads to under investment of backup capacity.

In the decentralized model, customers can only rely on a higher electricity price r to encourage the conventional supplier to invest more on the backup capacity. By comparing between S_D and S_C, even when $w = r$ such that the double marginalization is eliminated, the electricity price needs to be increased from r to $r + c_u$ to drive the investment up to the global optimum. However, it is not reasonable to let the customer bear this increased price. The customers are generally willing to pay higher price and encourage the investment on backup capacity to buffer their own demand uncertainty, such as demand spikes during peak periods. But the power shortage due to supply uncertainty is not the customers' problem, and they may not be willing to pay higher price for that. Therefore we need a market mechanism to encourage B to build up more backup capacity.

5.1.4 Coordination Model

We design a coordination contract (Model P) aiming to provide an incentive for B to prepare the backup capacity for G up to the global optimal level. According to the contract, G offers θS units of free TGC to B, where θ is a TGC offering rate decided by G. In this research we assume G generates sufficient TGC to cover the offering and sells the rest in the national TGC market.

Please notice that the form of TGC incentives is not limited to the free offering specified above. For example, offing θS units of free TGC is equivalent to sell K units of TGC in a discount price $(1-d)c_T$ to B, where $d < 1$ is the discount rate and c_T is the price of TGC in the national market, if $d = \theta S/(c_T K)$. There also exists other equivalent forms of TGC transaction, but we focus on free TGC offering in this research.

According to the contract, G buys electricity from B at a wholesale price w. The amount of revenue G gains from selling electricity is $(r - w)\sum_{t=1}^{m} \min(x_t, S)$ and B's revenue is $(w - c_v)\sum_{t=1}^{m} \min(x_t, S)$. The wholesale price serves as a lever to allocate the profit between the two parties. We assume both suppliers' unit profits through this coordination are positive, that is $r > w > c_v$.

The coordination model is shown in Figure 5.1. The contract defines a Stackelberg game where the sequence of events is as follows.

Stage 1: G decides the TGC offering rate θ and the wholesale price w.

Stage 2: B decides the backup capacity S.

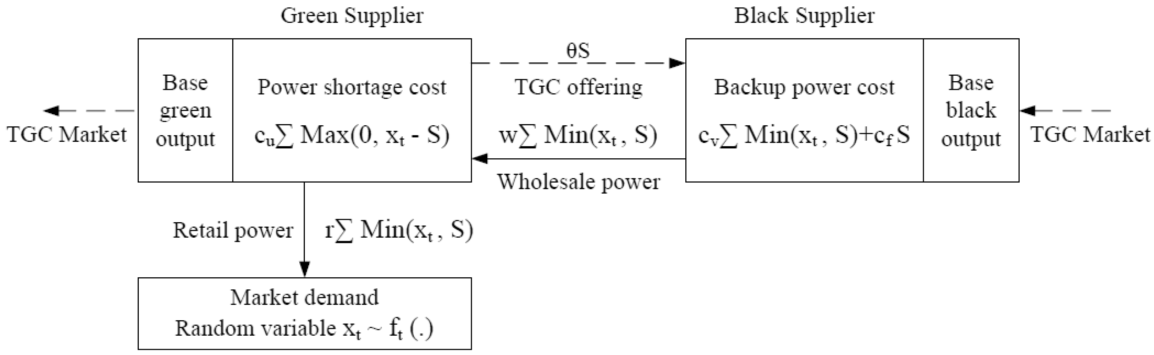

Figure 5.1: The Market Structure of Coordination Model

The profit functions of the two suppliers in the coordination model are as follows.

$$\begin{cases} \Pi_G(\theta, w) = R - c_u\bar{D} - \theta S + (r - w + c_u)Y(S) \\ \Pi_B(S) = (\theta - c_f)S + (w - c_v)Y(S) \end{cases} \tag{5.3}$$

5.2 Analytical Results

In this section we firstly perform the coordination analysis to show that the coordination contract drives the conventional supplier prepare backup capacity at the global optimal level. Then we perform the sensitivity analysis and the social welfare analysis to reveal more properties of the coordination model.

5.2.1 Coordination Analysis

Theorem 5.1 *The coordination model has the following properties.*

- *The system achieves coordination when the two parameters (θ, w) satisfy the following condition:*

$$\theta = c_f \frac{r - w + c_u}{r - c_v + c_u}. \tag{5.4}$$

- *By adjusting the wholesale price w, the system profit can be arbitrarily allocated between the two suppliers.*

- *When the system is coordinated, there exists a unique global optimal solution of backup capacity S_P that simultaneously maximizes the total profit and both suppliers' profits satisfying the following condition:*

$$\bar{F}(S_P) = m - \frac{c_f}{r - c_v + c_u}, \tag{5.5}$$

where $\bar{F}(.) = \sum_{t=1}^{m} F_t(.)$ is the sum of c.d.f. of the random demands in m periods.

Please refer to the appendix for all the proofs.

The coordination property is based on the design of the coordination mechanism that by offering free TGC, G shares a portion of the system risk with B and then encourages B investing on the backup capacity at the global optimal level. To intuitively explain the coordination condition specified in Theorem 5.1, let us compare Equation (5.3) with Equation (5.1). When (θ, w) meets the coordination condition as shown in Equation (5.4), we have

$$\begin{cases} \Pi_G(S) = a\Pi_C(S) - b \\ \Pi_B(S) = (1-a)\Pi_C(S) + b \end{cases}$$

where $\{a, b\}$ are parameters indicating the allocation of system profit between the two suppliers.

$$\begin{cases} a = \dfrac{\theta}{c_f} = \dfrac{r - w + c_u}{r - c_v + c_u} \\ b = (1-a)c_u\bar{D} \end{cases}$$

Then there exists a global optimal S to maximize $\{\Pi_C(S), \Pi_G(S), \Pi_B(S)\}$ simultaneously, and the optimal capacity in the coordination model reaches the global optimum as shown in the centralized model (Equation (5.2)), $S_P = S_C$. It also shows w is a lever to arbitrarily split the total profit.

5.2.2 Sensitivity Analysis

Here we examine the impacts of market conditions on the suppliers' decisions and their profits in the coordination model. We consider the following market conditions: the capacity cost (c_f), the electricity price (r), the variable cost (c_v), and the shortage cost (c_u). At the end of this section we summarize the results in Table 6.2.

Firstly we study the impacts on the two suppliers' decisions: backup capacity and TGC rate. According to Equation (5.4), the TGC rate (θ) is a linear function of wholesale price (w) when the system is coordinated. Since we are more interested in θ, we fix w to highlight the changing of θ.

Proposition 5.1 *When the wholesale price (w) is unchanged, the impacts of market conditions on the backup capacity (S_P) and the TGC offering rate (θ) are as follows.*

- *When the capacity cost (c_f) increases or the variable cost (c_v) increases, the backup capacity (S_P) decreases and the TGC offering rate (θ) increases.*
- *When the electricity price (r) increases or the shortage cost (c_u) increases, the backup capacity (S_P) increases and the TGC offering rate (θ) increases.*

The first result reveals that higher capacity cost or variable cost pushes up B's cost burden, and B's investment on the backup capacity decreases. Facing this change, G will increase TGC offering rate to encourage B's investment. The second result reveals that when the backup power becomes more valuable, G offers more TGC to encourage B investing more on the backup capacity.

Secondly we study the impacts on the profits.

Proposition 5.2 *The impacts of market conditions on the total profit and the two suppliers' profits are as follows.*

- *When the capacity cost (c_f) increases, the total profit (Π_C) decreases. Both the renewable supplier's profit (Π_G) and the conventional supplier's profit (Π_B) decrease.*

- *When the electricity price (r) increases or the variable cost (c_v) decreases, the total profit (Π_C) increases. Both the renewable supplier's profit (Π_G) and the conventional supplier's profit (Π_B) increase.*

- *When the shortage cost (c_u) increases, the total profit (Π_C) decreases, the renewable supplier's profit (Π_G) decreases but the conventional supplier's profit (Π_B) increases.*

The first result reveals that when the capacity cost is higher, the system-wide cost increases and the total profit decreases. It is a direct cost burden on B and its profit decreases. G shares this burden by offering more TGC (Proposition 5.1), and its profit also decreases. The second result reveals that when the margin of selling electricity is higher, the total profit increases. If r increases, G directly gains more profit and it offers more TGC to B (Proposition 5.1). If c_v decreases, B directly gains more profit and G reduces its TGC offering to B (Proposition 5.1). In both conditions the two suppliers share the profit gain and their profits increase. The third result reveals that when the shortage cost is higher, the system-wide cost increases and the total profit decreases. G needs more backup capacity to cover the electricity shortage. Such that G offers more TGC to B (Proposition 5.1), which leads to a decrease of G's profit and an increase of B's profit.

The sensitivity analysis results are summarized in Table 6.2.

	S_P	θ	Π_C	Π_G	Π_B
$c_f \uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$
$c_v \uparrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$
$r \uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$c_u \uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$

Table 5.1: Summary of the Sensitivity Analysis in Chapter 5

5.2.3 Social Welfare Analysis

An important purpose to promote renewable energy is to increase the social welfare, whose definition in Microeconomics is as follows (Tamas et al. (2010)):

social welfare = customer utility - production cost - environmental damage

To quantitatively measure the social welfare (W) in the regional market of our research, we adopt the following form:

$$W = U(Y(S)) - c_v Y(S) - c_u(\bar{D} - Y(S)) - c_f S$$

The first term $U(Y(S))$ is a general form of utility function for the generated electricity, which includes the environmental damage. We assume $U' > 0$ (monotonically increasing) and $U'' < 0$ (concave). The second term is the variable cost to generate backup power. The third term measures the society's disutility of power shortage. Being the only power supplier in the regional market, G takes all the reputation loss due to the inconvenience caused by power shortage. Thus we assume the society's disutility is close to G' shortage cost, and use the same c_u here. The last term is the capacity cost to build the backup capacity.

Proposition 5.3 *There exists a unique optimal capacity of S_W to maximize the social welfare in the regional market in the following form:*

$$\bar{F}(S_W) = m - \frac{c_f}{U' - c_v + c_u}.$$

To compare S_W with the optimal capacity in the coordination structure (S_P) and in the decentralized structure (S_D), we need a specific form of utility function. We let $U(Y) = u_1Y - (u_2+e)Y^2$, where u_1 is the unit utility of consuming power, u_2 evaluates the diminishing return property, and e is the environmental damage factor. This form is in line with Tamas et al. (2010) and other papers analyzing the utility of electricity power. Give the above $U(Y)$, we find the relationships between $\{S_W, S_P, S_D\}$ depend on the environmental damage (e) as follows.

Proposition 5.4 *Given $U(Y) = u_1Y - (u_2 + e)Y^2$, S_W decreases with the environmental damage e. To compare with S_P and S_D we have:*

- *when e is low such that $e \leq (u_1 - r)/(2Y) - u_2$, $S_D < S_P \leq S_W$;*
- *when e is high such that $e \geq (u_1 + c_u - w)/(2Y) - u_2$, $S_W \leq S_D < S_P$;*
- *when e is medium such that $(u_1 - r)/(2Y) - u_2 < e < (u_1 + c_u - w)/(2Y) - u_2$, $S_D < S_W < S_P$.*

To interpret the results, firstly we notice S_D is always lower than S_P, since the decentralized structure leads to under investment comparing to the coordination structure. Secondly, if the environmental damage e is low, building more backup capacity leads to higher power output without heavy environmental damage, which makes S_W larger; if e is high, the trend reverses and S_W becomes smaller. Please see Figure 5.2 illustrating the social welfare under different values of e, where $u_1 = 80$, $u_2 = 0.1$, and the other parameter values are the same as in Section 6.3.

5.3 Numerical Analysis

In this section we perform numerical analysis to illustrate the following properties of the coordination model. Firstly, when the TGC offering rate deviates from the optimal point, the system profit only decreases slightly. Secondly, the wholesale price

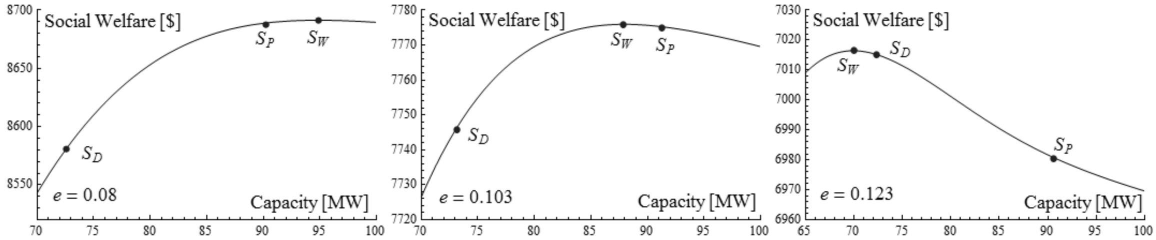

Figure 5.2: Social Welfare under Different Environmental Damage Value

serves as a lever to allocate the system profit between the two suppliers. Lastly, there exists a range of wholesale price where the coordination structure is a Pareto improvement for both suppliers comparing to the baseline case.

The parameter values presented in this section are of illustrative purpose and do not refer to a specific market. The data setting is $\{c_u = 5, r = 1.1, c_v = 0.1, c_f = 0.9, R = 100\}$, which is based on Marchenko (2007) and Marchenko (2008), whereas we increase the shortage cost and the capacity cost to highlight the impact of these two factors. The demand functions are a series of normal distribution as $\{x_t \sim N(\mu_t, \sigma_t), t = 1 \sim 4\}$ where $\{\mu_1 = 20, \mu_2 = 40, \mu_3 = 60, \mu_4 = 80, \sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 = 10\}$. The normal distribution data is based on Milligan et al. (2010), whereas we highlight the difference between the demands in different periods, such that the performance of coordination mechanism can be tested under high demand uncertainty.

Robustness of the Coordination Contract

Due to the complexity of the regional electricity market, it is difficult to accurately estimate and predict all market conditions. Thus the renewable supplier may not be able to make a perfect TGC offering rate θ at its optimal point which is 0.758 given the above parameters. To study the impacts of inaccurate TGC offering rate on the total profit, we allow an error of $\pm 15\%$ of the optimal point $(0.64 \sim 0.87)$. We find that the performance of the coordination model is robust. As shown in Figure 6.4, even when θ deviates from the optimal point to $\pm 15\%$, the total profit loss of coordination model is only up to 3% (the percentage is calculated as $(114.1 - 110.5)/114.1$, after dropping the basic revenue $R = 100$). The reduced profit 210.5 still significantly outperforms the decentralized model at 176.7.

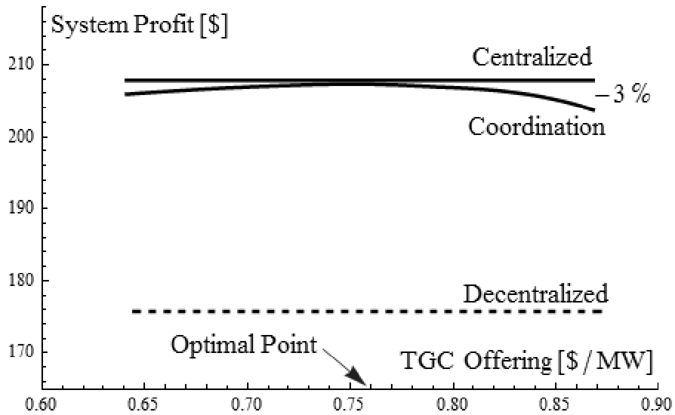

Figure 5.3: Robustness of the Coordination Model

Impacts of the Wholesale Price

In the coordination framework, the wholesale price w serves as a lever to allocate the system profit between the two parties. When w increases, the renewable supplier's profit $\Pi_G^P(w)$ decreases and the conventional supplier's profit $\Pi_B^P(w)$ increases. The total profit can be arbitrarily allocated between the two parties, as shown in Figure 5.4.

To ensure the coordination structure is a Pareto improvement for both suppliers comparing to the decentralized structure, the wholesale price must be properly decided. Firstly we notice the system profit in the coordination structure is more than in the decentralized structure where the capacity is under invested, which means $\Pi_B^P + \Pi_G^P > \Pi_B^D + \Pi_G^D$. Secondly, by adjusting the wholesale price w, the system profit can be arbitrarily allocated between the two suppliers in the coordination model. Then we can find the range of w where both suppliers have higher profits than in the

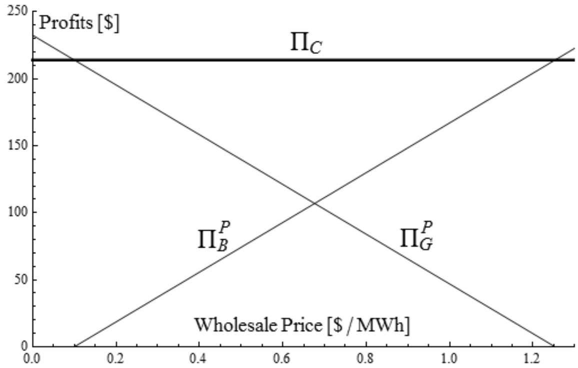

Figure 5.4: Arbitrary Split of System Profit

baseline case. Derived from $\Pi_G^P(w_U) = \Pi_G^D$, $\Pi_B^P(w_L) = \Pi_B^D$ and Equation (5.3), we have the close form of w's lower bound and upper bound as follows.

$$\begin{cases} w_L = (\Pi_B^D + (c_f - \theta)S)/Y(S) + c_v \\ w_U = r + c_u - (\Pi_G^D - R + \theta S + c_u\bar{D})/Y(S) \end{cases}$$

Notice $w_U > w_L$ is guaranteed by $\Pi_G^P + \Pi_B^P = (r + c_u - c_v)Y(S) - c_f S + R - c_u\bar{D}) > \Pi_G^D + \Pi_B^D \Rightarrow w_U > w_L$. As shown in Figure 5.5, given the previous parameters, in the decentralized structure G will set the wholesale price $w^* = 0.86$ to maximize its profit, such that $\Pi_G^D = 65.3$ and $\Pi_B^D = 78.6$. From the above equations we can calculate that $w_L = 0.523$ and $w_U = 0.9$. When $0.523 < w < 0.9$ the coordination structure is a Pareto improvement comparing to the decentralized structure.

5.4 Summary of Chapter 5

This chapter studies a coordination framework between a renewable supplier and a conventional supplier in a regional electricity market. The energy sources of the renewable supplier are intermittent and lead to random power shortage. To encourage the conventional supplier to build backup capacity to cover the shortage, we design a coordination mechanism where the renewable supplier offers the conventional supplier free tradable green certificate proportional to the backup capacity. The renewable

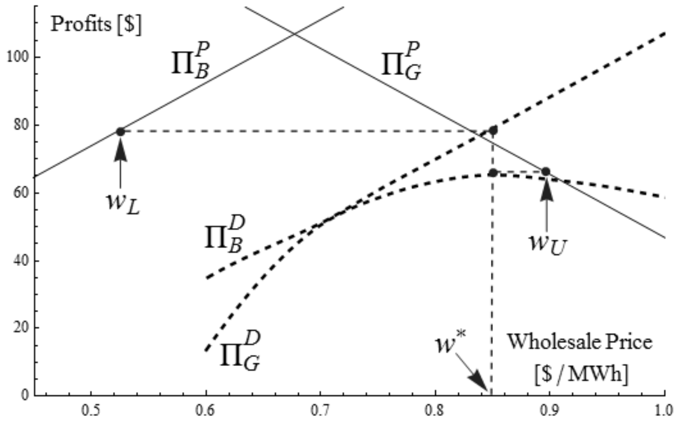

Figure 5.5: Pareto Improvement

supplier decides the TGC offering rate and the wholesale price of backup power, and then the conventional supplier decides the quantity of backup capacity.

With the close-form solution of this coordination model, we prove the contract achieves the system coordination. The system profit can be arbitrarily allocated between the two suppliers by adjusting the wholesale price. We study a baseline case without coordination and prove the baseline case leads to under investment of the backup capacity. By comparing to the baseline case, we find the coordination model can achieve Pareto improvement for both suppliers.

Sensitivity analysis is conducted on the impacts of following market conditions. Firstly, when the capacity cost increases, the backup capacity decreases and the TGC offering rate increases. Both suppliers' profits decrease and the total profit decreases. Secondly, when the electricity price increases or the variable cost decreases, the backup capacity increases and the TGC offering rate decreases. Both suppliers' profits increase and the total profit increases. Lastly, when the shortage cost increases, the backup capacity increases and the TGC offering rate increases. The total profit decreases, the renewable supplier's profit decreases but the conventional supplier's profit increases.

Social welfare analysis is conducted, and we find that the social welfare of the coordination structure will be greater than of the baseline case unless the environmental damage of conventional power is extremely high.

CHAPTER 6

Capacity Coordination between Renewable and Conventional Suppliers in Regional Electricity Markets with Interregional Transmission

In this chapter we study a capacity coordination mechanism between the renewable suppliers and the conventional suppliers in regional electricity markets with interregional transmission. The intermittent nature of the renewable suppliers leads to random power shortage. The conventional suppliers prepare backup capacity to cover the shortage, but there is no commitment that enough backup capacity will be prepared without any incentives to the conventional supplier. We design a coordination mechanism that the renewable suppliers offer tradable green certificate (TGC) in return for backup capacity committed by the conventional suppliers. The quantity of free TGC is proportional to the backup capacity. The conventional suppliers decide the interregional transmission prices between them. We prove that this mechanism coordinates the conventional suppliers' decisions on backup capacity and achieves the global optimum. In contrast, an uncoordinated baseline case leads to under investment of backup capacity and the system profit is less than the global optimum. In the coordination model, when the transmission cost increases, the backup capacity in a region increases if this region is a net importer of backup power, or decreases if it is a net exporter. By numerical analysis, we show that the coordination mechanism is robust.

6.1 Models

In this section we start from the assumptions and notations, and then establish a series of models to describe the market structures. Firstly we establish a centralized model where all suppliers in the two regions form a single decision maker, which leads to the global optimal decision of backup capacity. Secondly, we consider a horizontally decentralized model where the two regions operate independently and they negotiate a pair of transmission prices between them. We prove that it's best performance is equivalent to the centralized model, when the transmission prices are properly set to coordinate the system. Thirdly, we study a decentralized model (baseline case), where all suppliers operate independently. The baseline case leads to under investment of the backup capacity. Lastly, still considering the market structure with fully independent suppliers, we design a capacity coordination contract to drive the system to global optimum.

6.1.1 Assumptions and Notations

We study an electricity market across two regions $i, j = 1, 2$, and $i \neq j$. Each region is served by a renewable supplier (G_i). G_i utilizes intermittent energy sources which cause random power shortage. To cover this shortage, a local conventional supplier (B_i) prepares S_i units of backup capacity dedicated to buffer G_i's demand, and supplies power to G_i when the shortage occurs. Let $S_T = S_i + S_j$ denote the total backup capacity in the two markets. We assume G_i and G_j use the same type of generation technology, and so do B_i and B_j. Since the two regions are close to each other, it is reasonable to assume the revenue and cost of backup power in the two regions have no significant difference. Thus we assume a homogeneous electricity price and cost structure for both regions, and thus highlight the difference in their demand functions.

We assume all suppliers have public knowledge on the historical data of customer demand and the intermittency pattern of renewable energy sources. To represent the intermittency pattern in region i, let a series of random variables, x_i^t, $t = 1, ..., m$, denote the shortage faced by G_i at period t. The p.d.f. of x_i^t is $f_i^t(.)$. These random demands need not to be independent. For simplicity we assume the overall shortage cost is linear to the shortage quantity. Though B_i provides backup capacity to cover the shortage, it is possible that in some periods the shortage exceeds the backup capacity ($x_i^t > S_i$). We assume the shortage cost incurred on G_i is $c_u \sum_{t=1}^{m}(x_i - S_i)^+$ (we abbreviate $\max(0, X)$ as $(X)^+$ in this chapter), where $c_u > 0$ is the penalty for each unit of power shortage, including using expensive ancillary services or buying high price power at the balancing market, fine paid to the regional ISO due to demand cutting, reputation loss among the customers, etc.

To prepare the backup power, we assume B_i incurs a capacity cost that is linear to the backup capacity quantity as $c_f S_i$. We assume the variable cost is linear to the power output quantity as $c_v \sum_{t=1}^{m} \min(x_i^t, S_i)$, where c_v represents the unit variable cost related to power generation, including the fuel cost, operation and maintenance, dynamic balancing control, etc. The overall cost function of B_i is $c_f S_i + c_v \sum_{t=1}^{m} \min(x_i^t, S_i)$.

Let r denote the backup power price, and $v = r + c_u - c_v$ denote the unit value of generated power. To ensure the investment on the backup capacity is profitable, we assume $c_v < r$, the variable cost is less than the electricity price; and m is large enough such that $v \sum_{t=1}^{m}(\min(x_t, S_i) + \min(x_t, S_j)) > c_f(S_i + S_j)$, the overall revenue plus saving of shortage cost during m periods of operation is greater than the capacity cost.

Let c_t denote the homogeneous unit transmission cost between two regions, including power loss over distance, renting fee of the transmission lines, reactive power cost, etc. We assume $v > c_t$ such that the interregional power transmission is profitable.

After meeting G_i's and G_j's demands, B_i and B_j can sell the residue capacities on the balancing market if profitable. In this research, we normalize this residue value to zero, and it does not change our main results.

Since the power loss factor is very important in the transmission process, hereby we discuss how to approximate it as a component of the transmission cost. Let $0 < l < 1$ denote the loss percentage, such that for 1 unit sending out the receiver gets $1 - l$ unit. Firstly, for every unit power to be transmitted, the sender need to generate $1/(1-l)$ units of power. Then the enlarged unit variable cost is $c_v/(1-l) = c_v + \Delta c_v$, $\Delta c_v = c_v l/(1-l)$. Secondly, the investment on the backup capacity may also be enlarged. Let S_0 denote the original optimal capacity and $T_0 = \sum_{t=1}^{m} T_0^t$ denote the power to be sent out. After introducing l, the capacity needs to be enlarged to $S_0 + \Delta S$, where $\Delta S = (\max_{t=1\sim m}(x^t + T_0^t/(1-l)) - S_0)^+$. The enlarged capacity incurs extra capacity cost as $c_f \Delta S$, but also brings extra revenue in the local power market as $v \sum_{t=1}^{m} min((x^t - S_0)^+, \Delta S)$. Since ΔS causes deviation from the original optimal capacity, the overall effect is an enlarged capacity cost $\Delta c_f = c_f \Delta S - v \sum_{t=1}^{m} min((x^t - S_0)^+, \Delta S)$. Combining the above two points together, the unit cost associated to the power loss is $\Delta c_f / T_0 + \Delta c_v$. In summary, as the demand distributions are known, for any given power loss percentage l we can estimate its associated cost and then add into the overall transmission cost c_t.

6.1.2 Centralized Model

In the centralized model (Model C), we assume all suppliers form a single centralized firm. Power transmission will occur if one region's backup capacity cannot fully cover the local shortage while the other region has extra backup power. For example, if B_i cannot meet the local demand ($S_i < x_i^t$), it will ask B_j for a transmission quote. If B_j has extra backup capacity after satisfying its own demand ($S_j > x_j^t$), it will transmit all the extra to B_i (because it is profitable). Let $T_{ij}^t = \min((S_i - x_i^t)^+, (x_j^t - S_j)^+)$ denote the power transmitted from region i to region j at period t, and $T_{ij} = \sum_{t=1}^{m} T_{ij}^t$ denote the overall transmitted power. Though in each period $T_{ij}^t T_{ji}^t = 0$, generally $T_{ij}T_{ji} \neq 0$.

Notice in this research we exclude the scenario that G_i directly transmits its power to G_j. We assume the interregional transmission lines are only between B_i and B_j in the grid topology. This assumption reflects the reality that the conventional suppliers are close to major power loads and a well-connected grid have been established to accommodate them. On the contrary, in most cases the renewable power farms are located in remote areas and lack direct transmission lines between them.

Now the centralized firm decides the backup capacities in two regions $\{S_i, S_j\}$ to maximize its profit function as follows, with the feasibility constraints $S_i \geq 0$ and $S_j \geq 0$.

$$\begin{aligned}\Pi^C(S_i, S_j) =& R_i + R_j - c_u(\bar{D}_i + \bar{D}_j) - c_f(S_i + S_j) \\ &+ E\{v \sum_{t=1}^{m} (\min(x_i^t, S_i) + \min(x_j^t, S_j)) + (v - c_t)(T_{ij} + T_{ji})\},\end{aligned} \tag{6.1}$$

where $R_i = \sum_{t=1}^{m} R_i^t$ is a constant denoting the base revenue collected from region i. $\bar{D}_i = \sum_{t=1}^{m} \int_0^\infty x_i^t f_i^t(x_i^t) dx_i^t$, is a constant denoting the overall expected demand (shortage) in region i.

Lemma 6.1 *The profit function in Model C (Equation (6.1)) is concave in (S_i, S_j), and thus the global optimal capacity $\{S_i, S_j\}$ satisfies the following first order condition:*

$$\bar{F}_i(S_i) = m - c_f/v + (1 - c_t/v)(\bar{\beta}_{ij}(S_i, S_j) - \bar{\gamma}_{ij}(S_j, S_j)) \tag{6.2}$$

$\{\bar{F}_i, \bar{\beta}_{ij}, \bar{\gamma}_{ij}\}$ are summations of m event probabilities in region i. Their properties are as follows:

- $\bar{F}_i = \sum_{t=1}^{m} F_i^t$, where $F_i^t = Pr\{x_i^t < S_i\}$ (c.d.f. of the random variable x_i^t), is the probability that the local demand is less than the local capacity at period t. And then $\bar{F}_i$ is the expected number of periods that there is no shortage locally.

- $\bar{\beta_{ij}} = \sum_{t=1}^{m} \beta_{ij}^t$, where $\beta_{ij}^t = Pr\{x_j^t - S_j > S_i - x_i^t > 0\} = \partial E\{T_{ij}^t\}/\partial S_i$, is the probability that all the extra power of region i is needed to cover the shortage in region j at period t (Event E_i). $\bar{\beta_{ij}}$ is the expected number of periods that Event E_i happens.

- $\bar{\gamma_{ij}} = \sum_{t=1}^{m} \gamma_{ij}^t$, where $\gamma_{ij}^t = Pr\{S_j - x_j^t > x_i^t - S_i > 0\} = -\partial E\{T_{ji}^t\}/\partial S_i$, is the probability that the extra power of region j is more than enough to cover the shortage in region i at period t (Event I_i). $\bar{\gamma_{ij}}$ is the expected number of periods that Event I_i happens.

- If $\bar{\beta_{ij}} > \bar{\gamma_{ij}}$, region i is a "net exporter", i.e., the probability of sending power is higher than of receiving power; if $\bar{\beta_{ij}} < \bar{\gamma_{ij}}$, region i is a "net importer", i.e., the probability of receiving power is higher than of sending power. Please notice that a "net importer" might still export in some periods, and vice versa.

In Chapter 5 we have showed the interior solution property without the power transmission ($\bar{F}_i(S_i) = m - c_f/v > 0$ such that $S_i > 0$). Hereby to keep $S_i > 0$ with the power transmission feature, we need an additional condition $(1 - c_t/v)(\bar{\beta_{ij}}(S_i, S_j) - \bar{\gamma_{ij}}(S_j, S_j)) > -(m - c_f/v)$. The economical meaning is that the scales of power shortage in the two regions will not be extremely different. For example, assuming region j has a power shortage much larger than region i, then the centralized firm will build a large backup capacity in region j, and region i can always import from j and thus does not need a local backup capacity. In our research, we do not consider this heavily unbalanced scenario with only unidirectional transmission.

No transmission scenario (N)

To highlight the effect of interregional transmission, hereby we consider a no transmission scenario, which may be due to a lack of power lines or a heavy transmission loss making the power transmission uneconomical. The decisions in the two regions are independent in this case. The centralized firm decides the backup capacity S_i to maximize its profit in region i as follows, with the feasibility constraints $S_i \geq 0$ and $S_j \geq 0$.

$$\Pi_i^N(S_i) = R_i - c_u\bar{D}_i + E\{v\sum_{t=1}^{m}\min(x_i^t, S_i)\} - c_f S_i. \tag{6.3}$$

By comparing to the transmission scenario, it is easy to see $\Pi^C = \Pi_i^N + \Pi_j^N + E\{(v - c_t)(T_{ij} + T_{ji})\}$, such that $\Pi^C > \Pi_i^N + \Pi_j^N$ given $v > c_t$. In another word, the practice of power transmission is profitable if the value of backup power is greater than the transmission cost.

Lemma 6.2 *There exists a unique global optimal capacity $\{S_i, S_j\}$ in Model N which is determined by the following condition:*

$$\bar{F}_i(S_i^N) = m - c_f/v. \tag{6.4}$$

Comparing to the optimal capacity S_i in Model C, $S_i^N > (<) S_i$ if $\bar{\beta_{ij}} > (<) \bar{\gamma_{ij}}$.

Notice Model N is same to the centralized model in Chapter 5 and leads to the classical newsvender solution. Comparing Equation 6.2 and 6.4, the solution of capacities in the transmission scenario is an adjustment on the no-transmission solution based on the probability of power import and export. If region i is a "net exporter" ($\bar{\beta_{ij}} > \bar{\gamma_{ij}}$), the capacity in the transmission scenario is higher than in the no transmission scenario; if the trend reverses and region i becomes a "net importer", the capacity in the transmission scenario is lower. In summary, after allowing the power transmission, whether the backup capacity will increase or decrease depends on the demand distributions. This uncertainty is also discussed by Rudi et al. (2001), Dong and Rudi (2004), Hu et al. (2007) and Shao et al. (2011) in their respective model settings.

6.1.3 Horizontally Decentralized Model

In this section we study a horizontally independent structure (Model H) where each region has one supplier owning both the renewable and the conventional generators. There are a pair of transmission prices $\{p_{ij}^H, p_{ji}^H\}$ charged for the interregional power transmission, where p_{ij}^H is the price region i charges to region j and vice versa. We assume the power exporter bears the transmission cost and $c_t + c_v < p_{ij}^H(p_{ji}^H) < r + c_u$, such that the power transmission is profitable for both the exporter and the importer. The profit function of the supplier of region i is as follows, with the feasibility constraint $S_i \geq 0$.

$$\Pi_i^H(S_i, S_j) = R_i - c_u\bar{D}_i - c_f S_i + E\{v\sum_{t=1}^{m}\min(x_i^t, S_i) + (p_{ij}^H - c_t - c_v)T_{ij} + (r + c_u - p_{ji}^H)T_{ji}\}. \tag{6.5}$$

Comparing to Equation (6.1), it is easy to see Model H's total profit $\Pi^H = \Pi_i^H + \Pi_j^H = \Pi^C$ in Model C. Assuming the parameter values ensure an interior solution, the equilibrium decision of the supplier in region i can be described as follows.

Lemma 6.3 *There exists a unique equilibrium capacity $\{S_i, S_j\}$ in Model H which is determined by the following conditions:*

$$\bar{F}_i(S_i) = m - c_f/v + \frac{p_{ij}^H - c_t - c_v}{v}\bar{\beta}_{ij}(S_i, S_j) - \frac{r + c_u - p_{ji}^H}{v}\bar{\gamma}_{ij}(S_j, S_j) \tag{6.6}$$

We assume $\{p_{ij}^H, p_{ji}^H\}$ are stable equilibrium prices negotiated by the two regional suppliers after deliberate consideration and properly reflect each supplier's market power. We find that there exists a pair of $\{p_{ij}^H, p_{ji}^H\}$ which coordinate the system and drive the two suppliers' decisions achieve the global optimum, as the following lemma shows.

Lemma 6.4 *The system is coordinated when* $\{p_{ij}^H, p_{ji}^H\}$ *satisfy the following condition:*

$$p_{ij}^H = \frac{\bar{\beta_{ij}}\bar{\beta_{ji}}(r+c_u) - \bar{\gamma_{ij}}(\bar{\beta_{ji}}(r+c_u-c_t-c_v)+\bar{\gamma_{ji}}(c_t+c_v))}{\bar{\beta_{ij}}\bar{\beta_{ji}} - \bar{\gamma_{ij}}\bar{\gamma_{ji}}}. \tag{6.7}$$

And then the equilibrium decisions $\{S_i, S_j\}$ are the same as in Model C (Lemma 6.1), and will also be an interior solution giving the same assumptions of parameter values in Model C. Please see Rudi et al. (2001) and Hu et al. (2007) for more discusses on the coordinating transmission prices in a horizontally decentralized scenario. Hereby we emphasize the property that the best performance of Model H is equivalent to the centralized model, and it bridges between the centralized structure and the other two structures: the decentralized model and the coordination model.

6.1.4 Decentralized Model

The decentralized model (Model D) serves as a baseline case that the four suppliers operate independently. $B_i(B_j)$ sells backup power to $G_i(G_j)$ at a wholesale price w, and the transmission prices between B_i and B_j are $\{p_{ij}^D, p_{ji}^D\}$, where p_{ij}^D is the price B_i charges to B_j and vice versa. The amount of revenue G_i gains from selling electricity is $(r-w)(\sum_{t=1}^{m}\min(x_i^t, S_i)+T_{ji})$ and B's revenue is $(w-c_v)(\sum_{t=1}^{m}\min(x_i^t, S_i)+T_{ji})$. We assume all suppliers' margins are positive, that is $r > w > c_v$. B_i decides S_i to maximize its profit as follows, with the feasibility constraint $S_i \geq 0$.

$$\Pi_{B_i}^D(S_i, S_j) = E\{(w-c_v)\sum_{t=1}^{m}\min(x_i^t, S_i)+(p_{ij}^D-c_t-c_v)T_{ij}+(w-p_{ji}^D)T_{ji}\}-c_f S_i. \tag{6.8}$$

G_i is not a decision maker and its profit is

$$\Pi_{G_i}^D = R_i - c_u(\bar{D}_i - E\{\sum_{t=1}^{m}\min(x_i^t, S_i)+T_{ji}\}).$$

The system profit of decentralized model takes the same form as in the centralized model shown in Equation 6.1. Assuming the parameter values ensure an interior solution, the equilibrium decision of the supplier in region i can be described as follows.

Lemma 6.5 *There exists a unique equilibrium capacity $\{S_i, S_j\}$ in Model D which is determined by the following conditions:*

$$\bar{F}_i(S_i) = m - \frac{c_f}{w - c_v} + \frac{p_{ij}^D - c_t - c_v}{w - c_v}\bar{\beta_{ij}}(S_i, S_j) - \frac{r + c_u - p_{ji}^D}{w - c_v}\bar{\gamma_{ij}}(S_j, S_j) \qquad (6.9)$$

The optimal transmission prices $\{p_{ij}^D, p_{ji}^D\}$ are:

$$p_{ij}^D = \frac{\bar{\beta_{ij}}\bar{\beta_{ji}}w - \bar{\gamma_{ij}}(\bar{\beta_{ji}}(w - c_t - c_v) + \bar{\gamma_{ji}}(c_t + c_v))}{\bar{\beta_{ij}}\bar{\beta_{ji}} - \bar{\gamma_{ij}}\bar{\gamma_{ji}}}$$

Similar to the analysis for the decentralized model in Chapter 5, to ensure an interior solution, the wholesale price w needs to be large enough such that the right hand side of Equation (6.9) is greater than zero. Notice the above condition is similar to Model H with the only difference to replace $r + c_v$ with w. An intuitive explanation is, though the backup power should have a unit value of $r + c_u$ from the entire system's point of view, the decentralized backup power suppliers would only evaluate it as w, which is an underestimation and leads to the following result.

Lemma 6.6 *Under the decentralized model, the total backup capacity S_T in the two regions is less than the global optimum as under the centralized model. S_T decreases when the wholesale price w decreases.*

This property reveals that the decentralized model leads to an under investment of the backup capacity, and if the wholesale price decreases such under investment will be worse. The system profit in this baseline case is less than in the centralized model. It is because in the decentralized model the conventional suppliers only concern their own profits without considering the renewable suppliers' shortage cost. On the other hand, the renewable suppliers do not offer any incentive to share the risk of investing on the backup capacity with the conventional suppliers.

6.1.5 Coordination Model

We design a coordination contract (Model P) aiming to provide an incentive for the conventional suppliers to prepare enough backup capacity to the renewable suppliers. The contract is established on top of the backup power transactions from $B_i(B_j)$ to $G_i(G_j)$ with a wholesale price w, and the interregional transmission between B_i and B_j with a pair of transmission prices $\{p_{ij}, p_{ji}\}$, where p_{ij} is the price B_i charges to B_j and vice versa. G_i and G_j set a coordination parameter ρ which determines a free TGC offering rate and a local transmission premium, and a pair of interregional transmission premiums $\{\delta_{ij}, \delta_{ji}\}$.

Firstly, the quantity of free TGC that G_i offers to B_i is $\rho c_f S_i$, where S_i is the backup capacity prepared by B_i. In this research we assume each renewable supplier generates sufficient TGC to offer and sells the rest in the national TGC market. Secondly, though for the locally generated backup power G_i just pays the wholesale price w to B_i, for the transmitted power G_i will pay $w+\mu c_t$ to B_i, where μc_t is a local transmission premium. Notice B_i will send a portion of this payment $w+\mu c_t$ to B_j as p_{ji}. Lastly, for the transmitted power G_i will also pay an interregional premium δ_{ji} to G_j, because G_j contributes to the preparation of backup capacity in region j by offering TGC to B_j. Notice all suppliers can easily monitor how much power is transmitted per period because they know the quantity of power shortage and the maximal backup capacity in each region. Please see Figure 6.1 for the timeline of the contract.

The coordination model is shown in Figure 6.2. The contract defines a Stackelberg game where the sequence of events is as follows.
Stage 1: G_i and G_j set the coordination parameter ρ and the transmission premiums $\{\delta_{ij}, \delta_{ji}, \mu\}$; B_i and B_j set the transmission prices $\{p_{ij}, p_{ji}\}$.

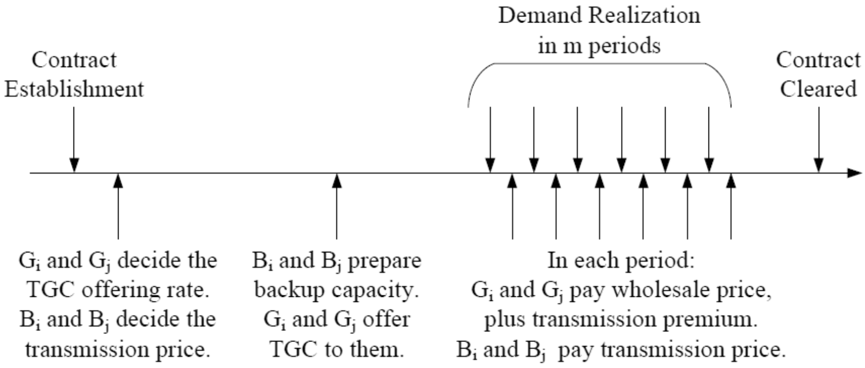

Figure 6.1: Timeline of the Coordination Contract

Stage 2: $B_i(B_j)$ prepares the backup capacity $S_i(S_j)$.

The profit functions of the suppliers in the coordination model are as follows.

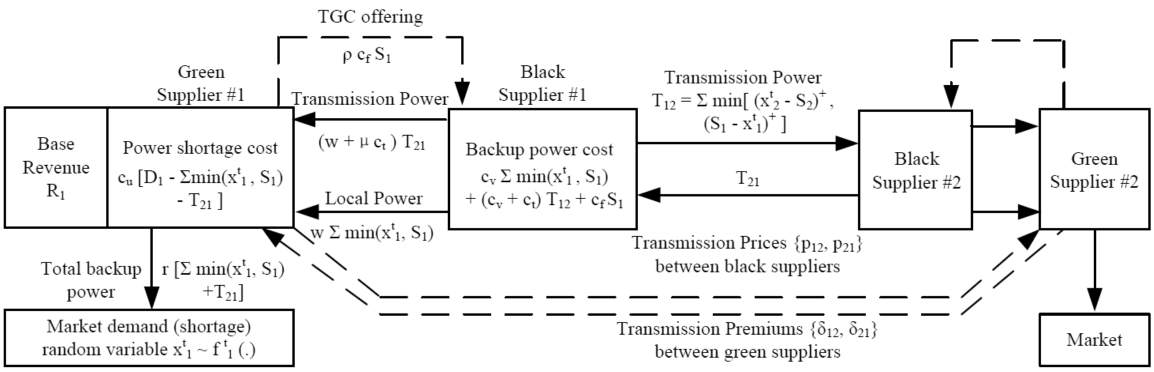

Figure 6.2: The Market Structure of Coordination Contract

$$
\begin{cases}
\Pi_{G_i}(S_i, S_j) = E\{(r + c_u - w)\sum_{t=1}^{m}\min(x_i^t, S_i) + (r + c_u - w - \mu c_t - \delta_{ji})T_{ji} + \delta_{ij}T_{ij}\} \\
\qquad\qquad - \rho c_f S_i + R_i - c_u \bar{D}_i \\
\Pi_{B_i}(S_i, S_j) = E\{(w - c_v)\sum_{t=1}^{m}\min(x_i^t, S_i) + (p_{ij} - c_v - c_t)T_{ij} + (w + \mu c_t - p_{ji})T_{ji}\} \\
\qquad\qquad - (1 - \rho)c_f S_i
\end{cases}
\tag{6.10}
$$

6.2 Analytical Results

In this section we firstly perform the coordination analysis to show that the coordination contract drives the conventional suppliers prepare backup capacity at the global optimal level. Then we perform the sensitivity analysis to reveal more properties of the coordination model.

6.2.1 Coordination Analysis

Theorem 6.1 *The coordination model has the following properties.*

- *The system achieves coordination when the parameters* $(\rho, \delta_{ij}, p_{ij}, \mu)$ *satisfy the following conditions:*

$$\begin{cases} \rho = \dfrac{r + c_u - w}{r + c_u - c_v} \\ \delta_{ij} = \rho p_{ij}^H - \rho(c_v + c_t) \\ p_{ij} = (1-\rho)p_{ij}^H + \rho(c_v + c_t) \\ \mu = \rho \end{cases} \tag{6.11}$$

  where $p_{ij}^H = \dfrac{\bar{\beta_{ij}}\bar{\beta_{ji}}(r + c_u) - \bar{\gamma_{ij}}(\bar{\beta_{ji}}(r + c_u - c_t - c_v) + \bar{\gamma_{ji}}(c_t + c_v))}{\bar{\beta_{ij}}\bar{\beta_{ji}} - \bar{\gamma_{ij}}\bar{\gamma_{ji}}}.$

- *When the system is coordinated, there exists a unique global optimal solution of backup capacities which simultaneously maximizes the system profit and the profit of each supplier. The solution is the same as in the centralized model (Equation 6.2).*

The coordination property is based on the design of the coordination mechanism. By offering free TGC and paying transmission premiums, the renewable suppliers share a portion of the system risk with the conventional suppliers which encourages the latter investing on the backup capacity at the global optimal level. To intuitively explain the coordination conditions specified in Theorem 6.1, let us compare the profit functions with Model H. When $\{\rho, \delta_{ij}, p_{ij}, \mu\}$ meet the coordination conditions defined in Equation 6.11, we have

$$\begin{cases} \Pi_{G_i}(S_i, S_j) = \rho\Pi_i^H(S_i, S_j) + (1-\rho)(R_i - c_u\bar{D}_i) \\ \Pi_{B_i}(S_i, S_j) = (1-\rho)\Pi_i^H(S_i, S_j) - (1-\rho)(R_i - c_u\bar{D}_i) \end{cases}$$

where Π_i^H is the profit of region i in Model H. Then there exists a global optimal $\{S_i, S_j\}$ to simultaneously maximize $\{\Pi_i^H, \Pi_{G_i}, \Pi_{B_i}\}$. From Lemma 6.4 we know Model H has the same solution of capacities $\{S_i, S_j\}$ and the same system profit as the centralized model. Therefore, the optimal capacity in the coordination model reaches the global optimum as described in the centralized model (Equation 6.2).

6.2.2 Profit Split Among The Players

Please see Table 6.1 which shows that when the system is coordinated, for one unit of power transmitted from region i to j, how the profit is split among the four suppliers.

Total unit revenue $(r + c_u - c_v - c_t)$			
Region i $(p_{ij}^H - c_v - c_t)$		Region j $(r + c_u - p_{ij}^H)$	
B_i	G_i	B_j	G_j
$(1-\rho)(p_{ij}^H - c_v - c_t)$	$\rho(p_{ij}^H - c_v - c_t)$	$(1-\rho)(r + c_u - p_{ij}^H)$	$\rho(r + c_u - p_{ij}^H)$

Table 6.1: The Profit Split between Suppliers in a Coordinated System

Besides the payment structure defined in Model P, there are also other equivalent forms of payment structure to achieve coordination, as long as they split the revenue as indicated in Table 6.1. In Figure 6.3, the left part shows the payment structure of Model P when one unit of power is transmitted from B_i to G_j through B_j, and the right part shows an alternative structure where B_i's power is directly transmitted to G_j. In the alternative structure, firstly G_j pays $w + \mu c_t + \delta_{ij}$ to B_i (receiver to sender), then B_i shares δ_{ij} to G_i and $w + \mu c_t - p_{ij}$ to B_j. G_i gets a portion of the profit because it offers TGC as part of the investment for B_i's capacity. For the profit sharing between B_i and B_j, it can be viewed as that they co-invest on the capacities in the two regions, and then share the profit generated in each region in a coordinated manner, such that the investments in their respective regions will be driven to the global optimal level. The alternative form is suitable for regions where $B_i(B_j)$ has direct connection through power grids to $G_j(G_j)$. It is equivalent to Model P, and thus also achieves coordination.

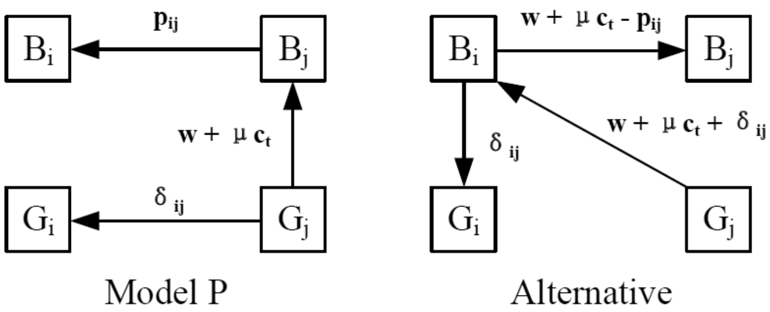

Figure 6.3: An Alternative Coordination Payment Structure

6.2.3 Sensitivity Analysis

In this section we examine the impacts of market conditions on the suppliers' decisions and their profits in the coordination model. We consider the following market conditions: the electricity price (r), the shortage cost (c_u), the variable cost (c_v), the capacity cost (c_f), and the transmission cost (c_t). Then we consider their impacts on the following decisions and profits: the TGC offering rate from the renewable suppliers to the conventional suppliers (ρ), the total capacity (S_T) or the capacity in region i (S_i) if applicable, the renewable suppliers' profits ($\Pi_G = \Pi_{G_i} + \Pi_{G_j}$), the conventional suppliers' profits ($\Pi_B = \Pi_{B_i} + \Pi_{B_j}$), and the total profit ($\Pi^C = \Pi_G + \Pi_B$). For those decisions not only depending on the market conditions but also on the demand distributions, such as the transmission prices (p_{ij}), since their trends are uncertain under a general demand distribution and thus complicate to analyze, we do not include them here. At the end of this section we summarize the results in Table 6.2.

Impacts on the suppliers' decisions: backup capacity and TGC offering rate

Proposition 6.1 *The impacts of market conditions on the backup capacity and the TGC offering rate are as follows.*

- *When the electricity price (r) increases or the shortage cost (c_u) increases, both the TGC offering rate (ρ) and the total capacity (S_T) increase.*
- *When the variable cost (c_v) increases, the TGC offering rate (ρ) increases but the total capacity (S_T) decreases.*
- *When the capacity cost (c_f) increases, the TGC offering rate (ρ) keeps the same. The capacity in region i (S_i) decreases.*
- *When the transmission cost (c_t) increases, the TGC offering rate (ρ) keeps the same. The capacity in region i (S_i) increases (decreases) when $\bar{\beta}_{ij} < (>) \bar{\gamma}_{ij}$.*

The first result reveals that when the backup power becomes more valuable, the renewable suppliers offer more TGC to encourage the conventional suppliers investing more on the backup capacities. The second result reveals that higher variable cost leads to heavier cost burden for the conventional suppliers, and their investments on the backup capacity decrease. Facing this change, the renewable suppliers will increase the TGC offering rate to encourage the conventional suppliers' investments. In the third result, higher capacity cost discourages the conventional suppliers' investments. Though the TGC offering rate keeps the same, the quantity of TGC offered by the renewable suppliers increases because it is proportional to the capacity cost.

In the last result when the transmission cost increases, firstly the TGC offering rate keeps the same because the coordination condition is unaffected by the transmission cost. Secondly, the impact on region i's backup capacity depends on whether this region is more possible to export or import. As discussed in Section 6.1, $\bar{\beta_{ij}}$ measures the probability of export and $\bar{\gamma_{ij}}$ measures the probability of import. If $\bar{\beta_{ij}} < \bar{\gamma_{ij}}$ (region i is an "net importer" in the sense of probability), when the transmission cost increases, the investment on local capacity increases to save the transmission fee; if $\bar{\beta_{ij}} > \bar{\gamma_{ij}}$ such that region i is an "net exporter", higher transmission cost discourages the investment on local capacity.

Impacts on the profits

Proposition 6.2 *The impacts of market conditions on the total profit and the suppliers' profits are as follows.*

- *When the electricity price (r) increases, the variable cost (c_v) decreases, the capacity cost (c_f) decreases, or the transmission cost c_t decreases, the total profit (Π^C) increases. Both the renewable suppliers' profits (Π_G) and the conventional suppliers' profits (Π_B) increase.*
- *When the shortage cost (c_u) increases, the total profit (Π^C) decreases, the renewable suppliers' profits (Π_G) decrease but the conventional suppliers' profits (Π_B) increase.*

This result reveals that when there are favorable (unfavorable) changes in most market conditions, the system profit increases (deceases) and the suppliers share the benefit (cost). The only exception is when the shortage cost increases, the renewable suppliers needs more backup capacity to cover the power shortage. Such that they offer more TGC to the conventional suppliers (Proposition 6.1), which leads to a decrease of the renewable suppliers' profits but an increase of the conventional suppliers' profits.

The sensitivity analysis results are summarized in Table 6.2.

	ρ	S_T	Π^C	Π_G	Π_B
$r \uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$c_u \uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$
$c_v \uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
$c_f \uparrow$	$\rightarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
$c_t \uparrow$	$\rightarrow$	$\updownarrow$	$\downarrow$	$\downarrow$	$\downarrow$

Table 6.2: Summary of the Sensitivity Analysis in Chapter 6

6.3 Numerical Analysis

Hereby we perform numerical analysis to illustrate the robustness of the coordination model, that when the TGC offering rate deviates from the optimal point, the system profit will not be significantly impacted. The parameter values presented in this section are of illustrative purpose and do not refer to a specific market. The data setting is $\{c_u = 4, r = 2.1, c_v = 0.1, c_f = 0.9, c_t = 4, R = 500\}$. The demand functions in region i are a series of normal distribution as $\{x_i^t \sim N(\mu_i^t, \sigma_i^t), t = 1 \sim 4\}$ where $\{\mu_i^1 = 35, \mu_i^2 = 45, \mu_i^3 = 55, \mu_i^4 = 65, \sigma_i^1 = \sigma_i^2 = \sigma_i^3 = \sigma_i^4 = 10\}$. The demand functions in region j are $\{x_j^t \sim N(\mu_j^t, \sigma_j^t), t = 1 \sim 4\}$ where $\{\mu_j^1 = 38, \mu_j^2 = 46, \mu_j^3 = 54, \mu_j^4 = 62, \sigma_j^1 = \sigma_j^2 = \sigma_j^3 = \sigma_j^4 = 10\}$. We perform a Monte Carlo simulation in Matlab to generate 1000 scenarios based on the above distributions and each scenario is equally weighted.

Due to the complexity nature of power markets with renewable penetration, it is difficult to accurately estimate and predict all market conditions. Thus the renewable suppliers may not make a perfect TGC offering rate ρ at its optimal point which is 0.783 given the above parameters. To study the impacts of inaccurate TGC offering rate on the total profit, we allow an error of $\pm 15\%$ of the optimal point $(0.666 \sim 0.9)$. We find that the performance of the coordination model is robust. As shown in Figure 6.4, even when ρ deviates from the optimal point to $\pm 15\%$, the total profit loss of coordination model is only up to 6.7% (the percentage is calculated as $(343-320)/343$, after dropping the basic revenue $R = 500$). The reduced profit 820 is still higher than the best performance of decentralized model at 730.7 (achieved by fixing $w = r$ such that the double marginalization is eliminated).

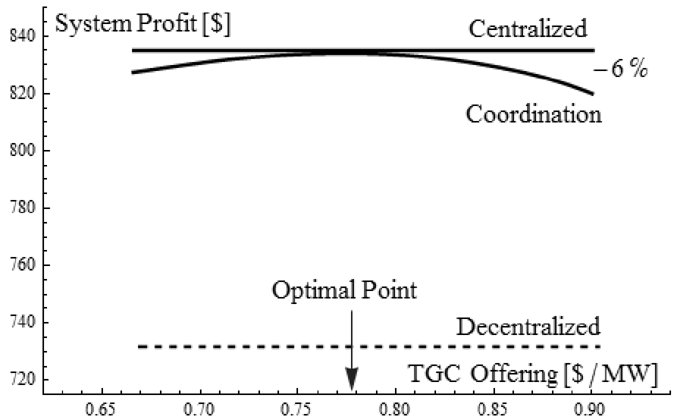

Figure 6.4: Robustness of the Coordination Contract

6.4 Summary of Chapter 6

This chapter studies a coordination framework between renewable suppliers and conventional suppliers in regional electricity markets with interregional power transmission. The energy sources of the renewable suppliers are intermittent and lead to random power shortage. To encourage the conventional suppliers to prepare enough backup capacities to cover the shortage, we design a coordination mechanism as follows. The renewable suppliers offer free tradable green certificates and deposit them into a pool. The conventional suppliers withdraw from the pool based on their contributions in the preparation of backup capacities. The renewable suppliers decide their respective TGC offering rates, and the conventional suppliers decide the power transmission prices and then the quantities of backup capacities.

We solve the close-form solution of this coordination model, and prove that the contract achieves the system coordination. We study a baseline case without coordination and prove the baseline case leads to under investment of the backup capacity, and the system profit of the baseline case is less than the coordination model. We show the coordination mechanism is robust, that if the TGC offering rate deviates from the optimal point, the system profit will not decrease significantly.

We conduct sensitivity analysis to find the impacts of following market conditions. Firstly, when the electricity price increases, both the total capacity and the TGC offering rate increase. All suppliers' profits and the system profit increase. Secondly, when the shortage cost increases, both the total capacity and the TGC offering rate increase. The system profit and the renewable suppliers' profits decrease, but the conventional suppliers' profits increase. Thirdly, when the capacity cost increases, the capacity in each region decreases while the TGC offering rate keeps the same. All suppliers' profits and the system profit decrease. Fourthly, when the variable cost increases, the total capacity decreases while the TGC offering rate increases. All suppliers' profits and the system profit decrease. Lastly, When the transmission cost increases, the TGC offering rate keeps the same. The capacity in a region increases (decreases) if this region is more possible to import (export) backup power. All suppliers' profits and the system profit decrease.

CHAPTER 7

CONCLUSIONS

This dissertation studies impacts of RPS regulation on regional electricity markets and firms' coordination behavior facing RPS regulation. Our research efforts can be divided into the following three parts.

Firstly, we establish analytical models for a monopoly market and a duopoly market. We solve the models and analyze the impacts of TGC price and RPS percentage on the green/black energy outputs, the electricity price and the suppliers' profit. We reveal that the increase of local RPS percentage may not guarantee an increase of local green output. Our analytical results indicate that the green power output decreases when the RPS percentage increases in the regional electricity market if the TGC price in the national market remains unchanged. In contrast, a higher TGC price can effectively promote the local green power output. A collective effort of increasing RPS percentage by many regions increases the overall demand of TGC across the country, and the national TGC price will increase. In summary, we suggest the regional regulators to set up their RPS development plans carefully in a synchronized way.

We compare the difference between two structures with numerical analysis. In the duopoly structure, the electricity price and suppliers' profits are lower, and the total electricity supply is higher than in the monopoly structure. The electricity outputs change slower when the TGC price increases in the duopoly structure than in the monopoly structure. The monopoly supplier only needs to pay attention to cost reduction and can respond rapidly; while the suppliers in the duopoly structure need to be concerned with both cost reduction and keeping their market shares. To maximize the social welfare, the optimal RPS percentage in the duopoly structure is higher than in the monopoly structure.

Secondly, we study a coordination contract based on TGC offering between a renewable supplier and a conventional supplier in a single region market. The energy sources of the renewable suppliers are intermittent and lead to random power shortage. To encourage the conventional supplier to build backup capacity to cover the shortage, we design a coordination contract where the renewable supplier offers the conventional supplier free tradable green certificate proportional to the backup capacity. The renewable supplier decides the TGC offering rate and the wholesale price of backup power, and then the conventional supplier decides the quantity of backup capacity. We prove the contract achieves the system coordination. The system profit can be arbitrarily allocated between the two suppliers by adjusting the wholesale price. We study a baseline case without coordination and prove the baseline case leads to under investment of the backup capacity. By comparing to the baseline case, we find the coordination model can achieve Pareto improvement for both suppliers.

Sensitivity analysis is conducted on the impacts of following market conditions. Firstly, when the fixed cost increases, the backup capacity decreases and the TGC offering rate increases. Both suppliers' profits decrease and the total profit decreases. Secondly, when the electricity price increases or the variable cost decreases, the backup capacity increases and the TGC offering rate decreases. Both suppliers' profits increase and the total profit increases. Lastly, when the shortage cost increases, the backup capacity increases and the TGC offering rate increases. The total profit decreases, the renewable supplier's profit decreases but the conventional supplier's profit increases. Social welfare analysis is conducted, and we find that the social welfare of the coordination structure will be greater than of the baseline case unless the environmental damage of conventional power is extremely high.

Thirdly, we study a capacity coordination mechanism based on TGC offering and transmission premium in a two-region market with interregional transmission. The renewable suppliers offer free tradable green certificates and pay transmission premiums to encourage the conventional suppliers to prepare enough backup capacity. The renewable suppliers decide the TGC offering rates and the transmission premiums, and the conventional suppliers decide the power transmission prices and then the quantities of backup capacities. We prove the above mechanism achieves the system coordination. We study a baseline case without coordination and prove the baseline case leads to under investment of the backup capacity, and the system profit of the baseline case is less than the coordination model. We show the coordination mechanism is robust, that if the TGC offering rate deviates from the optimal point, the system profit will not decrease significantly.

We conduct sensitivity analysis to find the impacts of following market conditions. Firstly, when the electricity price increases, both the total capacity and the TGC offering rate increase. All suppliers' profits and the system profit increase. Secondly, when the shortage cost increases, both the total capacity and the TGC offering rate increase. The system profit and the renewable suppliers' profits decrease, but the conventional suppliers' profits increase. Thirdly, when the fixed cost increases, the capacity in each region decreases while the TGC offering rate keeps the same. All suppliers' profits and the system profit decrease. Fourthly, when the variable cost increases, the total capacity decreases while the TGC offering rate increases. All suppliers' profits and the system profit decrease. Lastly, When the transmission cost increases, the TGC offering rate keeps the same. The capacity in a region increases (decreases) if this region is more possible to import (export) backup power. All suppliers' profits and the system profit decrease.

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APPENDIX A

PROOFS

Proof of Lemma 4.1

Proof. The monopoly supplier's profit function is twice differentiable as follows:
$\Pi(S_B, S_G) = [\frac{\alpha - S_B - S_G}{\beta}(S_B + S_G)] - [c_B(S_B) + \lambda c_T S_B] - [c_G(S_G) - (1-\lambda)c_T S_G]$.

At its local maximum the first order derivatives equal to zero:

$$\begin{cases} \dfrac{\partial \Pi}{\partial S_B} = \dfrac{\alpha - 2S_B - 2S_G}{\beta} - c'_B(S_B) - \lambda c_T = 0 \\ \dfrac{\partial \Pi}{\partial S_G} = \dfrac{\alpha - 2S_B - 2S_G}{\beta} - c'_G(S_G) + (1-\lambda)c_T = 0 \end{cases}$$

According to Bertsekas (1999), to ensure the strict concavity of $\Pi(S_B, S_G)$ such that its local maximum is the unique global maximum, the Hessian matrix of $\Pi(S_B, S_G)$ should be negative definite. This is equivalent to the following conditions:

$$\begin{cases} 2c''_B + 2c''_G + \beta c''_B c''_G > 0 \\ c''_B > -2/\beta \\ c''_G > -2/\beta \end{cases}$$

Given $c''_{B/G} > 0$, the above conditions are satisfied. ■

Proof of Lemma 4.2

Proof. The black supplier's payoff function is twice differentiable as follows:
$\Pi_B(S_B) = \frac{\alpha - S_B - S_G}{\beta} S_B - c_B(S_B) - \lambda c_T S_B$.
The green supplier's payoff function is twice differentiable as follows:

$$\Pi_G(S_G) = \frac{\alpha - S_B - S_G}{\beta} S_G - c_G(S_G) + (1-\lambda) c_T S_G.$$

According to Theorem 2 of Rosen (1965), the payoff functions $\{\Pi_B, \Pi_G\}$ need to be diagonally strictly concave to ensure the existence of unique Nash equilibrium. Let $\vec{S} = (S_B, S_G)^T$ and $\vec{\Pi} = (\Pi_B, \Pi_G)^T$. With the notations of our model, $\vec{\Pi}$ is diagonally strictly concave for every $\vec{S} \in R$, if for every $\vec{S}^0 \in R$ and a different $\vec{S}^1 \in R$ we have

$$(\vec{S}^1 - \vec{S}^0)^T \nabla \vec{\Pi}(\vec{S}^0) + (\vec{S}^0 - \vec{S}^1)^T \nabla \vec{\Pi}(\vec{S}^1) > 0$$

A sufficient condition to ensure diagonally strictly concavity can be built as follows. Let J be the Jacobian of payoff functions $\{\Pi_B, \Pi_G\}$, we have:

$$J = \begin{bmatrix} -2/\beta - c_B''(S_B) & -1/\beta \\ -1/\beta & -2/\beta - c_G''(S_G) \end{bmatrix}$$

It is easy to verify $J + J^T$ is negative definite. According to Theorem 6 of Rosen (1965), the payoff functions are diagonally strictly concave. And then a unique Nash equilibrium exists. ■

Proof of Proposition 4.1

Proof. From equation (4.4) we have the close-form solution of $\{S_B, S_G\}$ in the monopoly market. The electricity price p and the monopoly supplier's profit Π can be derived from $\{S_B, S_G\}$. Take a derivative on λ for $\{p, \Pi, S_B, S_G\}$, we have

$$\frac{\partial p}{\partial \lambda} > 0; \frac{\partial \Pi}{\partial \lambda} < 0; \frac{\partial S_B}{\partial \lambda} < 0; \frac{\partial S_G}{\partial \lambda} < 0$$

$\forall \lambda \in R$, given the assumptions for other parameter values hold. For example,

$$\frac{\partial p}{\partial \lambda} = \frac{c_T(b_2 + g_2)}{2(g_2 + b_2(1 + \beta g_2))}.$$

Then given the assumptions of $\{c_T, b_2, g_2, \beta\} > 0$ specified in the model description, $\frac{\partial p}{\partial \lambda} > 0 \ \forall \lambda \in R$.

From equation 4.5, we analyze the impact of λ in the duopoly market and have similar results. ■

Proof of Proposition 4.2

Proof. For both market structures, take a derivative on c_T for $\{S_B, S_G\}$, we have $\partial S_B/\partial c_T < 0$ and $\partial S_G/\partial c_T > 0$, $\forall c_T \in R$, given the assumptions for other parameter values hold.

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For the monopoly structure, take a derivative on c_T for the total profit Π:

$$\frac{\partial \Pi}{\partial c_T} = \frac{c_T - g_1 + (-1+\lambda)b_2(-\alpha + \beta(-1+\lambda)c_T + \beta g_1) - \alpha\lambda g_2 + \beta\lambda^2 c_T g_2 + b_1(1+\beta\lambda g_2)}{2(g_2 + b_2(1+\beta g_2))}.$$

Let

$$\bar{c}_{TM} = \frac{\alpha\lambda g_2 - \alpha(1-\lambda)b_2 + g_1 + \beta(1-\lambda)b_2 g_1 - b_1(1+\beta\lambda g_2)}{1 + \beta(1-\lambda)^2 b_2 + \beta\lambda^2 g_2}$$

denote the threshold. When $c_T < \bar{c}_{TM}$, $\partial\Pi/\partial c_T < 0$. When $c_T > \bar{c}_{TM}$, $\partial\Pi/\partial c_T > 0$. That is, when c_T increases, the profit first decreases then increases.

For the duopoly structure, take a derivative on c_T for the total profit, and a similar threshold $\bar{c}_{TN}$ can be found.

By taking a derivative on c_T for the black/green suppliers' profits $\Pi_{B/G}$, we have $\partial\Pi_B/\partial c_T < 0$ and $\partial\Pi_G/\partial c_T > 0$, $\forall c_T \in R$, given the assumptions for other parameter values hold.

For the monopoly structure, take a derivative on c_T for the electricity price p:

$$\frac{\partial p}{\partial c_T} = \frac{(-1+\lambda)b_2 + \lambda g_2}{2(g_2 + b_2(1+\beta g_2))}.$$

When $\lambda < \bar{\lambda}_M = b_2/(b_2 + g_2)$, $\partial p/\partial c_T < 0$. When $\lambda > \bar{\lambda}_M$, $\partial p/\partial c_T > 0$.

For the duopoly structure, take a derivative on c_T for the electricity price, and a similar threshold $\bar{\lambda}_N$ can be found. ■

Proof of Proposition 4.3

Proof. For the monopoly model, firstly we substitute the optimal $\{S_B, S_G\}$ from equation (4.4) into the social welfare function. Then we take the second order derivative of social welfare W on λ, and have the follows.

$$\frac{\partial^2 W}{\partial \lambda^2} = -\frac{\beta c_T^2(g_2^2 + b_2^2(1+2\beta g_2) + 2b_2 g_2(1+\beta g_2 \gamma_B))}{4(g_2 + b_2(1+\beta g_2))^2} < 0$$

It is easy to see W is quadratic and concave on λ, thus the unique optimal λ exist. Using the first order condition and solve $\partial W/\partial \lambda = 0$, we can get the optimal λ.

The solving of optimal λ in the duopoly model is similar and thus omitted. ■

Proof of Theorem 5.1

Proof.

The Stackelberg game proceeds in two stages. In stage one G decides the TGC offering rate θ and the wholesale price w to coordinate the system. In stage two B decides the backup capacity S to maximize its profit, which also maximizes G's profit and the system profit when the system is coordinated.

1) G decides θ and w:

From Equation (5.1), (5.3), and (5.4), when $\dfrac{\theta}{c_f} = \dfrac{r - w + c_u}{r - c_v + c_u}$, we have

$$\begin{cases} \Pi_G(S) = a\Pi_C(S) - b \\ \Pi_B(S) = (1-a)\Pi_C(S) + b \end{cases}$$

where $a = \dfrac{\theta}{c_f} = \dfrac{r - w + c_u}{r - c_v + c_u}$ and $b = (1-a)c_u\bar{D}$. Then there exists a global optimal S to maximize $\{\Pi_C(S), \Pi_G(S), \Pi_B(S)\}$ simultaneously, and the system is coordinated.

2) B decides S:

As shown in Equation (5.3), B's profit function is

$$\Pi_B(S) = (\theta - c_f)S + (w - c_v)Y(S)$$

Take a derivative on S we have

$$\frac{\partial \Pi_B}{\partial S} = \theta - c_f + (w - c_v)(m - \sum_{t=1}^{m} F_t(S))$$

where $F_t(.)$ is the c.d.f. of the random demand at period t. Let $F(.) = \sum_{t=1}^{m} F_t(.)$. It is easy to see $\partial \Pi_B / \partial S$ monotonically decreases on S and then Π_B is concave on S. Applying the first order condition $\partial \Pi_B / \partial S = 0$, we have the optimal capacity S for B as

$$F(S) = m - \frac{c_f - \theta}{w - c_v}.$$

Substituting the coordination condition $\theta = c_f \frac{r - w + c_u}{r - c_v + c_u}$ into the above expression, we have the optimal capacity S_P as

$$F(S_P) = m - \frac{c_f}{r - c_v + c_u}.$$

To verify S_P is also the global optimum, we consider the total profit function shown in Equation (5.1) which is

$$\Pi_C(S) = R - c_u \bar{D} + (r - c_v + c_u)Y(S) - c_f S$$

Applying the first order condition $\partial \Pi_C / \partial S = 0$, we get the same S_P.

The wholesale price w

Hereby we prove the system profit can be arbitrarily allocated between the two suppliers by adjusting the wholesale price w. The system profit Π_C keeps constant at the global optimum when θ is bound with w as Theorem 5.1 shows. Notice we keep the assumption $r > w > c_v$ which defines the lower bound and upper bound of w.

Firstly by taking $\theta = c_f \dfrac{r - w + c_u}{r - c_v + c_u}$ we can write Π_B as

$$\Pi_B = (w - c_v)Y(S) - c_f S \frac{w - c_v}{r - c_v + c_u} = (w - c_v)(Y(S) - \frac{c_f S}{r - c_v + c_u}).$$

Since $\Pi_B > 0$, we have

$$\frac{\partial \Pi_B}{\partial w} = Y(S) - \frac{c_f S}{r - c_v + c_u} > 0.$$

Secondly, when $w = c_v$ (lower bound) it is easy to see $\Pi_B = 0$ and $\Pi_G = \Pi_C$; when $w = r$ (upper bound) we have

$$\Pi_G = -\frac{c_u}{r - c_v + c_u} c_f - c_u(\bar{D} - Y(S)) < 0,$$

and then $\Pi_B = \Pi_C - \Pi_G > \Pi_C$.

In summary, when w increases from the lower bound to the upper bound, Π_B monotonically increases from 0 to a value greater than Π_C, which means the system profit can be arbitrarily allocated between the two suppliers. ■

Proof of Proposition 5.1

Proof.

From Theorem 5.1 we have the close-form solution of optimal $\{S, \theta\}$ in the coordination model. Take a derivative on $\{c_f, r, c_v, c_u\}$, and notice that when we take the derivative on a certain parameter, the assumptions for other parameter values hold. We find

$\dfrac{\partial S}{\partial c_f} < 0, \dfrac{\partial \theta}{\partial c_f} > 0, \forall c_f \in R;$

$\dfrac{\partial S}{\partial c_v} < 0, \dfrac{\partial \theta}{\partial c_v} > 0, \forall c_v \in R;$

$\dfrac{\partial S}{\partial r} > 0, \dfrac{\partial \theta}{\partial r} > 0, \forall r \in R;$

$\dfrac{\partial S}{\partial c_u} > 0, \dfrac{\partial \theta}{\partial c_u} > 0, \forall c_u \in R.$

■

Proof of Proposition 5.2

Proof.

For the convenience of proving, we may use θ directly or its close-form solution $\theta = c_f \frac{r - w + c_u}{r - c_v + c_u}$. Notice that when we take the derivative on a certain parameter, the assumptions for other parameter values hold.

Impact of c_f

Take a derivative on c_f for Π_G, we have $\frac{\partial \Pi_G}{\partial c_f} = -\frac{\partial \theta}{\partial c_f} S < 0, \forall c_f \in R$, for we know $\frac{\partial \theta}{\partial c_f} > 0$ from proposition 5.1.

Take a derivative on c_f for Π_B, we have $\frac{\partial \Pi_B}{\partial c_f} = -\frac{w - c_v}{r - c_v + c_u} S < 0, \forall c_f \in R$.

Since $\Pi_C = \Pi_G + \Pi_B$, we have $\frac{\partial \Pi_C}{\partial c_f} < 0, \forall c_f \in R$.

Impact of c_v

$\frac{\partial \Pi_G}{\partial c_v} = -\frac{\partial \theta}{\partial c_v} S < 0, \forall c_v \in R$, for we know $\frac{\partial \theta}{\partial c_v} > 0$ from proposition 5.1.

Take a derivative on c_v for Π_B, we have

$$\frac{\partial \Pi_B}{\partial c_v} = c_f S \frac{r - w + c_u}{(r - c_v + c_u)^2} - Y(S).$$

Since $\Pi_B = (w - c_v)Y(S) + (\theta - c_f)S = (w - c_v)Y(S) - c_f S \frac{w - c_v}{r - c_v + c_u} > 0$, we have

$$Y(S) > c_f S \frac{1}{r - c_v + c_u} > c_f S \frac{1}{r - c_v + c_u} \frac{r - w + c_u}{r - c_v + c_u},$$

then it can be seen that $\frac{\partial \Pi_B}{\partial c_v} < 0, \forall c_v \in R$.

Since $\Pi_C = \Pi_G + \Pi_B$, we have $\frac{\partial \Pi_C}{\partial c_v} < 0, \forall c_v \in R$.

Impact of r

$\frac{\partial \Pi_G}{\partial r} = Y(S) - c_f S \frac{w - c_v}{(r - c_v + c_u)^2}$. From above we have

$$Y(S) > c_f S \frac{1}{r - c_v + c_u} > c_f S \frac{1}{r - c_v + c_u} \frac{w - c_v}{r - c_v + c_u},$$

then it can be seen that $\frac{\partial \Pi_G}{\partial r} > 0, \forall r \in R$.
$\frac{\partial \Pi_B}{\partial r} = c_f S \frac{w - c_v}{(r - c_v + c_u)^2} > 0, \forall r \in R$.
Since $\Pi_C = \Pi_G + \Pi_B$, we have $\frac{\partial \Pi_C}{\partial r} > 0, \forall r \in R$.

Impact of c_u

$\frac{\partial \Pi_G}{\partial c_u} = -\frac{\partial \theta}{\partial c_u} S - (\bar{D} - Y(S)) < 0, \forall c_u \in R$, for we know $\frac{\partial \theta}{\partial c_u} > 0$ from proposition 5.1.
$\frac{\partial \Pi_B}{\partial c_u} = c_f S \frac{w - c_v}{(r - c_v + c_u)^2} > 0, \forall c_u \in R$.
$\frac{\partial \Pi_C}{\partial c_u} = -(\bar{D} - Y(S)) < 0, \forall c_u \in R$. ∎

Proof of Proposition 5.3

Proof.

The social welfare is

$$W = Y(S)U - c_u(\bar{D} - Y(S)) - c_f S$$

where $U = u - e - c_v$.

Applying the first order condition $\partial W / \partial S = 0$, we have the optimal capacity S_W to maximize the social welfare as

$$S_W = F^{-1}(m - \frac{c_f}{U + c_u}) = F^{-1}(m - \frac{c_f}{u - e - c_v + c_u}).$$

∎

Proof of Proposition 5.4

Proof.

From proposition 5.3 we have the close-form solution of optimal S_W. Take a derivative on e we find $\frac{\partial S_W}{\partial e} < 0, \forall e \in R$, given the assumptions for other parameter values hold.

Notice $S_P = F^{-1}(m - \frac{c_f}{r - c_v + c_u})$ and $S_D = F^{-1}(m - \frac{c_f}{r - c_v})$, it is easy to see $S_D < S_P \leq S_W$ when $e \leq u - r$; $S_W \leq S_D < S_P$ when $e \geq u - r + c_u$; $S_D < S_W < S_P$ when $u - r < e < u - r + c_u$. ■

Proof of Lemma 6.1

Proof.

As shown in Equation (6.1), the total profit function is

$$\begin{aligned}\Pi^C(S_i, S_j) =& R_i + R_j - c_u(\bar{D}_i + \bar{D}_j) - c_f(S_i + S_j) \\ &+ E\{v \sum_{t=1}^{m} (\min(x_i^t, S_i) + \min(x_j^t, S_j)) + (v - c_t)(T_{ij} + T_{ji})\}.\end{aligned}$$

Notice that $\partial E\{\min(x_i^t, S_i)\}/\partial S_i = 1 - F_i^t = 1 - Pr\{x_i^t < S_i\}$; $\partial E\{T_{ij}^t\}/\partial S_i = \beta_{ij}^t = Pr\{x_j^t - S_j > S_i - x_i^t > 0\}$; $\partial E\{T_{ji}^t\}/\partial S_i = -\gamma_{ij}^t = -Pr\{S_j - x_j^t > x_i^t - S_i > 0\}$. Take a derivative of Π^C on S_i, we have

$$\frac{\partial \Pi^C}{\partial S_i} = v(m - F_i) + (v - c_t)(\bar{\beta_{ij}} - \bar{\gamma_{ij}}) - c_f = 0,$$

where $F_i = \sum_{t=1}^{m} F_i^t$, $\bar{\beta_{ij}} = \sum_{t=1}^{m} \beta_{ij}^t$, and $\bar{\gamma_{ij}} = \sum_{t=1}^{m} \gamma_{ij}^t$.

Now we show the concavity of $\Pi^C(S_i, S_j)$, and thus the above first-order condition is sufficient for optimality. $\Pi^C(S_i, S_j)$ is the summation of the following m per period profit functions $\Pi_t^C(S_i, S_j)$, plus a constant $K = R_i + R_j - c_u(\bar{D}_i + \bar{D}_j)$:

$$\Pi_t^C(S_i, S_j) = -(S_i + S_j)c_f/m + E\{v(Y_i^t + Y_j^t) + (v - c_t)(T_{ij}^t + T_{ji}^t)\}, t = 1 \sim m.$$

The first term is the per period capacity cost. $Y_i^t = \min(x_i^t, S_i)$, is the local sale in region i. $T_{ij}^t = \min(Z_i^t, W_j^t)$, is the power transmitted from i to j, where $Z_i^t = \max(S_i - x_i^t, 0)$ is the power surplus in region i, and $W_j^t = \max(x_j^t - S_j, 0)$ is the power shortage in region j. Y_j^t and $T_{ji}^t = \min(Z_j^t, W_i^t)$ have similar economical meanings.

The optimization problem expressed by $\Pi_t^C(S_i, S_j)$ can be reformulated as a two-stage stochastic programming problem as follows.

Max $\quad \Pi_t^C(S_i, S_j) = -(S_i + S_j)c_f/m + E\{v(Y_i^t + Y_j^t) + (v - c_t)(T_{ij}^t + T_{ji}^t) - M(Z_i^t + W_i^t + Z_j^t + W_j^t)\}$

s.t. $\quad S_i \geq 0, S_j \geq 0;$

$Y_i^t \leq x_i^t, Y_i^t \leq S_i, Y_i \geq 0;$

$Y_j^t \leq x_j^t, Y_j^t \leq S_j, Y_j \geq 0;$

$T_{ij}^t \geq 0, T_{ij}^t \leq Z_i, T_{ij}^t \leq W_j, Z_i \geq S_i - x_i^t, W_j \geq x_j^t - S_j;$

$T_{ji}^t \geq 0, T_{ji}^t \leq Z_j, T_{ji}^t \leq W_i, Z_j \geq S_j - x_j^t, W_i \geq x_i^t - S_i.$

$\{x_i^t, x_j^t\}$ are non-negative random variables defined in a convex probability space. $\{S_i, S_j\}$ are the first stage decision variables. $\{Y_i^t, Y_j^t, T_{ij}^t, T_{ji}^t\}$ and $\{Z_i^t, W_i^t, Z_i^t, W_i^t\}$ are the second stage decision variables. Notice $\{Z_i^t, W_i^t, Z_i^t, W_i^t\}$ are artificial variables and M is a large enough positive parameter.

According to Slyke and Wets (1966), since the operators are all linear and the feasible regions of the decision variables are all convex, the above two-stage stochastic programming problem is concave in $\{S_i, S_j\}$. Then $\Pi^C(S_i, S_j)$ is also concave as the summation of m concave functions $\Pi_t^C(S_i, S_j)$. ■

Proof of Lemma 6.2

Proof.

By using the first order condition $\partial\Pi_i^N(S_i)/\partial S_i = 0$, we can find the unique global optimal solution of backup capacity S_i^N to maximize the centralized firm's profit as

$$\bar{F}_i(S_i^N) = m - c_f/v.$$

Notice $(r + c_u - c_v)mS \geq v \sum_{t=1}^{m} \min(x_t, S) > c_f S$, such that $m - c_f/v > 0$. Also it is easy to verify that $\bar{F}_i(0) = 0$ and $\bar{F}_i(S_i)$ monotonically increases on S_i. Then $S_i^N > 0$ is an interior solution.

By using the second order condition , we have $\partial^2\Pi_i^N(S_i)/\partial S_i^2 = -v\sum_{t=1}^{m} f_t(.) < 0$. Such that Π_i^N is strictly concave and the first order condition defines the unique global optimal solution of backup capacity S_i^N.

Comparing Equation 6.2 and 6.4, we have $F_i(S_i)-F_i(S_i^N) = (1-c_t/v)(\bar{\beta_{ij}}(S_i,S_j)-\bar{\gamma_{ij}}(S_j,S_j))$. Notice $F_i(.)$ is a monotonically increasing function and $1-c_t/v > 0$. It is easy to see $S_i^N > (<) S_i$ if $\bar{\beta_{ij}} > (<) \bar{\gamma_{ij}}$. ■

Proof of Lemma 6.3

Proof.

The Nash equilibrium is given by the first order conditions as Equation 6.6 shows. To establish the existence of a unique Nash equilibrium, it is sufficient to show that the reaction functions are monotonic, and the absolute value of the slop is less than 1 (see Proposition 1 of Rudi et al. (2001)). For this purpose, we show $\partial S_i/\partial S_j < 0$ and $-\partial S_i/\partial S_j < 1$ as follows.

We define the following marginal probabilities:

$$\begin{cases} a^t = f_{x_i^t}(S_i) \\ b_1^t = Pr\{x_i^t < S_i\} f_{x_i^t+x_j^t|x_i^t<S_i}(S_i+S_j) \\ b_2^t = Pr\{x_i^t + x_j^t > S_i+S_j\} f_{x_i^t|x_i^t+x_j^t>S_i+S_j}(S_i) \\ g_1^t = Pr\{x_i^t > S_i\} f_{x_i^t+x_j^t|x_i^t>S_i}(S_i+S_j) \\ g_2^t = Pr\{x_i^t + x_j^t < S_i+S_j\} f_{x_i^t|x_i^t+x_j^t<S_i+S_j}(S_i) \end{cases}$$

Such that $\partial F_i^t/\partial S_i = a^t$, $\partial F_i^t/\partial S_j = 0$, $\partial \beta_{ij}^t/\partial S_i = -b_1^t + b_2^t$, $\partial \beta_{ij}^t/\partial S_j = -b_1^t$, $\partial \gamma_{ij}^t/\partial S_i = g_1^t - g_2^t$, $\partial \gamma_{ij}^t/\partial S_j = g_1^t$. Please notice $a^t = b_2^t + g_2^t$.

Take a total derivative of Equation 6.6 on S_j, we have

$$-va\partial S_i/\partial S_j + (p_{ij}^H - c_t - c_v)[(-b_1+b_2)\partial S_i/\partial S_j - b_1] - (r + c_u - p_{ji}^H)[(g_1-g_2)\partial S_i/\partial S_j + g_1] = 0,$$

where $a = \sum_{t=1}^{m} a^t,\ b_1 = \sum_{t=1}^{m} b_1^t,\ b_2 = \sum_{t=1}^{m} b_2^t,\ g_1 = \sum_{t=1}^{m} g_1^t,\ g_2 = \sum_{t=1}^{m} g_2^t$. Please notice $v = r + c_u - c_t$. Rearranging the above and we have

$$-\frac{\partial S_i}{\partial S_j} = \frac{(p_{ij}^H - c_t - c_v)b_1 + (r + c_u - p_{ji}^H)g_1}{va + (p_{ij}^H - c_t - c_v)(b_1 - b_2) + (r + c_u - p_{ji}^H)(g_1 - g_2)}.$$

Given the assumption $c_t + c_v < p_{ij}^H(p_{ji}^H) < r + c_u$, it is easy to see the numerator of the above function is positive. Additionally, given $a = b_2 + g_2$, it is easy to verify that $va > (p_{ij}^H - c_t - c_v)b_2 + (r + c_u - p_{ji}^H)g_2$, and then the denominator is greater than the numerator. Then we have $-\partial S_i/\partial S_j < 1$ and $\partial S_i/\partial S_j < 0$. ■

Proof of Lemma 6.4

Proof.

To find the coordinating transmission prices, it is sufficient to find a pair of $\{p_{ij}^H, p_{ji}^H\}$ which induce the firms to choose the global optimal capacity $\{S_i, S_j\}$. By equating the right side of Equation 6.2 and 6.6, we can form two linear equations with two variables $\{p_{ij}^H, p_{ji}^H\}$. Solving them yields the unique coordinating transmission prices as Equation 6.7 shows. ■

Proof of Lemma 6.5

Proof.

Compare the profit function of conventional supplier B_i in Model D ($\Pi_{B_i}^D$ in Equation 6.8) with the profit function of regional supplier i in Model H (Π_i^H in Equation 6.5), it is easy to see $\Pi_{B_i}^D$ is just to replace $r + c_u$ in Π_i^H with w, and then minus a constant $K_i = R_i - c_u\bar{D}_i$. Following the same process of Lemma 6.3 and 6.4, we can find the unique Nash equilibrium and the coordinating transmission prices in Model D, which are to replace $r + c_u$ with w in Equation 6.6 and 6.7. ■

Proof of Lemma 6.6

Proof.

Lemma 6.5 shows that the capacity $\{S_i, S_j\}$ in Model D is to replace v with $w - c_u$

in the capacity in Model H, which is the same as the capacity in Model C (Lemma 6.4). To prove the total capacity $S_T = S_i + S_j$ in Model D is less than in Model C, we only need to prove $\partial S_T/\partial v > 0$ in Model C, since $w - c_u < v$. Then it is natural that S_T in Model D decreases when w decrease.

Now consider the total profit function $\Pi^C(v, S_i, S_j)$ as shown in Equation 6.1. By the Implicit Function Theorem, we have

$$\frac{\partial S_i}{\partial v} = \frac{(\partial^2\Pi^C/\partial S_i\partial S_j)(\partial^2\Pi^C/\partial S_i\partial v) - (\partial^2\Pi^C/\partial S_i^2)(\partial^2\Pi^C/\partial S_j\partial v)}{-|H|},$$

where H is the Hessian matrix of $\Pi^C(S_i, S_j)$. Notice $-|H| > 0$ since $\Pi^C(S_i, S_j)$ is concave as shown by Lemma 6.1. Now consider

$$\frac{\partial S_T}{\partial v} = \frac{(\partial^2\Pi^C/\partial S_i\partial v)[(\partial^2\Pi^C/\partial S_i\partial S_j) - (\partial^2\Pi^C/\partial S_j^2)] + (\partial^2\Pi^C/\partial S_j\partial v)[(\partial^2\Pi^C/\partial S_i\partial S_j) - (\partial^2\Pi^C/\partial S_i^2)]}{-|H|}.$$

Using the notations $\{F_i, \bar{\beta_{ij}}, \bar{\gamma_{ij}}\}$ defined in Lemma 6.1 and $\{a, b_1, b_2, g_1, g_2\}$ defined in Lemma 6.3, we have (A) $\partial^2\Pi^C/\partial S_i\partial v = 1 - F_i - \bar{\gamma_{ij}} + \bar{\beta_{ij}} > 0$; (B) $\partial^2\Pi^C/\partial S_i\partial S_j - \partial^2\Pi^C/\partial S_i^2 = (v - c_t)(-b_1 - g_1) - [(v - c_t)(-b_1 + b_2 - g_1 + g_2) - va] = c_t a > 0$. By exchanging i with j in the above two conditions, we have (C) $\partial^2\Pi^C/\partial S_j\partial v > 0$ and (D) $\partial^2\Pi^C/\partial S_j\partial S_i - \partial^2\Pi^C/\partial S_j^2 > 0$. Based on conditions (A) to (D), we have $\partial S_T/\partial v > 0$. ■

Proof of Theorem 6.1

Proof.

The coordination contract can be considered as two parts: (1) $G_i(G_j)$ offers a certain amount of TGC and pays transmission premiums to share the system cost; (2) $B_i(B_j)$ receives the TGC offering and the transmission premium, and transmits power based on a pair of transmission prices. Given the contract parameters in Theorem 6.1, we show that the system is coordinated as follows.

$G_i(G_j)$**'s profit**

From Equation (6.5), (6.10), and (6.11), substitute $\delta_{ij} = \rho p_{ij}^H - \rho(c_v + c_t)$ into Π_{G_i}. Notice $\Pi_i^H = \Pi_{G_i} + \Pi_{B_i}$ and $p_{ji}^H = p_{ij} + \delta_{ij}$. We have

$$\Pi_{G_i} = E\{\rho(p_{ij}^H - c_t - c_v)T_{ij} + \rho(r + c_u - p_{ji}^H)T_{ji} + \rho v \sum_{t=1}^{m} \min(x_i^t, S_i)\} - \rho c_f S_i + R_i - c_u \bar{D}_i$$
$$= \rho \Pi_i^H(S_i, S_j) + (1-\rho)(R_i - c_u \bar{D}_i)$$

Then there exists a same solution of capacities $\{S_i, S_j\}$ to maximize $\Pi_i^H(S_i, S_j)$ and $\Pi_{G_i}(S_i, S_j)$ simultaneously.

$B_i(B_j)$**'s profit**

From Equation (6.5), (6.10), and (6.11), substitute $p_{ij} = (1-\rho)p_{ij}^H + \rho(c_v + c_t)$ into Π_{B_i}. We have

$$\Pi_{B_i} = E\{(1-\rho)(p_{ij}^H - c_t - c_v)T_{ij} + (1-\rho)(r + c_u - p_{ji}^H)T_{ji} + (1-\rho)v \sum_{t=1}^{m} \min(x_i^t, S_i)\}$$
$$- (1-\rho)c_f S_i$$
$$= (1-\rho)(\Pi_i^H(S_i, S_j) - (R_i - c_u \bar{D}_i))$$

Then there exists a same solution of capacities $\{S_i, S_j\}$ to maximize $\Pi_i^H(S_i, S_j)$ and $\Pi_{B_i}(S_i, S_j)$ simultaneously.

From Lemma 6.4 we know Model H ($\Pi_i^H(S_i, S_j)$) has the same solution of capacities $\{S_i, S_j\}$ and the same system profit as the centralized model. Therefore, the optimal capacity in the coordination model reaches the global optimum as described in the centralized model (Equation 6.2). ■

Proof of Proposition 6.1

Proof.

From Theorem 6.1 we have $\rho = \dfrac{r + c_u - w}{r + c_u - c_v}$, which is not affected by c_f and c_t. Take a derivative on $\{r, c_v, c_u\}$, and notice that when we take the derivative on a certain parameter, the assumptions for other parameter values hold. We find $\partial\rho/\partial r > 0, \forall r \in R; \partial\rho/\partial c_v > 0, \forall c_v \in R; \partial\rho/\partial c_u > 0, \forall c_u \in R.$

In Lemma 6.6 we have proved $\partial S_T/\partial v > 0$, where $v = r + c_u - c_v$. Then it is easy to see $\partial S_T/\partial r > 0, \forall r \in R; \partial S_T/\partial c_u > 0, \forall c_u \in R; \partial S_T/\partial c_v < 0, \forall c_v \in R.$

From Equation 6.2 we have the optimal condition of S_i:

$$F_i(S_i) = m - c_f/v + (1 - c_t/v)(\bar{\beta_{ij}}(S_i, S_j) - \bar{\gamma_{ij}}(S_j, S_j))$$

Notice $F_i(S_i)$ monotonically increases on S_i and vice versa. From $\partial F_i/\partial c_f = -1/v < 0$ we have S_i decreases on c_f. From $\partial F_i/\partial c_t = -(\bar{\beta_{ij}} - \bar{\gamma_{ij}})/v$, we have S_i increases (decreases) on c_t if $\bar{\beta_{ij}} - \bar{\gamma_{ij}} < (>)0$. ∎

Proof of Proposition 6.2

Proof.

For the convenience of proving, we rewrite the three profit functions as follows.

$$\begin{cases} \Pi^C(S_i, S_j) = K - c_f(S_i + S_j) + E\{vY + (v - c_t)(T_{ij} + T_{ji})\} \\ \Pi_G(S_i, S_j) = K + E\{(r + c_u - w)(Y + T_{ij} + T_{ji}) - \rho c_t(T_{ij} + T_{ji})\} - \rho c_f(S_i + S_j) \\ \Pi_B(S_i, S_j) = E\{(w - c_v)Y + (w - c_v - (1 - \rho)c_t)(T_{ij} + T_{ji})\} - (1 - \rho)c_f(S_i + S_j) \end{cases}$$

Notice $v = r + c_u - c_v$, $\rho = (r + c_u - w)/(r + c_u - c_v)$, $Y = \sum_{t=1}^{m}(\min(x_i^t, S_i) + \min(x_j^t, S_j))$ denoting the locale sale of backup power, and $K = R_i + R_j - c_u(\bar{D}_i + \bar{D}_j)$ denoting the basic revenue without backup capacity. Also notice when we take the derivative on a certain parameter, the assumptions for other parameter values hold.

Impact of r

$\partial\Pi^C/\partial r = E\{Y + T_{ij} + T_{ji}\} > 0, \forall r \in R$ is straightforward.

$\partial\Pi_B/\partial r = E\{c_t(T_{ij} + T_{ji}) + c_f(S_i + S_j)\}\partial\rho/\partial r > 0, \forall r \in R$, since $\partial\rho/\partial r > 0$ (Proposition 6.1).

$\partial\Pi_G/\partial r = (r + c_u - w)[(Y - S_T c_f/v) + (1 - c_t/v)(T_{ij} + T_{ji})] > 0, \forall r \in R$, from two assumptions in Section 6.1, $v\sum_{t=1}^{m}\min(x_i^t, S_i) > c_f S_i$ (preparing backup capacity is profitable) and $v > c_t$ (interregional transmission is profitable).

Impact of c_u

$\partial\Pi^C/\partial c_u = -(\bar{D}_i + \bar{D}_j - E\{Y + T_{ij} + T_{ji}\}) \leq 0, \forall c_u \in R$ is straightforward, as the backup power consumption cannot exceed the total shortage.

$\partial\Pi_B/\partial c_u = E\{c_t(T_{ij} + T_{ji}) + c_f(S_i + S_j)\}\partial\rho/\partial c_u > 0, \forall c_u \in R$, since $\partial\rho/\partial c_u > 0$ (Proposition 6.1).

From the above two results and $\Pi_G = \Pi^C - \Pi_B$, we have $\partial\Pi_G/\partial c_u < 0, \forall c_u \in R$.

Impact of c_v

$\partial\Pi^C/\partial c_v = -E\{Y + T_{ij} + T_{ji}\} < 0, \forall c_v \in R$ is straightforward.

$\partial\Pi_B/\partial c_v = -E\{Y + T_{ij} + T_{ji}\} - E\{c_t(T_{ij} + T_{ji}) + c_f(S_i + S_j)\}(\partial\rho/\partial c_v) < 0, \forall c_v \in R$, since $\partial\rho/\partial c_v > 0$ (Proposition 6.1).

$\partial\Pi_G/\partial c_v = -E\{c_t(T_{ij} + T_{ji}) + c_f(S_i + S_j)\}(\partial\rho/\partial c_v) < 0, \forall c_v \in R$.

Impact of c_f

$\partial\Pi^C/\partial c_f = -(S_i + S_j) < 0, \forall c_f \in R$.

$\partial\Pi_B/\partial c_f = -(1 - \rho)(S_i + S_j) < 0, \forall c_f \in R$.

$\partial\Pi_G/\partial c_f = -\rho(S_i + S_j) < 0, \forall c_f \in R$.

Impact of c_t

$\partial\Pi^C/\partial c_t = -(T_{ij} + T_{ji}) < 0, \forall c_t \in R.$

$\partial\Pi_B/\partial c_t = -(1-\rho)(T_{ij} + T_{ji}) < 0, \forall c_t \in R.$

$\partial\Pi_G/\partial c_t = -\rho(T_{ij} + T_{ji}) < 0, \forall c_t \in R.$ ∎

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