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Cap-and-Trade Modeling and Analysis: Congested Electricity Market Equilibrium

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by

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Abstract

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Doctor of Philosophy in Engineering – Industrial Engineering and Operations Research

University of California, Berkeley

Professor Shmuel S. Oren, Chair

This dissertation presents an equilibrium framework for analyzing the impact of cap-and-trade regulation on transmission-constrained electricity market. The cap-and-trade regulation of greenhouse gas emissions has gained momentum in the past decade. The impact of the regulation and its efficacy in the electric power industry depend on interactions of demand elasticity, transmission network, market structure, and strategic behavior of firms. I develop an equilibrium model of an oligopoly electricity market in conjunction with a market for tradable emissions permits to study the implications of such interactions. My goal is to identify inefficiencies that may arise from policy design elements and to avoid any unintended adverse consequences on the electric power sector.

I demonstrate this modeling framework with three case studies examining the impact of carbon cap-and-trade regulation. In the first case study, I study equilibrium results under various scenarios of resource ownership and emission targets using a 24-bus IEEE electric transmission system. The second and third case studies apply the equilibrium model to a realistic electricity market, Western Electricity Coordinating Council (WECC) 225-bus system with a detailed representation of the California market.

In the first and second case studies, I examine oligopoly in electricity with perfect competition in the permit market. I find that under a stringent emission cap and a high degree of concentration of non-polluting firms, the electricity market is subject to potential abuses of market power. Also, market power can occur in the procurement of non-polluting energy through the permit market when non-polluting resources are geographically concentrated in a transmission-constrained market.

In the third case study, I relax the competitive market structure assumption of the permit market by allowing oligopolistic competition in the market through a conjectural variation approach. A short-term equilibrium analysis of the joint markets in the presence of market power reveals that strategic permit trading can play a vital role in determining economic outcomes in the electricity market. In particular, I find that a firm with more efficient

technologies can employ strategic withholding of permits, which allows for its increase in output share in the electricity market at the expense of other less efficient firms. In addition, strategic permit trading can influence patterns of transmission congestion.

These results illustrate that market structure and transmission congestion can have a significant impact on the market performance and environmental outcome of the regulation while the interactions of such factors can lead to unintended consequences. The proposed approach is proven useful as a tool for market monitoring purposes in the short run from the perspective of a system operator, whose responsibility has become indirectly intertwined with emission trading regulation.

To my mother,

Achana Limpaitoon,

the only reason for my doctorate.

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Waruntorn for her courage to lead me all the way to the top of Half Dome! I thank Pongsin for his example of generosity. I thank Chayut for teaching me the possibility of multitudinous perspectives on the very same question. My special appreciation goes to Apin and Naragain for their unlimited mental support which has meant to me beyond what they realized.

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Chapter 1

Introduction

The evidence for climate change has been mounting in recent decades, generating much concern and controversy. Whether it is the higher ambient and ocean temperatures, the melting of glaciers and polar ice, or the rising global sea level, all observations point to rapid changes in the global climate system.[1] One of the major causes of climate change is the increasing level of greenhouse gases (GHG) emitted by human activities to the atmosphere (Intergovernmental Panel on Climate Change [IPCC], 2007). GHG is defined as any gas that absorbs and emits long wave, namely infrared, radiation in the earth's atmosphere. The accumulation of such gases in the atmosphere will trap heat, resulting in rising global temperature. There are many kinds of GHGs, but the main GHGs contributing to climate change are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Fossil fuel use and land-use change[2] are the main factors for the global increase in concentration of CO_2, while the concentrations of CH_4 and N_2O are mostly attributed to modern agricultural practices (IPCC, 2007). These activities have proliferated in recent decades, but their origins can be traced back to our long history of the Agricultural and Industrial Revolutions.

As early as mid-seventeenth century, the Agricultural Revolution began in England. Peasants started to adopt various farming practices, such as convertible husbandry (alternation of grass and arable) and the cultivation of legumes that increased concentrations of nitrogen compounds in the environment (Allen, 1999). As such practices slowly spread around the world, about a century later the Industrial Revolution took place. Manufacturing-based economies that have resulted from industrialization have resulted in GHG concentrations that are now exponentially greater than the pre-industrial values. These industrial activities have raised CO_2 levels in the atmosphere from 280 in the year 1750 to 379 parts per million in 2005 (IPCC, 2007). Although such industrial activities have led to advancements of our modern civilization, they also have brought along GHG emissions that have caused much of

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[1] See U.S. Environmental Protection Agency (2010) for some scientific facts on climate change.

[2] The United Nations Framework Convention on Climate Change (UNFCCC) defines land use, land-use change and forestry as: "A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities." (UN, n.d.).

the observed rising global temperatures over the recent decades. According to EPA (2012), the GHG emissions in the U.S. increased by 10.5% from 1990 to an alarming level of 6,821.8 MMTCO2e[3] in 2012. These figures, while striking, may not sway public opinion, as there is a perception that prosperity outweighs the environmental costs. However, that may not necessarily be the case.

These economic revolutions have, on the one hand, led to a massive increase in standard of living and economic prosperity. On the other hand, it is also a subject of inquiry for the expansive ramifications it brought to the environment, which could in turn impede the world's long-term economic growth. For example, global warming, as scientists have long argued, has been linked to higher intensity or frequency of hurricanes (Webster et al., 2005). Natural disasters have proven to be expensive, and will become even more expensive in the future. Livestock and crop production are also facing adaptation challenges because of weather extremes, rising heat, water stress, and other environmental changes. Public health is continually being threatened by heat stress and various kinds of diseases that originate from climate change (Karl et al., 2009). In fact, the Stern Review of the Economics of Climate Change (Stern, 2007) argued that the threat of catastrophic climate change—associated with impacts on water resources, food production, and health—to the world's economy far exceeds the costs of addressing it now.Therefore, as long as human activities continue on the current emissions path, not only could the world's economic growth lose its strength, but the world itself could also face catastrophic consequences that far offset the level of wealth that we currently enjoy.

With such looming concerns, there is an urgent need for global cooperation to combat climate changes that could potentially drive the earth toward an irreversible path. Efforts towards stopping climate change have gained momentum in the world's economic and political stages in recent years. The United Nations Framework Convention on Climate Change (UNFCCC), whose objective is to stabilize GHG concentrations, is the first treaty that many countries agreed upon in 1992. It was not, however, until 1997 that several UNFCCC members adopted the Kyoto Protocol that sets binding targets on GHG emissions for 37 industrialized countries and the European community for the period 2008-2012 (United Nations [UN], 1998). Despite several conferences thereafter, the accumulation of GHGs, particularly CO_2, has continued to increase rather than decline[4], mainly because international cooperative effort has been blindsided by the domestic economic concerns and political challenges in implementing measures to subdue the causes of emissions. Nonetheless, the latest agreement reached at the UN Climate Change Conference, Durban 2011, to adopt for the first time a universal legal framework by 2015 may be viewed as a crucial step towards the participation of the high-emitting nations (UN, 2011).

Developed countries, especially in the European Union (EU) and the U.S., have already

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[3] MMTCO2e stands for million metric ton of carbon dioxide equivalent, which is used to measure the level of various GHG emissions.

[4] Measurements of carbon dioxide have been taken at the Mauna Lao Observatory, Hawaii, by the National Oceanic and Atmospheric Administration.

begun to cope with the causes of GHG emissions by means of programs that encourage energy efficiency and that set standards for "clean" emissions that would effectively replace fossil fuels with sustainable sources. For example, the EU has launched the European Climate Change Program (ECCP) that sets out a number of measures to enhance carbon sequestration in agricultural soils, as well as to promote the use of biofuels (ECCP, 2001). In the U.S., the Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) have developed and implemented regulations that promote the improvements of fuel-economy of passenger cars and commercial vehicles (NHTSA, 2012). The EPA has also proposed the New Source Performance Standard under the Clean Air Act to limit CO_2 emissions coming from new power plants (EPA, 2012a). The move could effectively ban the future construction of conventional coal-fired power plants. One of the remarkable programs in combating global climate change is the emissions trading system (ETS), also known as the cap-and-trade program (C&T). This program creates a market in which GHG emissions can be priced and traded as a means to efficiently reduce emissions. In theory, the larger the scope of the program is, the less costly the emissions reduction is. The EU ETS and the California's C&T program have been the pioneers in regulating CO_2 emissions, primarily from sectors that require intensive use of fossil fuels, such as electricity generation, transportation, and other industrial production, while the Regional Greenhouse Gas Initiative (RGGI) has targeted the electricity sector alone. The C&T program has created a market for trading emissions permits (allowances)[5] among and within the participating sectors. In order to achieve significant reduction in GHG emissions, any implemented regulation must not overlook emissions from the various sectors mentioned above. It must also be carefully crafted to take into consideration the impacts of such regulation, as those sectors are fundamental to the economy.

The electricity generation sector has been among the top-emitting sectors because of its need for fossil fuel combustion. In 2009, generation of electricity and heat was the largest contributor of CO2 emissions and was responsible for 41% of the world CO2 emissions (International Energy Agency [IEA], 2011). In the U.S., the largest source of GHG emissions by sector is the electric power sector (EPA, 2012c). This sector is therefore important to intensive emissions reductions, not only because of the emissions directly attributable to it, but also because the sector is becoming a backbone for other high-emitting sectors as they are being "electrified." For example, there has been a shift from internal combustion engine vehicles to electric vehicles in attempt to reduce emissions from the transportation sector. Apparently, the scale of such reduction is determined by the carbon intensity of the electric power sector. Similarly, the residential sector is also moving towards switching out of direct fuel uses in buildings to electricity. Such a large-scale electrification, along with stringent emission regulations, would therefore require a major transformation in how electricity markets and power systems function; the electricity sector is thus pivotal to the future economic and environmental success.

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[5] For the purpose of this dissertation, the terms 'permits' and 'allowances' are used interchangeably.

The remainder of this chapter is divided into five sections. Section 1.1 discusses the role of electricity and addresses how it is central to achieving emissions targets. Section 1.2 provides an overview of current GHG regulations in the electricity sector in Europe and the U.S. Section 1.3 explores issues arising from the implementation of C&T regulation in electricity sector and its implications on the markets with the focus on the state of California. Section 1.4 provides a brief literature review on modeling approaches to analyze the impacts of emissions regulations in the electricity sector. Section 1.5 concludes this chapter with the scope of this dissertation.

1.1 The Crucial Role of Electricity

Intense GHG reductions in one sector can have potential trigger-down effects on other industry sectors due to complex interrelationships. Electricity generation, in particular, can easily affect other electricity-intensive sectors; as fossil fuel-reliant electricity becomes expensive to generate, it will drive up the electricity price. Electricity generation is therefore the crucial part of the movement towards sustainable emission level, as it is a basis for the growth of other industries. In addition to numerous mandates to curb GHG emissions, it is essential to have energy-efficiency that can compensate for the potential rise in energy costs. A study has shown that energy conservation correlates with real income and economic growth in developed countries such as the U.S., Canada, and the Netherlands (Lee, 2006). Rising electricity costs would make it difficult for private individuals, especially the low-income families as electric bills tend to represent relatively higher share of their income. Given the trade-offs between economic concerns and environmental preservation, it is important to enhance the overall efficiencies in both electricity generation and energy usage to achieve both environmental and economic goals.

Energy efficiency can refer to various improvements in energy use, ranging from less fuel being required to generate each kWh to end-saving light bulbs. One of the recent trends in energy efficiency is known as “electrification”, including electric cars, smart grids, energy-efficient buildings, and other “green” technologies. While having potential positive impacts, it is often one-sided, emphasizing the products themselves as a tool to help reduce emissions, while disregarding the big picture. Much of the electricity generation supporting such technologies still relies heavily on fossil fuel combustion. According to Energy Information Administration (2011), about two-thirds of U.S. electricity generation was supplied by fossil fuels in the form of natural gas, coal, and petroleum. Importantly, approximately 83% of the GHG emissions in 2009 is CO_2, a by-product of fossil fuel combustion, making fossil fuel combustion the largest source of overall GHG emissions. Therefore, such massive electrification of transportation, industrial production, and buildings, cannot achieve substantial reduction targets without a major overhaul of the electric power industry. Without significant improvement in energy efficiency, aggressive emissions targets together with increasing demand for electricity by other “electrified” sectors would require the power industry to almost entirely abandon fossil fuel use in electricity generation and rely solely on alternative sources (Williams et al., 2012).

Decarbonization of electricity is, therefore, the key to a greener energy supply in the future. However, an essential question for such transformation concerns the costs of the process. How expensive would it be to decarbonize electricity? Assuming the emissions target of 83% below 2005 levels for developed countries by 2050, the Electric Power Research Institute (EPRI) estimated that the average cost of carbon could be as high as \$250/MTCO2e (2007\$). This estimate assumed the absence of CO_2 capture and storage (CCS), Plug-in Electric Vehicles (PEVs), further cost breakthroughs, and no expansion or replacement of the nuclear fleet. Even if the availability of CCS and PEVs, advanced nuclear, significant improvement in costs and in end-use efficiency are possible, there would be a two-fold increase in the average cost of electricity generation when compared to 2007 (EPRI, 2009). Therefore, it is imperative that the roadmap for the transition to an economy that can mitigate climate change must be comprehensive, without relying exclusively on either energy efficiency or "decarbonized" energy supply. Moreover, a large-scale centralized use of fossil fuel can be more efficient than direct use of fossil fuel combustion; for instance, centralization will enable technologies, like CCS, to control emissions more efficiently. The transition must therefore be coupled with a large-scale electrification of transportation and participation of other sectors (Williams et al., 2012).

Recognizing the possibility of rising electricity costs, many countries have explored a wide range of alternatives to conventional energy in order to ease the decarbonization of electricity generation in preparation for massive electrification. These alternatives include efficiency improvements of energy conversion, fuel switching, carbon sequestration, and renewable integration. Nuclear energy has also been considered as such an alternative to decarbonization. However, the economic and social ramifications of the Fukushima disaster on March 11, 2011, are far greater than anyone would have expected (Mayumi et al., 2012). The meltdowns and explosions of the Fukushima Daiichi nuclear plant have led Japan to take many nuclear reactors offline across the country, thereby causing the country to become more reliant on natural gas imports. This, along with industrial shutdowns, has thrown a decades-long trade surplus of Japan into deficit in the following year, reported in Sharp (2012). The country now depends heavily on natural gas in compliance with the Kyoto protocol. Other nations in Europe are also exploring alternatives to nuclear power. Reported in Baetz (2011), Germany will shut down all of its nuclear plants by 2022, and Switzerland by 2034.

Therefore, the best means to achieve the target without hindering economic prosperity and competitiveness is still the subject of debate. While decarbonization and large-scale electrification seem inevitable, any transformation of existing infrastructure in energy-intensive sectors and the status quo (e.g., conventional vs. renewable energy or fuel-combustion vs. electric vehicles) must be done meticulously, as they could potentially present opportunities for enhancing competitiveness as well as pose threats to the economy. One such threat that is posed by environmental regulations is price uncertainty. The experience from phase I of the EU ETS has already showed that carbon prices could be volatile (Wråke et al., 2012). Such price uncertainty could translate into higher costs and risks imposed on other sectors of the economy because the increase in wholesale electricity prices may be directly passed onto retail consumers.[6]

It is certain that a low carbon path necessitates the transformation of the electricity industry. Of particular interest in this dissertation is the extent of the impacts that market mechanisms such as C&T programs, which aim to facilitate such transformation, have on electricity markets.

1.2 Overview of GHG Regulations in Electricity

It is important to consider the electricity sector when crafting a comprehensive climate change policy. Current policies have utilized a wide range of tools across various scales, including emissions pricing, policies to promote research and development, regulations favorable for clean energy, and public investments. These have been implemented mainly in parts of North America and Europe. While more can be expected in the near future, prospective policies need to incorporate various tools in the electricity sector, such as market mechanisms and direct regulations.

In recent years, C&T programs have been widely adopted to put a price on GHG emissions and internalize the social cost of pollution. By trading emissions allowances, the main objective of a C&T program is to incentivize private entities under the program to coordinate emission activities effectively, thereby minimizing the overall abatement costs in achieving an emission target (Newell & Stavins, 2003). The EU ETS was the first carbon-pricing program set up in 2005. It is considered the most comprehensive program to address climate change and also the largest emissions trading system to date. The first phase of the program began in January 2005 and is currently in the second phase that will end in December 2012. In 2020, emissions are expected to be 21% lower than in 2005 (European Commission, 2010).

Compared to the European instrument, similar large-scale attempts have been relatively unsuccessful in the U.S. for various reasons. One major reason is that politics at the federal level may hinder long-run regulatory development and implementation. For instance, the outcome of the mid-term election in 2010 may have hampered the pace of a comprehensive federal energy and climate policy.[7] Another reason is that different states have their own jurisdictions and perspectives on climate change issues. This circumstance has led to numerous smaller-scale efforts on the regional or state level. Currently, there are three main regional collaborative programs among several local governments in North America for tackling climate change and promoting green energy innovations. First is the Regional Greenhouse

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[6] See more discussions on risks that can undermine the EU ETS in Grubb and Neuhoff (2006).

[7] See American Clean Energy and Security Act of 2009 (passed by House on June 26, 2009 but was never passed by the Senate). This legislation aimed to "create clean energy jobs, achieve energy independence, reduce global warming pollution and transition to a clean energy economy."

Gas Initiative (RGGI) on the East Coast, which only covers the electric power sector. The RGGI is a collaborative effort between the Northeastern states[8], which provides a platform for trading emission allowances among electric utilities. The program distributes allowances through auctions, from which the proceeds are used to fund investment in developing clean and renewable energy, as well as energy efficiency. Second, the Midwestern Greenhouse Gas Reduction Accord (MGGRA), which is the climate pact for Midwestern states. Although the pact had issued the final rule for a cap-and-trade program and other complementary policy measures, there has been no further progress or actual implementation since early 2010. Third, perhaps, one of the most comprehensive regional efforts is the Western Climate Initiative (WCI), which includes California and four other Canadian provinces.[9] The WCI has set a regional target for GHG reductions and designed a market-based program that, unlike RGGI, extends to cover sectors other than electricity generation, partly because it also aims to create "green" jobs and reduce dependence on imported oil (WCI, 2010). All of these regional efforts may be considered intermediate steps to the national level.

There are many other policies to complement the cap-and-trade mechanism. Examples include energy efficiency standards, renewable energy standards, and other R&D supports in areas such as fuel cells and other storage technologies. Some notable GHG programs that have been rolled out in a relatively large scale include renewable portfolio standard (RPS) and renewable energy credits (RECs). RPS is a state policy that fundamentally requires a minimum percentage of electricity generation from renewable energy resources, such as biomass, geothermal, solar energy, wind, and small hydroelectric. Currently, as many as 29 states and the District of Columbia already have RPS policies in effect[10]. One of the most stringent RPSs in the country is California's RPS, which requires investor-owned utilities (IOUs)[11], community choice aggregators, and electric service providers to increase procurement share from RPS-eligible resources to 33% of total procurement by 2020. Another market mechanism, as part of renewable energy programs, is the tradable renewable energy credits. RECs can be used to reduce costs and increase flexibility for RPS compliance obligations. Some U.S. states, including California, have approved the use of these RECs to complement their RPS programs; a utility or other load-serving entity can substitute one unit of its RPS requirement by purchasing one unit of REC (typically measured in kilowatt-hour (kWh)).

There are also other voluntary approaches, such as corporate collaboration, information dissemination, and education (see, e.g., Price, 2005). These approaches have proven to

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[8] According to the official RGGI website, there are nine participating states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. Retrieved from `http://www.rggi.org/`

[9] According to WCI website, the WCI partners are British Columbia, California, Manitoba, Ontario, and Quebec.

[10] See Database of State Incentives for Renewables and Efficiency ([DSIRE], 2012)

[11] California's three large IOUs are Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E).

contribute positively towards climate change mitigation efforts; however, they usually work on a smaller scale. Thus, for such a large-scale, complicated issue like global climate change, it is important for any jurisdiction to impose mandatory policies, like the C&T program; at the same time, voluntary approaches should be encouraged among private individuals, households, institutions, and organizations to complement the backbone policy.

1.3 Issues Concerning Cap and Trade Programs in Electricity: the Case of California

In the United States, California has been the front-runner in adopting climate change legislation, namely the Global Warming Solutions Act of 2006, or Assembly Bill (AB) 32. The bill required the California Air Resources Board (CARB) to prepare a plan, now known as the AB 32 Scoping Plan, to identify and develop market mechanisms and regulations to reduce statewide GHG emissions to 1990 levels by 2020. The initial mandatory cap begins in 2013. With the size of economy comparable to those of Japan and Western European countries and as one of the largest GHGs emitters, California has aggressively worked to reduce GHG emissions. Its approach may provide a good example to both domestic and international economies. Thus, California will be central to our discussion regarding policy issues in the electricity sector.

The California's AB 32 Plan is a multi-faceted climate change policy. By taking into account both the supply and demand side of the markets, the Plan is comprised of a market-based mechanism (C&T program) and other complementary measures, including the increased use of renewable energy, the implementation of the Low Carbon Fuel Standard, and energy-efficiency programs. As part of the Plan, California has already invested millions of dollars in research and demonstration of smart grid, energy storage, and demand response, which aim to encourage efficient use and conservation of energy. Such comprehensiveness will not only help California to meet its ambitious emissions target, but it will also help promote energy efficiencies that facilitate the emission reductions in a cost-effective manner.

California's C&T program is considered the nation's most comprehensive scheme to reduce GHG emissions, enforcing mandatory emission ceilings on major GHG emission sources such as refineries, power plants (and/or first deliverers of electricity), industrial facilities, and transportation fuels. The program also provides regional linkage with the WCI, which can further improve economic efficiency. Through the enforcement of a mandatory cap, the program defines the quantity of reductions and provides accurate emission forecast.

Although a quantity-based mechanism like C&T can induce firms to abate their pollution efficiently, it poses various challenges for a successfully sustainable implementation of the program within the sector. Since electricity generation accounts for as much as a quarter of all GHG emissions in California[12], the mandatory cap would inevitably impact the markets.

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[12] See CARB (2011c).

Any C&T program, unlike other price-based mechanisms, poses potential uncertainty in marginal cost of emissions reductions, resulting in economic volatility. Furthermore, any manipulation of the market rules, or gaming, would distort prices, which could potentially lead to unnecessary investments in abatement technologies and high costs to the economy in achieving targeted emissions reduction. All these can ultimately undermine the overall economic efficiency and environmental goals of the program. Other policy goals, such as building competitive advantage and mitigating cost impacts, also play an important role in the design of the program.

Since the AB 32 Plan primes California for the long-term goal of 80 percent emissions reduction below the 1990 level by 2050, it is crucial to study, from the beginning, the interaction between the electricity and emission markets to prevent unintended adverse impacts on the performance and operation of the electricity markets, as well as other economic and environmental consequences. Since one of the objectives of this dissertation is to identify potential gaming opportunity that may arise from market designs, it is necessary to discuss some features and issues prior to introducing any market modeling approach. The following discussion will explore the California's C&T program in terms of its important features and issues that are relevant to the electric power sector and may merit further market simulations.[13]

1.3.1 Market Structure

Total GHG emissions from all regulated entities are subject to the mandatory declining emissions cap scheme; therefore, the number of tradable allowances gradually decreases over time. The program is expected to cover more than 80% of California's economy by 2015 (EPRI, 2011). According to CARB's Final Regulation Order (2011b), the first compliance period is effective from January 1, 2013 to December 31, 2014. At the beginning, the initial cap for the year 2013 will be set to 162.8 MMTCO2e, which is the expected emission of that year. The cap will decline by 2% in 2014. In 2015, the cap increases to 394.5 MMTCO2e to include fuel suppliers. The cap will decline thereafter by 12 MMTCO2e annually.

In the C&T program, the two main types of compliance instruments are allowances (permits) and offsets. Each offset or allowance is equal one MTCO2e. The covered entities need to surrender one compliance instrument for each MTCO2e of any GHGs they emit. These entities can also trade compliance instruments. The market price of these instruments will create incentives for them to reduce emissions when it is less expensive than acquiring additional compliance instruments.

While allowances are compliance instruments that directly allow entities to emit the equivalent amount of GHGs, another instrument, 'offsets,' are credits given to projects that are qualified as emissions reductions. That is, entities can purchase offset credits from four

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[13] As directed by Resolution 11-32, the California Air Resource Board (CARB) has established a market simulation group to identify situations that might lead to market disruptions. The issues discussed below are consistent with CARB. See CARB (2012) for more details for the market simulation group.

currently acceptable protocols: U.S. forest projects, livestock, ozone depleting substances, and urban forests. These protocols offer a means to reduce the overall emissions by taking CO_2 out of the atmosphere or decrease emissions from sources outside the program. Any entity, both under and outside the cap, can receive offset credits; in other words, any entity can get paid for their emissions reduction. These offsets can be traded or can also be used for compliance obligation. Nonetheless, the scope and scale of these offsets are subject to some requirements and restrictions.[14]

1.3.2 Compliance Timeframe

According to CARB (2011b), the compliance period of the AB 32 plan between 2013 and 2020 is divided into three periods. The first compliance period covers the years of 2013 and 2014, while the second compliance period begins in January 2015, and the third begins in 2018. All covered entities are required to submit compliance instruments that match their emissions at the end of each compliance period. Beginning in 2013, electricity generators, cogeneration sources, operators of stationary combustion, and large industrial facilities emitting at least 25,000 MTCO2e per year are subject to the C&T regulation. In addition, any out-of-state generators, delivering electricity to the California's electricity transmission and distribution system, are also subject to the regulation. Additional sources that will be included in the C&T regulation in the second compliance period of C&T are the fuel supplies, or entities that supply fuels (e.g., natural gas, gasoline, diesel, and ethanol) to all industrial, commercial, and residential sectors. All entities have an annual compliance obligation that is equal to the total annual emissions from its regulated facilities.

A long compliance period has raised concern over sizeable potential default. To mitigate such issues, entities are required to surrender compliance instruments for an annual compliance obligation, which is equal to 30 percent of the previous year's obligation. These compliance instruments are counted towards the total compliance obligation for the entire compliance period. This requirement does not impose any limit on the use of the offsets instruments (CARB, 2011b).

1.3.3 Compliance Behaviors and Point of Regulation

With only gross per capita GHG emissions of 11.3 MTCO2e/person in 2007, California's per capita GHG emission level is about 40% below national average per capita emissions (CARB, 2011a). In the year 2009, California's electricity consumption is supplied by approximately 70% in-state generation and 30% imports, however, the emissions from the latter account for almost half of the total emissions from the electricity generation sector.[15] Therefore,

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[14] These offsets apply only to projects located in the U.S., Canada, or Mexico; however, the limitation may be relaxed once the program is extended to link with other external programs in the future.

[15] See California Energy Commission (2011) for data on California electrical energy generation; CARB (2011c) for California GHG emissions inventory.

the imported electricity, while fulfilling only 30% of California's electricity demand, has considerably higher carbon intensity. Any attempt to regulate only in-state resources will have negative effects on the overall cost of emissions reductions and productions (Fowlie, 2009).

Because the C&T program is implemented on a local/regional level, such geographic limitations may lead entities to pursue strategic behaviors, manipulating their emissions reports, which would eventually undermine the program. Firms that have production facilities in multiple locations have incentives to circumvent the emission requirements by engaging in strategic behaviors such as emission leakage and resource shuffling.

Emissions Leakage. Emission leakage can occur when there is an offsetting emission increase in other unregulated states that provide exports to California. Furthermore, relative price changes induce a shift in production towards the unconstrained states. As the C&T program places an upward pressure on production costs in California, electricity-intensive industry may relocate to neighboring states and export its goods back to California. This is the so-called *pollution haven hypothesis*, which could compromise the overall emission reduction and result in reduced incentives to invest in green technologies.

Resource Shuffling. Emission leakage can also occur through resource shuffling, also known as contract shuffling. This occurs when a deliverer shuffles its dispatch points to earn credits for emissions without actual reduction in emissions. For example, the deliverer switches from a high-emitting source to a low-emitting source and diverts power from the high-emitting source elsewhere.[16] In CARB (2011b), it is formally defined as "any plan, scheme, or artifice to receive credit based on emissions reductions that have not occurred, involving the delivery of electricity to the California grid."

In response to those issues discussed above, the policies with different point of regulation in the California's electric power sector which have received most attention include: source-based, load-based, and first-deliverer approaches. The source-based approach, also known an 'upstream' approach, places the point of reporting and compliance obligation at the point of fuel combustion. Facilities that emit the pollution are obligated to acquire allowances. The load-based approach, also known a 'downstream' approach, places the point of reporting and compliance obligation at load-serving entities (LSEs). LSEs are responsible for the pollution that is emitted by upstream electricity generators. The first-deliverer approach places the point of reporting and compliance obligation at the first deliverer of electricity into California (CARB, 2011b). All in-state generating facilities are automatically first deliverers. Entities that import out-of-state power into California are also subject to compliance obligation. For in-state generating facilities, the first-deliverer approach is like a source-based approach. For electricity importers, the first-deliverer approach is like a load-based approach.

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[16] See, e.g., Bushnell et al. (2008).

The source-based approach poses a significant risk of resource shuffling. The load-based approach is inferior to the other approaches because of its administrative complexity and adverse impacts on dispatch efficiency (Wolak et al., 2007). The other concern with the load-based approach is contract shuffling (Bushnell, 2008). Therefore, CARB is pursuing the first-deliverer approach; the broader scope of the C&T program is projected to reduce emission leakage as the program expands.

1.3.4 Emissions Allowances: Allocation and Auctions

In the California's electric power sector, allowances are distributed through two mechanisms: free allocation and auction. The two mechanisms will help balance the competing forces of efficiency and distributional concerns as free allocation reduces the burdens on regulated entities. According to CARB (2011b), at the beginning of the first compliance period, in 2013, most allowances will be allocated to electric distribution utilities for free. The purpose is to facilitate the transition by reducing initial increase in costs and allowing time for "green" investments to occur. The total allowance allocation for the electric power sector is equal to 90% of the sector's emissions in 2008, or about 97.7 MMTCO2e.[17] As the role of efficiency weighs more while the program proceeds, the portion of free allocations will linearly decrease to 83 MMTCO2e in 2020, with more allowances auctioned off. In the electric power sector, free allowances that are given to electric distribution utilities must be offered at auction. The proceeds accrued from the auction will be used exclusively to compensate for increased electricity prices, only for the benefit of ratepayers.

For the California's C&T program, the pre-determined apportionment of allowances (percentage allocation factors) to individual utilities will not be automatically updated during the course of the program that ends in 2020; however, adjustments may be made. This is to allow the utilities to make a long-term plan for investments. The allocation methods take into account ratepayer cost burden, energy efficiency achievements, and Early Action in renewable resources (CARB, 2011a).

Auctions of current and future vintage allowances will take place every quarter. There are restrictions upon the number of allowances each entity can purchase at an auction. For current vintage allowances, IOUs can purchase up to 40%, all other covered entities up to 15%, voluntarily associated entities can buy up to 4%, of the total number offered at auction. For future vintage allowances, all entities can only buy up to 25% of the total number offered at auction (CARB, 2011b).

1.3.5 Other Market Operation Features

Along with the core instruments and features, the Plan also contains other elements and features that aim to allow the overall market operations to run smoothly and effectively.

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[17] See CARB, (2011a) for allocation of allowances to the electric sector.

The policy has specified precise rules, the scope, and extent of its regulation, while leaving some flexibility for the markets to reflect new information. The noteworthy rule is a feature with regards to banking and borrowing (Stern, 2007; Aldy et al., 2010). To prevent possible extreme fluctuation of instrument prices, price containment apparatuses, namely price floor and price ceiling, are clearly defined and enacted.

Banking and Borrowing. The main purposes of banking and borrowing are to provide intertemporal flexibility and to protect against price volatility through financial instruments, as was the case in the first two phases of EU-ETS. Allowances from previous years may be sold or surrendered for compliance. There is no expiration on any "banked" allowances. However, there is a restriction on the number of banked allowances an entity may hold (discussed in details under Holding Limits). The value of allowance banking is added via the scarcity due to the emission cap that declines over time. It is predicted that, in the short run, the price of allowances will initially increase, as firms make abatement investments and defer the surrender of allowance for future compliance obligations. The increase in price will continue until it is equal to the rate of interest under perfectly competitive assumptions without uncertainty (Rubin, 1996). But this result can be complicated further by the presence of market power (Montero, 2009). Recently, Hasegawa and Salant (2012) analyze the effects of safety valves under delayed compliance. They identify two potential consequences: speculative attacks and nonexistence of equilibrium.

Although unconstrained borrowing adds to the program bi-directional flexibility, the California's C&T program allows borrowing only from future periods to satisfy any excess compliance obligation in the current period. Excessive borrowing can create risk of price spikes in future periods as supply of allowances are limited (Holland & Moore, 2012). Generally, it can be counter-productive if it leads to significantly large debts in the future; such a scenario does not reduce emissions and would require debt relief in the future (Burtraw et al., 2006).

Holding Limits. There are two separate holding accounts for current and future-period allowances, for which different holding limits apply. The holding limits define the maximum number of allowances an entity can hold. First, no entity is allowed to hold approximately more than 2.5% of total allowances issued for the current year.Second, no entity is allowed to hold more than approximately 2.5% of total allowances sold at an advance auction for the future period.

Direct Volatility Mechanisms. Price volatility can undermine the C&T program for reasons discussed earlier. "Safety valves" or "price collars" would set a minimum or maximum price of allowances by adjusting the number of allowances available to the market. They are known to provide adjustment mechanisms that relieve pressures on allowance prices.[18]

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[18] See, e.g., Murray et al. (2009).

In California, this concept is applied through two main direct volatility mechanisms: allowance price containment reserve (APCR) and floor price. Along with various other mechanisms such as borrowing and offsets to protect against excessive upward movements in price, APCR is a direct mechanism for price relief. ACPR is a "soft" price collar, which provides a limited reserve of allowances at the price ceiling. Fell et al. (2012) compare"soft" and "hard" collars (unlimited reserve) under a stochastic dynamic framework with uncertainty in the baseline level of emissions. They find that the variability in allowance prices and the expected abatement costs decrease with increasing size of reserve (changing from a soft collar to a hard collar), but at a diminishing rate.

According CARB (2011b), a portion of allowances is withheld from auction for APCR every year: 1% for the years 2013-2014, 4% for 2015-2017, and 7% for 2018-2020. These withheld allowances will become available for the covered entities to purchase when the price reaches predetermined thresholds. These allowances are priced in three equal tiers of \$40, \$45, and \$50. The prices will increase by 5% annually plus the inflation rate.

Floor price is set to \$10 for auction in 2013. It will also increase by 5% annually plus the inflation rate per year. The floor does not act as a minimum price guarantee, but rather the price is defended through a controlled reduction in supply of allowances, not through a standing offer to purchase allowances at the floor price (CARB, 2011b).

1.4 Modeling Approaches

The AB 32 Scoping Plan can be one of the most complicated to draft and implement. With many stakeholders involved, modeling and simulation are useful tools throughout the process of creation, implementation, and evaluation of the Plan. They are also useful for future adjustments and improvements to the policy elements and measures. Not only can these tools help analyze the impacts on California's economy, they also help regulators prevent any potential adverse consequences.

For the purposes of this dissertation, there are generally two types of models: macroeconomic analysis models (top-down) and sector analysis models (bottom-up). Although this dissertation is focused on the bottom-up approach, it is important to understand contributions and relations of different modeling approaches. The macroeconomic analysis models are macroeconometric or computable general equilibrium (CGE) models with highly aggregated sectors, while only CGE models can provide an analysis of carbon leakage channels and terms-of-trade effects (Neuhoff et al., 2008). The top-down models are mainly used to provide advice and foresight in developing the AB 32 Scoping Plan, as well as to provide the ex-ante impacts on California's economy. The sector analysis models are used to evaluate the impact of the Plan on the electric power sector. More importantly, they are also used to identify other potential inefficiencies that arise from the pursuance of strategic compliance behaviors and the key elements of the Plan, mentioned in the previous section. However, the sector analysis models lack interaction with the rest of the economy.

1.4.1 Macroeconomic Analysis Models (Top-down)

California ARB has conducted an economic analysis of the AB 32 Scoping Plan by embracing two main economic models: the Energy 2020 model and the Environmental Dynamic Revenue Assessment Model (E-DRAM).[19]

Energy 2020 is a multi-region energy model, which is used to simulate the demand and supply scenarios for all fuel types in order to evaluate various policy options. The model is also used to analyze changes in investment and fuel expenditures, as well as the impacts of GHG emissions reductions on WCI partners.

E-DRAM is a computable general equilibrium (CGE) model, a standard economic tool for empirical analysis. By utilizing realistic economic data, CGE models are used to evaluate the aggregate welfare effects across multiple markets. E-DRAM complements Energy 2020 by providing analysis of the impacts on output, income, and employment in California.

Charles River Associates (CRA) also developed another CGE model for the same purposes (CRA, 2010). CRA evaluated the impact of the Plan on the overall California economy. Both CARB and CRA have predicted strong economic growth after the implementation of AB 32. Their studies also find that the amount of offsets, as small as four percent of the emissions cap, can significantly reduce the allowance prices. According to the studies by CARB and CRA, such price reduction can be about 80 percent and 33 percent below the case in which no offset is allowed, respectively. The main difference between the two studies is the effect of complementary measures. While CARB reported that these measures would reduce the costs of complying with AB 32, CRA study found otherwise, i.e., such command and control measures would increase costs as flexibility is reduced. The difference is fundamentally due to the fact that CRA did not include market failures in terms of energy use as one of its assumption like CARB did.[20]

1.4.2 Electricity Analysis Models (Bottom-up)

The liberalized electricity system consists of several segments, including generation, transmission, distribution, and retailing services, which are linked by multiple unbundled markets for energy, transmission, and reserves. The auxiliary markets created under various environmental regulations further complicate the system. Moreover, the nature of electricity itself is an intricate matter; there are several operational considerations of various technical constraints, such as real-time balancing of supply and demand, transmission constraints, and unit commitment. With all these complex interactions, market design has always been an important part of oligopolistic electricity markets. Therefore, in order to develop and design appropriate regulatory frameworks, it is important to understand market behaviors of the

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[19] See CARB (2010) for the detailed economic analysis of the AB 32 Scoping Plan.

[20] CARB model assumes that market failures prevent individual decisions regarding use of energy-efficient devices. By assuming such market failures, the efficiency potential exists when well-designed complementary measures (standards) are implemented.

interconnected markets, thereby requiring detailed and flexible modeling techniques.

In analyzing the impacts of environmental policies, such as the AB 32 Plan, on the electricity markets, there are two modeling techniques that can be applied: agent-based models and equilibrium models. This dissertation aims to study issues concerning market power, which is an equilibrium phenomenon. Hence, an equilibrium model is a natural approach to study economic equilibrium problems in the context of market-based regulatory instruments in the liberalized electricity markets (Twomey et al. 2005). Nonetheless, it is worthwhile to discuss agent-based modeling and its contributions.

Agent-based Models. Agent-based modeling and simulation (ABMS) can be useful for modeling dynamic interaction of agents to gain insights into complex economic systems (Tesfatsion, 2006). A distinctive feature of ABMS is its capability of modeling strategies that are rapidly adaptive, leading to a more detailed analysis. ABMS is not restricted to homogeneity in type or size of agents being modeled, which is typically assumed in analytical modeling (Weidlich & Veit, 2008b).

The literature on the analysis of electricity markets using ABMS has been relatively vast in both scope and scale.[21] ABMS is widely used to model sophisticated strategies across electricity bidders through variations of reinforcement learning. The common agents in ABMS in electricity markets include a system operator, generators, and LSEs. ABMS can also be extended to include other stakeholders, such as regulator, network representation, and even retail customers. The market simulations are based on the interactions among these agents.

While there has been much study on electricity markets, little research has been done applying ABMS approaches directly to emissions markets in conjunction with electricity markets. The analysis of interactions between emissions and electricity markets, which is modeled by using the ABMS approach, is found in Weidlich and Veit (2008a) and Wang et al. (2009). In contrast to the former, the latter explicitly modeled trading decisions on purchasing and selling allowances in the emissions market.

While the ABMS approach, with its advantages, has been developed and used extensively to simulate the current electricity markets, the ABMS models contain substantial shortcomings and issues, as follows (Weidlich & Veit, 2008b):

- Simulated agents repeat interactions with each other following heuristics for strategies and objectives; therefore, the choice of algorithm for agent learning behavior is hardly justified.
- Equilibria are not required nor necessary.
- Non-equilibrium solutions or multiple equilibria are difficult to interpret.
- Most research is focused on the convergence towards stable market outcomes, while often disregards the dynamics of the underlying markets.

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[21] See Weidlich and Veit (2008b) for a survey of ABMS research on wholesale electricity markets.

- It is difficult to validate outcomes with empirical data (Tesfatsion, 2006).
- Transmission congestion is often ignored.

Equilibrium Models. Equilibrium models are commonly applied to study the potential for market power and costs of C&T policies in (transmission-constrained) electricity markets. Using the solution concept in game theory, equilibrium models for electricity markets represent the constrained optimization problems of electricity generation firms, LSEs, arbitragers, and system operators. The equilibrium approach allows the analysis of strategic behavior of market participants, which can be represented with an oligopoly framework such as Bertrand, Cournot, Stackelberg equilibria, as well as supply function equilibrium and conjectural variation equilibrium (Ventosa et al., 2005). The approach is capable of incorporating relevant technical constraints such as an emission cap, transmission ratings, and generation capacity limits.

Although equilibrium models have often been criticized for lacking an option to model sophisticated bidding strategies and dynamic "learning"[22], its analysis has yielded several insights into oligopoly electricity markets and their interplay with other emissions markets.

A number of studies have used equilibrium models to examine the effects of emissions trading programs on the electric power sector. One stream of studies involves the analysis of the short- and long-run impacts on the markets by using either analytical or simulation models. In these studies, the short-run analysis assumes that generation capacity is fixed, whereas the long-run analysis relies on dynamic models that entail modification of generation mix (e.g., capacity expansion). Another stream of studies using the equilibrium framework is the empirical approach. They can identify the exercise of market power by comparing counterfactual market simulations against actual market outcomes.[23]

Equilibrium models have been used to evaluate the long-run implications of emissions trading programs on market outcomes such as electricity prices and profits. For example, Linares et al. (2006) applied a Nash-Cournot capacity-expansion model to study the electricity sector of Spain, in terms of the effects of various allocation schemes on electricity prices and firms' profits. Their study found significant windfall profits to firms. Another example is Zhao et al. (2010), which presented an equilibrium model for analyzing the long-run efficiency of various allocation schemes, and identified factors that distort investment decisions.

In addition to the implications in the long run, the short-and medium-run impacts have also been studied. Bonacina and Gulli (2007) presented an auction model of a dominant firm in order to examine the impact of ETS. The results asserted that when market power exists, CO_2 costs potentially passed on to electricity prices could exceed 100% under certain conditions. Chen et al. (2008) identified factors in which CO_2 cost pass-through rates are affected in a transmission-constrained oligopoly market. Lise et al. (2010) then extended

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[22] See, e.g., Rothkopf (1999); Bunn and Oliveira (2001).

[23] See, e.g., Borenstein and Bushnell (1999); Borenstein et al. (2002); Bushnell et al. (2008).

Chen et al. (2008) to include more countries and a wide range of carbon costs. They showed that cost pass-through rates depend not only on the level of CO_2 prices, but also on the incidence of market power and the price responsiveness of demand for electricity.

A more recent example for analytical approaches is Hintermann (2011) that derived a threshold of free allocation in the presence of market power in both emission and electricity markets. The results illustrated that a dominant firm could abate less and purchase more allowances to inflate the price of allowances.

As existing literature illustrates, the equilibrium approach is more appropriate in studying market power issues in electricity markets. Therefore, the approach is taken in this dissertation.

1.5 Scope of the Dissertation

This dissertation begins with an introduction. The first chapter provides the general knowledge and concepts necessary to comprehend this entire study. It discusses the role of electric power sector in achieving emissions reduction targets deemed to mitigate global climate change. Then, an overview of the relevant GHG emissions regulations is presented as a prelude to California's cap and trade program. It describes the program's important features and discusses various issues. The chapter then ends with a substantial section on modeling approaches. The section presents a brief literature review on specific modeling approaches underlying the assessment of the AB 32 Plan, as well as the analysis of impacts on the electric power sector. This chapter stands alone and can be useful to anyone who wishes to gain a broad understanding as well as specific implementation details of the C&T program in California.

Beginning with a review of related work, Chapter 2 presents a modeling framework of the interplay between a transmission-constrained electricity market and a carbon C&T program. By assuming Cournot equilibrium in electricity market and perfect competition in the carbon permits market, a mathematical formulation of a baseline equilibrium model is provided. This chapter illustrates the capability of the model through the short-run analyses of two case studies: the IEEE 24-bus system and the Western Electricity Coordinating Council (WECC) 225-bus system. Various scenarios are simulated for different market structures to examine the economic and emissions impacts of C&T programs in response to different levels of emissions cap. While the IEEE 24-bus case study explores various resource ownership assumptions, the WECC 225-bus case study uses actual resource ownership data that represent the California market.

Chapter 3 presents a variant of the baseline equilibrium model, which is modified to account for the case in which the permit market is not perfectly competitive. A conjectural variation approach is proposed to model market power in permit trading. The conjectural variation parameters are derived "empirically" through an iterative approach. In addition, the model proposed in this chapter is readily modified to account for other sectors participating in the permit market. A case study is presented to illustrate an analysis of the C&T program's impacts on the California markets by using the WECC 225-bus system. The main interest in this case study is to understand the potential strategies pursued by firms, when they are given different permit endowments.

Chapter 4 summarizes all findings and discusses challenges to modeling the electricity market in conjunction with the C&T program. Future research directions are also discussed.

Chapter 2

The Impact of Carbon Cap and Trade Regulation on Congested Electricity Market Equilibrium

In 2009, the electric power sector accounted for 40% of US energy consumption, of which 70% was supplied by fossil fuels such as natural gas, coal, and petroleum (Energy Information Administration, 2010). A major change in regulation of greenhouse gas (GHG) emissions from the sector will, therefore, inevitably impact the markets. Such GHG regulations are already in effect in parts of Europe and North America, and more are expected in the near future. In Europe, the European Union Emissions Trading System (EU ETS) is well underway for its second phase from 2008 to 2012. In the United States, the effort has been concentrated on the regional or state level.[1] For example, California regulators adopted the nation's most comprehensive plan under the AB 32 Global Warming Solutions Act to curb carbon emissions using the cap-and-trade (C&T) model. On the East Coast of the US, the Regional Greenhouse Gas Initiative, in which ten states are participating, continues to be a forum for trading emissions allowances for electric utilities.

Regulations on limiting GHG emissions can be implemented through several market-based alternatives. Examples include renewable portfolio standards (RPS), GHG emissions tax, and C&T program. One of the strengths of these market-based instruments is their ability to couple with competitive electricity markets. Nevertheless, such interactions and their ultimate impact on the operation of the electricity markets as well as the environmental consequences must be carefully analyzed to avoid unintended adverse consequences.

In a perfectly competitive market, for instance, a carbon tax levied upstream on power plants would shift production toward low-carbon technologies such that total emissions

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[1] Although the outcome of the recent mid-term election might slow down the pace of a comprehensive federal energy and climate policy, the US Environmental Protection Agency (EPA) has planned on regulation of GHG emissions from coal-fired power plants through the new source performance standard under the Clean Air Act (Hughes, 2010).

should be reduced. Such intuition, however, may not hold when the behavior of strategic firms (owners of power plants) and demand response are taken into consideration. Under an emissions tax, these firms will face higher energy generation costs, and they will therefore alter their production schedules accordingly while taking into account emissions costs. In a locational marginal price (LMP)-based electricity markets, changes in energy outputs from plants at different locations might alleviate or intensify transmission congestion, thereby altering congestion patterns that possibly lead to some unintended consequences. For example, Downward (2010) illustrates through a stylized two-node system that overall carbon emission can increase after a carbon tax is imposed. When a carbon tax is levied on power plants, "cleaner" firms may become more competitive. Changes in the relative costs could eliminate congestion, thereby lowering energy prices. As a result, lower prices may induce higher electricity consumption, in effect lifting the overall carbon emissions. Even though this example represents a theoretical market anomaly, which may not be prevalent in practice, it highlights the need to consider the interactions and the potential unexpected consequences of environmental regulation in the electricity sector. Under the C&T approach, changes in a firm's output affect not only its marginal abatement cost, but also other firms' marginal costs through changes in the permit price (Kolstad & Wolak, 2003). Since the market-based permit price can be unpredictable and volatile, the interaction of strategic behavior and C&T in the presence of transmission constraints can complicate the outcomes further.

In strategic models, the analysis of the impact induced by alternative regulatory mechanisms is complicated by the presence of transmission network. The inclusion of transmission constraints can result in surprising equilibria (Neuhoff et al., 2005). Although the effect of transmission constraints on strategic interactions in transmission networks has been studied extensively, the research on the impact of emissions regulation in power markets mainly consists of empirical studies.[2] One exception is by Chen & Hobbs (2005), who demonstrate how generators could manipulate the power market by using $\mathrm{NO_x}$ emissions permits.

While typical analyses of market power focus on small scale networks in order to gain insights into the interaction of firms (e.g. Cardell et al., 1997; Borenstein et al., 2000), we extend the analysis to a more realistic setting taking into account loop-flow and examine the effect of ownership and transmission constraints under the C&T policy. We employ an oligopoly equilibrium model in which generators behave strategically to maximize their profits. To make such a model computationally tractable, we employ a direct current (DC) approximation of the network, which is commonly used in analyses of market power in the electric industry (Wei & Smeers, 1999; Pang et al., 2001).

This chapter studies the impact of the carbon C&T policy through two test cases: the IEEE 24-bus[3] system and the Western Electricity Coordinating Council (WECC) 225-bus system. In the 24-bus test case, we calibrate our equilibrium results with Shao & Jewell

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[2] See e.g., Kolstad & Wolak (2003); Capros et al. (1998).

[3] The term "bus" is used by power engineers to refer to a power system node (location). The terms—bus and location—are used interchangeably in this chapter.

(2010) in which the alternating current (AC) counterpart of this analysis is investigated under the assumption that the market is perfectly competitive. In addition, we use the WECC 225-bus system to simulate a realistic market that will allow us to gain insights into short-run equilibrium outcomes of the California market. This 225-bus system is a reduced representation of the WECC transmission system, which was also implemented in Yu et al. (2010) under an agent-based framework. In both test cases, we further simulate various scenarios to explore the policy impact on market outcomes in response to different levels of emissions cap and ownership structure of resources. We have three central findings in this chapter. First, under a C&T program, a power market in which non-polluting resources are highly concentrated among a few players is subject to potential abuses of market power. Second, a higher level of market competition, together with a tight cap, affect the distribution of producer surpluses among producers as relatively polluting producers are no longer competitive under high carbon costs. Third, if non-polluting resources operating in a congested network are geographically concentrated, there arises the concern over potential abuses of market power in the procurement of clean energy through the permit market.

This chapter is organized as follows. Section 2.1 presents a GHG-incorporated equilibrium model, including mathematical programming problems and equilibrium conditions of all market stakeholders. Section 2.2 outlines the calibration procedure for the AC model and scenario assumptions for the 24-bus system; Section 2.3 discusses economic implications of the system. Section 2.4 introduces the WECC 225-bus system and outlines various scenarios for an analysis, which is discussed in Section 2.5.

2.1 Model

We introduce a GHG-incorporated equilibrium model that is a variant of the model proposed by Yao et al. (2008). This model is extended to account for GHG constraints by 1) associating emissions with the generation facilities and 2) coupling the equilibrium model with an emissions cap constraint. The price of permits is determined endogenously within the equilibrium framework by imposing a complementarity constraint[4] as a market clearing condition. We assume that the permit market is perfectly competitive with demand derived from the production decisions of electricity producers who behave as price-takers in the permit market.

To account for strategic behaviors and transmission constraints simultaneously, the equilibrium model is based on a lossless DC load flow model where transmission flows are constrained by thermal capacities of the lines. The flows in the system are governed by the Kirchhoff's laws through the Power Transfer Distribution Factors (PTDFs). The producers are Cournot players who own multiple generators competing to sell energy at different locations in an LMP-based market, where prices are set by the Independent System Operator

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[4] A complementarity constraint is defined as follows: $x \geq 0$, $f(x) \geq 0$, and $f(x)^T x = 0$, where $x \in R^n$ and the function $f : R^n \rightarrow R^n$ are given (Cottle et al., 1992). In this chapter, we denote the orthogonality by $\perp$.

(ISO). As Cournot players, producers maximize their profit by adjusting production levels given their respective residual demand, but they behave as price takers with regard to emission permit prices and locational congestion markups are set by the ISO. Consumers at each location are assumed to be price-takers and their demand is represented by a price-responsive inverse demand function.

For computational ease, a virtual location (bus) is created for each additional generator at those locations with multiple generators. These virtual locations are connected to their corresponding original location through a line with unlimited thermal capacities. Each location then has at most one generator. In what follows, we introduce notations used in the model and subsequently present the GHG-incorporated equilibrium model that describes the optimization problems faced by each entity.

Let N denote the set of buses (or locations) and L be the set of transmission lines whose elements are ordered pairs of distinct buses. Let G be the set of firms, and $N_g \subset N$ be the set of buses where generators owned by firm $g \in G$ are located. Let i and l be the elements in N and L, respectively. Note that by construction each i refers to bus i and also refers to the plant located at bus i, if a plant exists.

Let the fuel costs of plant $C_i(q)$ be a quadratic function of megawatt (MW) power output q defined as $C_i(q) = \frac{1}{2}s_i q^2 + c_i q, \forall i \in N$. The emission quantities of power plants are given by $F_i(q) = e_i q, \forall i \in N$, where e_i's are the emission rate of plant i. Consumers in each location i are represented by the inverse demand functions $P_i(q) = a_i - b_i q, \forall i \in N$, where a_i and b_i are constants.

2.1.1 ISO's Problem

The ISO is assumed to maximize welfare (2.1)—taking into account the output quantity decisions of the firms—subject to the lossless energy-balance constraint in the network (2.2), the transmission constraints (2.3), the non-negativity constraint (2.4), and the emission cap (2.5). By controlling power imports/exports at all locations (r_i's), the ISO can use shadow prices of the transmission constraints as a price signal corresponding to transmission congestion to control line flows. Line flows are simply a function of the import/export at all terminal locations, in which the MW flow on line l as a result of a MW transfer from location i to the reference location is measured by the PTDF, $D_{l,i}$. In addition, the flow on each transmission line l is constrained by its thermal limit K_l measured in MW in DC models.

In the formulations for optimization problems in Subsections 2.1.1 and 2.1.2, the variables in parentheses next to the constraint are the Lagrange multipliers corresponding to that constraint. The Lagrange multiplier of (2.2), p, is the system marginal energy cost or price at the reference market. The Karush-Kuhn-Tucker (KKT) conditions of optimization problem is summarized as follows. λ_l^+ and λ_l^- correspond to the shadow prices of the upper and lower transmission limits in (2.3), and ξ is the multiplier assigned to non-negative constraint (2.4). The variable φ_i, as written in (2.6), can then be represented as the sum of difference of λ_l^+

and λ_l^- over all the lines l weighted by the i-th row of the PTDF matrix minus ξ_i. In a sense, φ_i is the marginal congestion cost that reflects the cost contributions of the various transmission elements experiencing congestion associated with i, as measured between that bus i and the reference bus. Reflected by (2.7), the market clearing LMP at bus i is then $p+\varphi_i$, where the demand at location i is equal to the MW power generated by plant i plus the MW import, expressed by q_i+r_i. The load, q_i+r_i, must be non-negative because electricity is non-storable. The Lagrange multiplier μ corresponding to the emissions constraint reflects the price of carbon permits that the ISO will use as a penalty mechanism (see (2.9)) to suppress the emissions level when the cap constraint (2.5) is binding at M tons, and μ is also the price of carbon permits for any permit trading among energy producers.

ISO's Optimization Problem

$$\max_{r_i:i\in N} \quad \sum_{i\in N}\int_0^{r_i+q_i} P_i(\tau_i)d\tau_i - C_i(q_i) \tag{2.1}$$

$$\text{s.t.} \qquad \sum_{i\in N} r_i = 0 \qquad (p) \tag{2.2}$$

$$-K_l \le \sum_{i\in N} D_{l,i} r_i \le K_l, \qquad (\lambda_l^-, \lambda_l^+) \quad \forall l \in L \tag{2.3}$$

$$r_i + q_i \ge 0, \qquad (\xi_i) \qquad \forall i \in N \tag{2.4}$$

$$\sum_{i\in N} F_i(q_i) \le M, \qquad (\mu) \tag{2.5}$$

KKT Conditions

$$\varphi_i = \sum_{l\in L}(\lambda_l^+ - \lambda_l^-)D_{l,i} - \xi_i, \qquad \forall i \in N \tag{2.6}$$

$$P_i(r_i+q_i) - p - \varphi_i = 0, \qquad \forall i \in N \tag{2.7}$$

$$\sum_{i\in N} r_i = 0, \tag{2.8}$$

$$0 \le \lambda_l^- \perp \sum_{i\in N} D_{l,i} r_i + K_l \ge 0, \qquad \forall l \in L$$

$$0 \le \lambda_l^+ \perp K_l - \sum_{i\in N} D_{l,i} r_i \ge 0, \qquad \forall l \in L$$

$$0 \le \xi_i \perp r_i + q_i \ge 0, \qquad \forall i \in N$$

$$0 \le \mu \perp M - \sum_{i\in N} F_i(q_i) \ge 0$$

2.1.2 Firms' Problem

Each firm g considers the output of all other firms and optimally sets its own output so as to ultimately maximize its profits, expressed in (2.9), when facing a price-responsive demand curve. As for revenues represented by the first term of (2.9), firms earn $p + \varphi_i$ for each unit of energy generated at plant i as their competing outputs simultaneously determine the reference-bus marginal energy cost p, while treating the locational congestion markup φ_i, determined by the ISO, as exogenous. This assumption can be perceived as bounded rationality of firms and is credible when the network is not radial (Neuhoff et al., 2005). The costs of firm g are represented by the last two terms in (2.9): the total fuel costs and the emissions costs which include the opportunity cost of the permit price μ for each unit of emission. Constrained by minimum operating limit ($\underline{q}_i$)[5] and maximum operating limit ($\bar{q}_i$) in (2.10), firms will vary outputs to maximize their profits, subject to the residual demand curve in which sales from other producers are treated as fixed. Modeling the firms' problem this way allows us to explore strategic interaction of firms as generation facilities of each firm are best responding to others throughout the system.

The KKT conditions imply the set of conditions for each firm g. Note that the residual demand constraint (2.11) can also be viewed as the market clearing condition (2.13), which can be written as $\sum_{i \in N} q_i = \sum_{i \in N} (P_i)^{-1}(p + \varphi_i)$, where the reference price p is implied by the joint production decisions of all the generators in the same way as the price in a conventional Cournot model.

Firms' Optimization Problem

$$\max_{q_i : i \in N_g, p} \quad \sum_{i \in N_g} (p + \varphi_i) q_i - C_i(q_i) - \mu F_i(q_i) \tag{2.9}$$

$$\text{s.t.} \quad \underline{q}_i \le q_i \le \bar{q}_i, \qquad (\rho_i^-, \rho_i^+) \quad \forall i \in N_g \tag{2.10}$$

$$\sum_{i \in N_g} q_i = \sum_{i \in N} (P_i)^{-1}(p + \varphi_i) - \sum_{i \in N \setminus N_g} q_i \qquad (\beta_g) \tag{2.11}$$

KKT Conditions

$$\begin{aligned} p + \varphi_i - \beta_g + \rho_i^- - \rho_i^+ - \frac{dC_i(q_i)}{dq_i} - \mu \frac{dF_i(q_i)}{dq_i} &= 0, \qquad \forall i \in N_g \\ \beta_g \sum_{i \in N} \frac{d}{dp} (P_i)^{-1}(p + \varphi_i) + \sum_{i \in N_g} q_i &= 0 \end{aligned} \tag{2.12}$$

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[5] The model abstracts from representing the startup, shut-down, ramping, and other non-convex costs that are typically considered in unit-commitment models. This implies that our approach of modeling fixed minimum production limits without possibilities of de-commitment may overestimate the emissions from these plants for which such limits are imposed.

$$\begin{aligned} \sum_{i \in N} q_i = \sum_{i \in N} (P_i)^{-1}(p + \varphi_i) & & (2.13) \\ 0 \leq \rho_i^- \perp q_i - \underline{q}_i \geq 0, & \quad \forall i \in N_g \\ 0 \leq \rho_i^+ \perp \bar{q}_i - q_i \geq 0, & \quad \forall i \in N_g \end{aligned}$$

2.1.3 Equilibrium Conditions

The market equilibrium conditions, consisting of all the KKT conditions for the ISO's and the firms' problems, constitute a mixed nonlinear complementarity problem. When ignoring the emissions trading, Yao et al. (2008) shows that the complementarity problem can be written in the form of a linear complementarity problem if the marginal cost functions and the inverse demand functions are linear. Extended to account for the emissions regulation, our market equilibrium conditions remain in the form of a linear complementarity problem because the emission functions are linear.

In equilibrium, the reference price p is determined simultaneously by all firms' decision on outputs. Eq. (2.7) and (2.8) in the ISO KKT conditions imply the market clearing conditions (2.11) and (2.13). However, including (2.11) and thereby (2.13) in the generators' problem implies oligopoly behavior where the producers account for the effect of their joint decision on the reference price. In modeling perfect competition, all suppliers behave as price takers with respect to both the reference price and the locational congestion markups; thus, (2.11) and thereby (2.13) are removed, while (2.12) is replaced with $\beta_g = 0, \forall g \in G$, yielding the same result as a cost-minimizing dispatch model.

The inverse demand function at each bus is assumed to be linear with a price elasticity of -0.1. Although short-run elasticities are nearly zero, this level of elasticity is consistent with empirical studies (Azevedo et al., 2011). For computational purposes, we assume the existence of price-responsive demand at all locations, and hence the demand curve at a location with no load is set as almost vertical with the intercept being a very small positive number.

2.2 Case Study: IEEE 24-Bus System

The system has 24 buses, 38 transmission lines and transformers, and a total load of 2,850 MW. The total generation capacity is equal to 3,405 MW (Table 2.1).

We use a lossless DC approximation, although ignoring electrical resistance might alter flow patterns that could lead to different congestion patterns under some network topologies (Baldick, 2003). As reported later in this section, the results obtained from the DC model, however, are fairly compatible with the AC model and, with proper calibration, provide a reasonable approximation for our purpose (which focuses on environmental policy). We outline the calibration procedure and report our results in the next subsection.

Table 2.1: Properties of generation units in the modified 24-bus system

Fuel Type	Fuel Costs [$/MMBtu]	CO_2 Rate [lbs/MMBtu]	# of units	Capacity [MW]
Oil	12	160	4	80
Gas	9.09	116	11	951
Coal	1.88	210	9	1,274
Hydro	0	0	6	300
Nuclear	0	0	2	800

2.2.1 Calibration Procedure and Results

The calibration procedure begins with an optimization model—hereafter referred to as DC optimal power flow (OPF)—that minimizes the system-wide energy costs, subject to fixed locational demand, while satisfying constraints (2.2)–(2.5) and (2.10). The model yields the most cost effective way to produce energy to meet demand. The optimal outputs will take into account the cost of carbon permit, which is reflected in the form of the shadow price of the emissions cap constraint (2.5), determined endogenously by the model. The DC OPF model is identical to the equilibrium model under perfect competition assumption.

The test system is then modified to investigate the effects of C&T and strategic interaction of firms. The 951 MW of steam fossil oil is replaced with 951 MW of steam gas in order to explore the implication of the regulation. This modification is consistent with the work reported by Shao and Jewell (2010) which employs AC power flow framework under perfect competition.

Figure 2.1a shows the total power outputs (summing over all producers) of all fuel types. A must-run level is imposed on the oil power generation because an output that is lower than this level would yield negative marginal costs. As a result, the oil-fueled generation stays flat at its must-run level because the oil power generation is not optimally cost-effective to produce in this model. When the cap is not imposed nor it is binding, the emissions level under the DC OPF is at 921 tons/h, fairly comparable to what was reported by the AC OPF analysis (Shao & Jewell, 2010). Furthermore, the sale-weighted average LMP is 16 $/MWh, which is slightly lower than that of the AC OPF model, partly because the market experienced relatively lower transmissions congestion. Nevertheless, at CO_2 prices higher than 180 $/ton, the sale-weighted average LMP is within 5% lower than that of the AC OPF model.

As shown in Figure 2.1b, at a CO_2 price of 112 $/ton, gas-fueled units begin to replace coal because the average marginal cost of gas power generation is 112.2 $/MWh, which is cheaper than that of coal (i.e., 113 $/MWh) when the CO_2 cost is considered. Therefore, when CO_2 price increases further, the higher price puts a downward pressure on the polluting coal units, causing a decline in total coal-fired power generation and the total CO_2 emission respectively. Although the AC OPF model gives a lower level of CO_2 price (70 \$/ton)[6] when merit order switch between gas and coal plants occurs, the two models reach qualitatively similar conclusions as the reduction in coal outputs differs by less than 5%. For instance, when the permit price increases from 0 \$/ton to 180 \$/ton, the reduction in MWh output of coal power generation is 52% in the AC OPF model, compared with a 47% reduction in the DC OPF model. Therefore, we conclude that the AC and DC OPF produce comparable results and proceed to our oligopoly analysis in the next subsection.

2.2.2 Scenario Assumptions

All analyses are performed on a one-hour basis because adding assumptions on time-variant loads would provide little insights to our purposes. In order to quantify the impact of the interaction of the energy market and the emissions market in a transmission-constrained network, we simulate various scenarios with different levels of emissions cap and changes in resource ownership. To investigate the effects more specifically, we set the emissions constraints at three cap levels: loose (1205 tons, 90% of no-cap case), moderate (815 tons, 60% of no-cap case), and extreme (515 tons, 38% of no-cap case). These levels are selected because they allow us to explore different market outcomes.

Table 2.2 presents seven different market scenarios along with detailed descriptions. Each scenario has an equal number of plants (32) but differs by the resource ownership structure. In PC-32 scenario, all firms are assumed to be perfectly competitive. Therefore, the different ownership (which firm owns what) does not lead to different market equilibria. Under the monopoly scenario (MP-1), all facilities are assumed to be owned by a single producer. The perfect competition (PC-32) and monopoly (MP-1) scenarios are used as benchmarks bounding other scenarios' equilibria.

The scenarios in Table 2.2 are ranked by their competitiveness from the most competitive (top, PC-32) to the least competitive one (bottom, MP-1) with respect to the number of firms in the market. The remaining five scenarios are Cournot-Nash oligopoly. They differ by their

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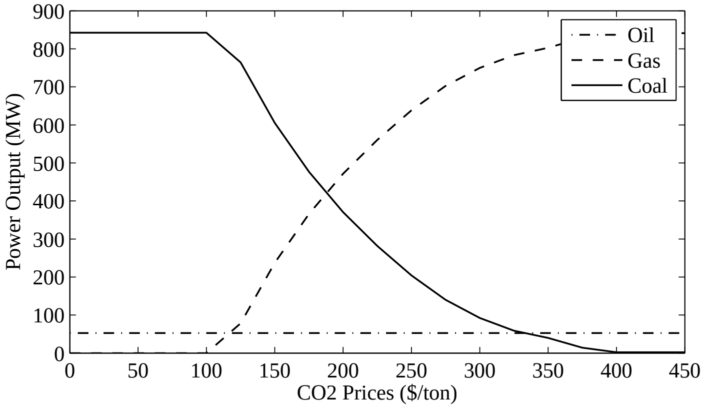
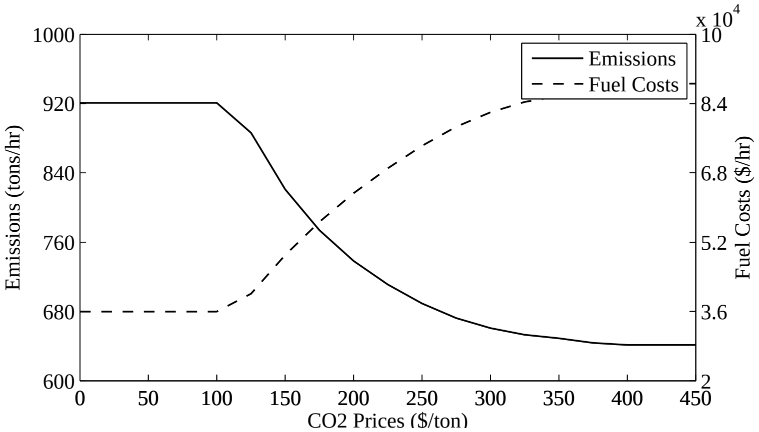
[6] Theoretically, the level of CO_2 costs or threshold price that will lead to a switch of production order (coal vs. natural gas) is determined by the interplay of several factors: the difference in the relative fuel costs and emission rates as well as the network effects. The AC OPF model gives a CO_2 price of 70 \$/ton when the fuel switch occurs, and this price is within the range of what has been reported elsewhere (McKinsey and Company, 2007). Without the transmission limits, however, the AC OPF model gives a much higher CO_2 price of 130 \$/ton. Typically, the threshold price is defined by arranging the production cost in ascending order without considering transmission congestion. However, in the presence of transmission congestion, identifying the threshold price is complicated because it requires rearranging production order by accounting for plants availability due to network effects when considering emissions costs. In the IEEE 24-bus case, low-emission facilities, which otherwise cannot export their energy when the network is congested, are allowed to replace high-emission facilities when transmission is ignored, effectively lowering the CO_2 price and elevating the CO_2 threshold price. Since the DC OPF assumes the same fuel cost and emission rate as the AC OPF, it implies that the difference in the CO_2 cost at which the fuel switch occurs between the two models is possibly because of the simplified representation of the transmission network in the DC OPF model without transmission losses.



(a) Outputs by fuel types



(b) CO_2 emission and fuel costs

Figure 2.1: Sensitivity analysis on CO_2 price

generation portfolios and ownership structures. In defining market scenarios, we use N, H and G to denote nuclear (2), hydro (6), and gas (11), respectively (the numbers in parenthesis denote the number of plants for each technology). We further group these technologies as clean technologies, hereafter referring to relatively low- or zero-carbon-emission technologies.

To begin with, the scenario 32F represents the most competitive Cournot case, where each firm owns one facility. In order to further explore the implications of concentrated ownership and technologies, market scenarios assume a variety of technology-ownership grouping. In N/H-26, one firm is assigned to own all the nuclear facilities and another one owns all the hydro facilities; the remaining 24 facilities (32-2-6 = 24) are owned by 24 firms. This scenario will provide insights into the market wherein two clean firms dominate many other small firms. Furthermore, we model the case where two clean firms (i.e., N (2) and H (6)) operate in a less competitive market by consolidating the rest of the market into two firms with comparable portfolios (N/H-4). To model even more extreme cases of the heterogeneity

Table 2.2: Market scenario description

Scenario[a]	Description
PC-32	Perfect competition with 32 firms in total
32F	Oligopoly with 32 firms in total: each firm owns only one facility.
N/H-26	Oligopoly with 26 firms in total: one nuclear firm, one hydro firm, and 24 thermal firms
N/H-4	Oligopoly with 4 firms in total: one nuclear firm, one hydro firm, and two thermal firms
NH/G-3	Oligopoly with 3 firms in total: one firm owns all nuclear and hydro facilities, second firm owns all gas facilities, and the third firm owns all coal and oil facilities.
NHG-2	Duopoly: one firm owns all clean facilities, i.e., nuclear, hydro, and gas while the other firm owns all coal and oil facilities.
MP-1	Monopoly: all facilities belong to only one firm.

[a] The number denoted in the name of each scenario represents the number of firms in each of them.

of technologies, the NH/G-3 and the NHG-2 scenarios assign all the facilities with clean technologies to one firm and the ones with dirty technologies to another. The only difference between these two scenarios is that NH/G-3 has an additional firm that owns all the gas facilities, thus separating this moderate carbon emission technology from the other clean ones.

2.3 Economic Analysis of the 24-Bus System

This section summarizes the economic analysis results. Tables 2.3-2.5 summarize the comparative statics, including total CO_2 emissions, total energy consumption, average sale-weighted LMPs, permit price (CO_2 Price), CO_2 emissions rate, congestion revenues, system fuel costs, and productive inefficiencies. Figure 2.2 reports the shares of power generation by fuel types for scenarios under loose cap, moderate cap, and extreme cap. Table 2.6 shows the distribution of economic surpluses.

Electricity Price. The average sale-weighted LMPs rise as the market becomes less competitive (fewer firms or more concentrated ownership), as shown from left to right in Tables 2.3-2.5. Consequently, the rise in prices leads to the decline in energy generations (consumptions). Under a tighter emissions cap where the equilibrium LMPs tend to be higher, such market prices arise in the less demand-responsive portion of the demand curve. The latter in turn grants higher market power to hydro, nuclear and gas facilities. For example, with the extreme cap, total hydro output in NH/G-3 is withheld by about 90% (=(300-27)/300) of its capacity (see Figure 2.2). Also, the average LMP in NHG-2 is the highest among oligopolies (Tables 2.3-2.5) because the "clean" firm in NHG-2, under all cap levels, withholds more than 25% of its nuclear capacity to drive up prices.

Table 2.3: Comparative statics: loose cap level (=1,205 tons)

	PC-32	32F	N/H-26	N/H-4	NH/G-3	NHG-2	MP-1
CO_2 Emissions [tons]	1,060	1,205	1,205	942	833	765	370
Energy Consumption [MWh]	2,160	2,000	1,924	1,702	1,599	1,452	1,086
Average LMP [$/MWh]	18	99	137	249	301	376	564
CO_2 Price [$/ton]	0	12	66	0	0	0	0
CO_2 Emissions Rate [tons/MWh]	0.491	0.603	0.626	0.553	0.521	0.527	0.341
Congestion Revenues [K$]	0	0	0	0	0	0	10
Total Fuel Costs [K$]	39	57	67	36	63	33	25
Productive Inefficiencies [K$]	0	21	32	4	32	4	0

Table 2.4: Comparative statics: moderate cap level (=815 tons)

	PC-32	32F	N/H-26	N/H-4	NH/G-3	NHG-2	MP-1
CO_2 Emissions [tons]	815	815	815	815	815	765	370
Energy Consumption [MWh]	1,962	1,871	1,750	1,631	1,586	1,452	1,086
Average LMP [$/MWh]	123	164	225	286	308	376	564
CO_2 Price [$/ton]	143	138	226	90	21	0	0
CO_2 Emissions Rate [tons/MWh]	0.415	0.436	0.466	0.500	0.514	0.527	0.341
Congestion Revenues [K$]	48	0	0	0	0	0	10
Total Fuel Costs [K$]	46	56	68	34	62	33	25
Productive Inefficiencies [K$]	0	17	35	2	31	4	0

Table 2.5: Comparative statics: extreme cap level (=515 tons)

	PC-32	32F	N/H-26	N/H-4	NH/G-3	NHG-2	MP-1
CO_2 Emissions [tons]	515	515	515	515	515	515	370
Energy Consumption [MWh]	1,734	1,648	1,556	1,537	1,367	1,294	1,086
Average LMP [$/MWh]	249	288	323	333	419	456	564
CO_2 Price [$/ton]	444	402	432	238	405	317	0
CO_2 Emissions Rate [tons/MWh]	0.297	0.312	0.331	0.335	0.377	0.398	0.341
Congestion Revenues [K$]	171	91	0	0	0	0	10
Total Fuel Costs [K$]	67	61	64	56	49	28	25
Productive Inefficiencies [K$]	0	1	10	5	18	1	0

Perfect vs. Oligopoly Competition. Although energy consumption declines with rising market power and/or tighter cap, lower energy consumption does not always decrease the total emissions. Table 2.3 shows that the energy consumption is lower in the 32F scenario, as compared to the PC-32; however, the 32F results in higher emissions. This circumstance occurs because the 32F yields an inferior CO_2 emissions rate due to inefficient economic dispatch of resources, i.e., clean low-cost units (nuclear) are withheld and/or replaced with gas-fueled generation (referring to the loose-cap results in Figure 2.2). As firms behave strategically, we can see that the system fuel costs are higher in 32F relative to PC-32, even though more energy (160 MWh more) is consumed in PC-32. To be precise, productive inefficiencies[7] show that the 32F is economically \$ 21k less efficient if the demand was met under perfect competition. These results illustrate the inefficiency resulted from the strategic interaction of firms competing under the C&T policy.

Emissions Permit Price. In general, the permit price, which is determined by firms' production decision, should rise as the quantities demanded and the wholesale market becomes more competitive. Under certain market conditions, the permit price can create even greater incentive for clean firms to pursue strategic withholding. When clean technologies concentratedly owned by a few firms, these firms would withhold their production from relatively cleaner resources in a way that allows production from more polluting resources to fill in the demand, effectively raising the demand for permits and driving up their LMPs (cf. Chen & Hobbs, 2005). One example is that, under the extreme cap, even a coal firm operating in duopoly (NHG-2) is outcompeted by the clean firm because the permit price soars to 317 \$/ton (Table 2.5 and Figure 2.2). The issue of strategic withholding could be aggravated further through its impact on the permit price if the rest of the market becomes more competitive, or if they possess little or no market power. In particular, Table 2.5 illustrates that the CO_2 price increases by 82% from 238 \$/ton in N/H-4 to 432 \$/ton in N/H-26 because the demand for permits increases as more of high-carbon fuels is burned (Figure 2.2). In the extreme case (not shown) if most polluting resources are owned by price-taking firms, the permit price would be pushed upward even further.

Transmission Constraints. The permit price is not only influenced by market power, but it is also adversely affected by transmission constraints. As shown in Table 2.6, the producer surplus in the 32F rises slightly from \$ 125k to \$ 138k as the cap level changes from loose to moderate, but it unexpectedly plummets as the cap is tightened further to the extreme level—as opposed to an increase evidenced in the N/H-26. Unlike N/H-26, there are two nuclear firms in the 32F competing to produce electricity, leading to more congestion[8]

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[7] The productive inefficiencies indicate how much fuel costs in a scenario deviates from the most effective economic way to meet the same demand.

[8] When there is no congestion in a network, the congestion revenues by default are equal to zero as no scarcity rent is associated with transmission.

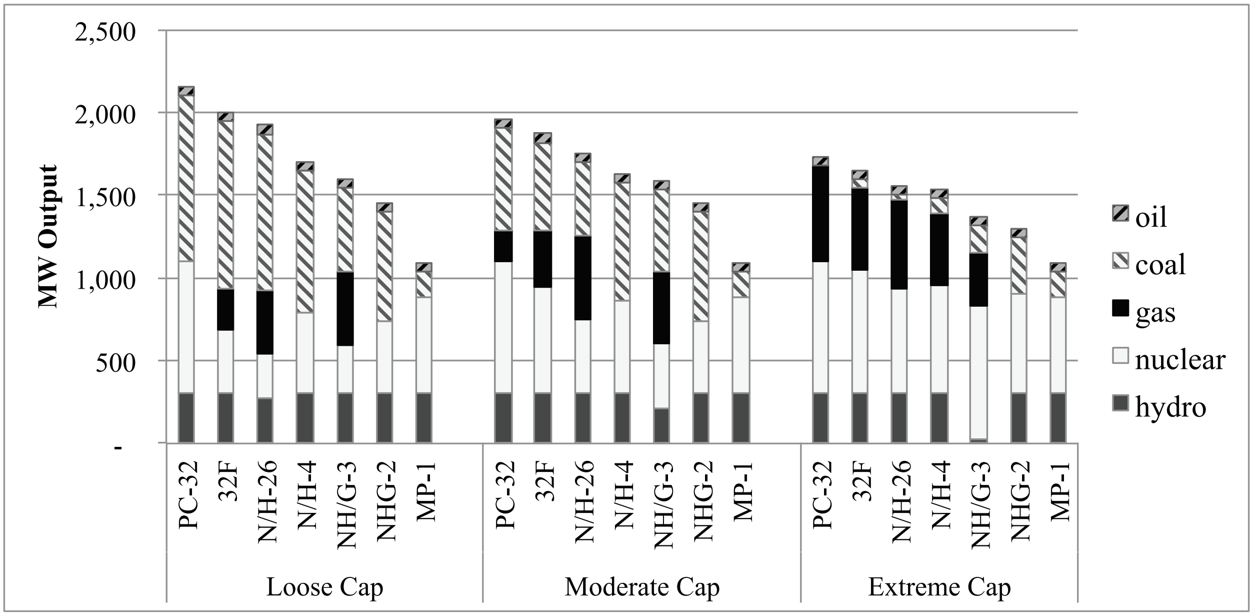

Figure 2.2: Power outputs at different cap levels

(see Table 2.5), which eventually limits the nuclear access to the market. Consequently, the demand for permit grows, costing firms higher permit price in addition to congestion rents. This observation emphasizes how the interaction between a less competitive market and transmission network can influence the exercised market power under emissions cap, leading to various unintended consequences.

Economic Surplus. At a fixed cap, Table 2.6 shows that consumer surplus declines as the number of firms decreases or ownership becomes concentrated. Meanwhile, in most cases, producer surplus increases as producers benefit from higher LMPs due to increasing market power. Overall, the increase in producer surplus is more than offset by the decline in consumer surplus, and the total social surpluses in all oligopolies fall within 10% as compared with their corresponding perfect competition case. As expected, producers benefit mostly in MP-1 at the expense of consumers. In fact, MP-1 gives the same equilibrium results across three levels of caps because the caps are non-binding. In contrast, the perfectly competitive market (PC-32) shows that some firms will no longer be profitable in equilibrium as suggested by the negative level of their producer surpluses. The negative producer surplus is attributable to the fact that some firms maintain its output at a must-run level even when the energy price is lower than their marginal cost.

Table 2.6: Economic results for the 24-bus system (in thousands of dollars)

	Cap	PC-32	32F	N/H-26	N/H-4	NH/G-3	NHG-2	MP-1
Social Surplus	Loose	1,236	1,208	1,189	1,177	1,122	1,102	939
	Moderate	1,215	1,192	1,156	1,160	1,119	1,102	939
	Extreme	1,145	1,136	1,108	1,109	1,052	1,041	939
Consumer Surplus	Loose	1,236	1,068	993	789	703	589	351
	Moderate	1,018	942	831	729	693	589	351
	Extreme	781	722	668	654	529	479	351
Producer Surplus	Loose	-1	125	117	388	419	513	577
	Moderate	32	138	141	359	409	513	577
	Extreme	-35	116	217	333	315	399	577

2.4 Case Study: WECC 225-Bus System

In this section, we perform an equilibrium simulation on a realistic western 225-bus electricity system with real heat rate data and load data, based on the model introduced in section 2.1.

2.4.1 Characteristics of the WECC 225-Bus System

The system model represents the essentials of the California ISO (CAISO) area, which is composed of 293 transmission lines and 225 buses. Our simulated hour is the median of the total hourly system load to represent the typical system condition. Of course, the permit price should be determined by the supply and demand condition over an extended time period, such as a typical compliance period of one year. Nevertheless, focusing on the one-hour analysis allows us to explore the market outcomes when producers respond to the C&T more aggressively.[9] Within the CAISO area, there are 23 aggregated thermal generators, 2 nuclear facilities, and a total of 15 aggregated hydroelectric and other renewable energy generators. The aggregated thermal generators have been grouped as "gas", because gas is the predominant fuel. Table 2.7 summarizes the resource mix of this system.[10]

The net imports into the CAISO area are aggregated to several import points, i.e. Ade-

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[9] Had the model been extended to an annual simulation, the permit price would be more elastic as producers are capable of coordinating their production decisions over extended periods. In fact, the model can be modified to account for annual simulations. For example, Chen and Hobbs (2005) presented a similar framework that allows the price of NOx emission permits to be determined endogenously. However, coupling multiple periods would likely complicate our analyses with limited additional insights.

[10] For greenhouse gas such as CO_2, the constant emission rate is commonly used in modeling energy policies, e.g., IPM (Integrated Planning Model) used by U.S. Environmental Protection Agency (2011). In contrast, strong nonlinearity associated with output level for other air pollutants, e.g., NOx (nitrogen oxides), is observed from a dataset provided by EPA CEMS (Continuous Emission Monitoring System, 2007). If the CO_2 emission rate was modeled as proportional to the quadratic fuel cost, it would discourage power plants from producing at a higher level since they would incur higher carbon costs.

Table 2.7: Resource mix of the WECC 225-bus system

Fuel Type	Avg. MC[a] (\$/MWh)	CO_2 (lbs/MWh)	# of units	Total MW	Percent
Hydro	7	0	6	10,842	23%
Nuclear	9	0	2	4,499	10%
Gas	70	1,281	23	26,979	57%
Biomass	25	0	3	558	1%
Geothermal	0	0	2	1,193	3%
Renewable	0	0	1	946	2%
Wind	0	0	3	2,256	5%
			40	47,273	100%

[a] Source: Marginal costs, except for gas, are from Energy Information Administration, Annual Energy Outlook 2010, DOE/EIA-0383 (2009)

Table 2.8: State average CO_2 emissions rate

Import State	CO_2 (lbs/MWh)
Arizona	1,219
Nevada	1,573
Oregon	456

Source: eGRID2006 V2.1, April 2007

lanto, El Dorado, Malin, Palo Verde, and Sylmar LA. In order to model the import supplies, we assume that each import point represents a competitive fringe with a price-responsive supply curve, which can be constructed using the same approach as the generation of the demand curves. To account for emissions, the state average CO_2 emission rates are used for imports (Table 2.8). The net exports to the Sacramento Municipal Utility District (SMUD)—a separate control area surrounded by the CAISO control area—are assumed to be electrical loads (electricity consumptions).

In addition to the thermal transmission constraints accounted for by eq. (2.3) in Subsection 2.1.1, the CAISO enforces a list of additional transmission constraints, often referred to as "bubble constraint", to ensure reliable operation in the case of unpredictable generation contingencies in so-called "load pockets". The purpose of such constraints is to enable emergency imports into the load pocket. The list includes several groups of transmission lines (branch groups). Let S be the set of branch groups (BG) and L_s be the set of lines included in group $s \in S$. The BG constraints are expressed as follows:

$$0 \leq \omega_s \perp W_s + \sum_{l \in L} h_{s,l} \sum_{i \in N} D_{l,i} r_i \geq 0, \qquad \forall s \in S, \tag{2.14}$$

where W_s's are power limits; ω_s's are their Lagrange multipliers; and

$$h_{s,l} = \begin{cases} 1 & \text{if } l \in L_s \text{ and } l \text{ is defined in the same direction,} \\ -1 & \text{if } l \in L_s \text{ and } l \text{ is defined in the opposite direction,} \\ 0 & \text{if } l \notin L_s. \end{cases}$$

Accounting for these branch groups, the marginal congestion cost is then equal to

$$\varphi_i = \sum_{l \in L} (\lambda_l^+ - \lambda_l^-) D_{l,i} - \xi_i - \sum_{s \in S} \sum_{l \in L} \omega_s h_{s,l} D_{l,i}, \qquad \forall i \in N. \tag{2.15}$$

The last term of eq. (2.15) reflects the additional cost of the branch groups that experience congestion. Hence, we add eq. (2.14) to the equilibrium conditions and replace eq. (2.6) with eq. (2.15).

The owners and fuel types include aggregations of some owners and fuel types within each zone. The biggest non-investor-owned utility (non-IOU) owners are retained, and the others are aggregated into the IOUs' portfolio since many of them would actually be under the IOUs' contracts. In total, there are 10 aggregated owners (firms) and 1 competitive fringe representing imports into the CAISO.

We define "dirtiness" of a firm by the capacity-weighted average of emissions rates of its available resources. Figure 2.3 displays the resource mix by firms that are ranked by their dirtiness from the highest rate (left) to the lowest rate (right). Clearly, the market is dominated by firms 9 and 10. The capacity-weighted Herfindahl-Hirschman Index[11] (HHI) of the market is 2,100, which is within the critical range between 1800 and 2500, suggesting moderate market concentration (Cardell et al., 1997).

2.4.2 Scenario Assumptions

We simulate two market scenarios: perfect competition and oligopoly, where the impacts of transmission constraints are studied through the presence or absence of network constraints. In the absence of transmission constraints, we simply elevate the thermal limits of all transmission lines such that it is sufficient to decongest the network completely. Hence, we can examine the impact of the C&T program on the congestion-prone market as compared with the non-congested market (a market without transmission constraints). We further investigate the effects of binding emissions constraint by assuming that the emission target is set at 4,889 tons per hour, which is 20% below the CO_2 emission level corresponding to the no-cap transmission-constrained perfect competition case. The 20% was chosen to study the producers' response and market outcomes when the industry faces a stringent emission cap. In reality, the compliance schedule under a C&T policy is relatively loose at the beginning, and gradually ramps up to allow industries to respond by undertaking pollution controls or adopt clean technologies.

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[11] The HHI provides a rough measurement of the scope and distribution of the horizontal market power.

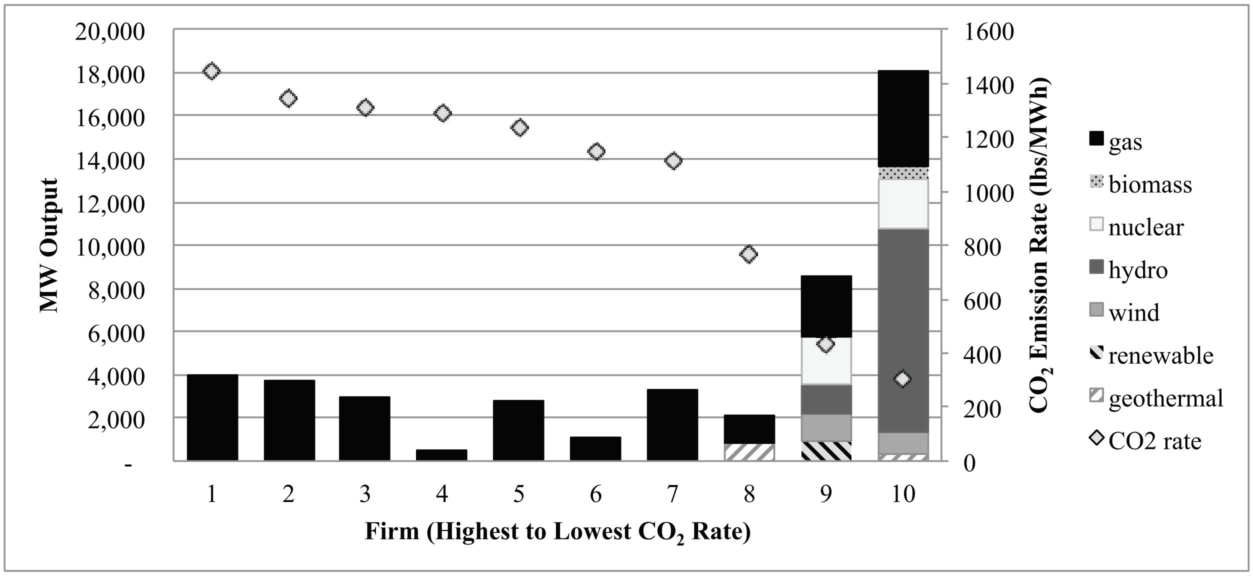


Figure 2.3: Generation mix by firms in the WECC model

As aforementioned, the price-responsive demand functions are assumed to be linear with demand elasticity of -0.1. Similarly, the price-responsive supply functions for imports into California are assumed to be linear with supply elasticity of 0.005 (Tsao et al., 2010).

2.5 Economic Analysis of the 225-Bus System

This section summarizes the economic analysis results for the 225-bus system. Tables 2.9 and 2.10 report the total emissions, the total energy consumption, average LMP, CO_2 price, CO_2 emissions rate, and the import-only CO_2 emissions rate for scenarios with/without transmission constraints. Tables 2.11 and 2.12 display the social surplus, consumer surplus, producer surplus, congestion revenues, total carbon value, in-state fuel costs, and import costs for scenarios with/without transmission constraints, respectively. Figure 2.4 presents the equilibrium results of firm outputs, and Figure 2.5 shows the equilibrium imports and generation outputs of all technologies.

As shown in Tables 2.9 and 2.10, the CO_2 cap raises the LMPs in all scenarios, leading to the reduction in energy consumption. For example, after the cap is imposed, the average LMP of the perfectly-competitive market with transmission constraints (Table 2.9) increases by 60% (from 59 \$/MWh to 94 \$/MWh), leading to a 6% drop in energy consumption. As expected, the cap induces lower emissions intensity in all scenarios. This suggests that electricity is on average produced by relatively less polluting resources. The CO_2 price reported in Table 2.9 is higher than what has been experienced in both the RGGI and EU ETS markets. The price reflects our assumption of a 20% reduction from the no-cap case

Table 2.9: Comparative statics (with transmission constraints)

	Perfect Competition			Oligopoly		
	No Cap	Cap	Change	No Cap	Cap	Change
CO_2 Emissions [tons/h]	6,111	4,889	-20%	9,766	4,889	-50%
Energy Consumption [MWh]	30,362	28,576	-6%	28,060	25,040	-11%
Average LMP [$/MWh]	59	94	60%	97	154	59%
CO_2 Price [$/ton]	-	74		-	155	
CO_2 Emissions Rate [tons/MWh]	0.201	0.171	-15%	0.348	0.195	-44%
Import-only CO_2 Rate [tons/MWh]	0.465	0.465	0%	0.464	0.464	0%

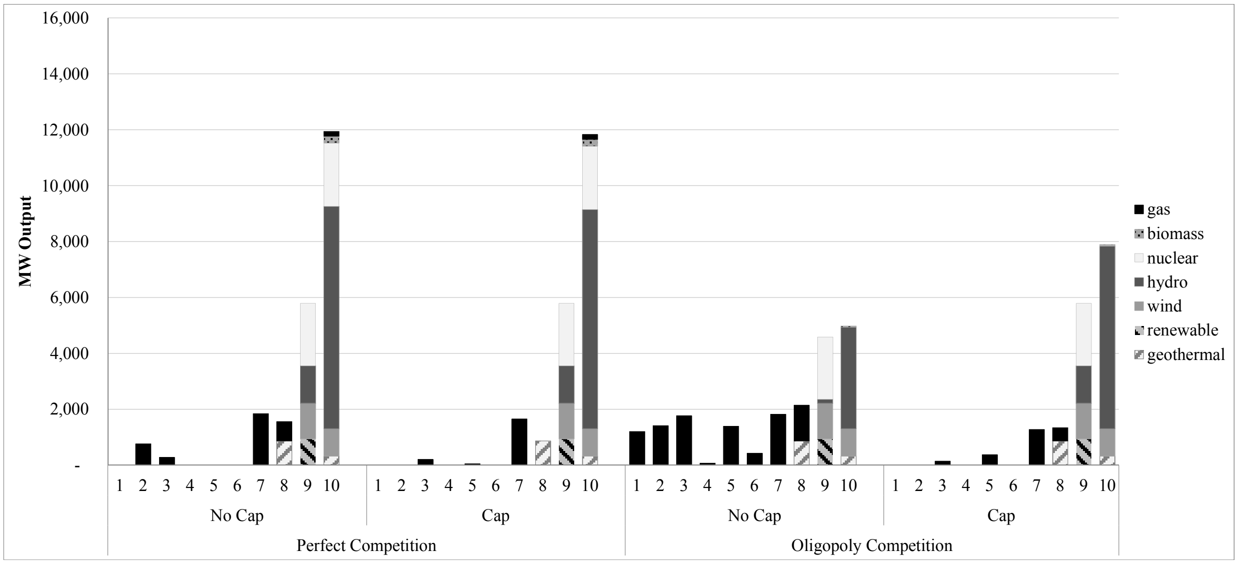
Table 2.10: Comparative statics (without transmission constraints)

	Perfect Competition			Oligopoly		
	No Cap	Cap	Change	No Cap	Cap	Change
CO_2 Emissions [tons/h]	4,977	4,889	-2%	9,611	4,889	-49%
Energy Consumption [MWh]	30,471	30,286	-1%	28,184	25,170	-11%
Average LMP [$/MWh]	53	56	6%	95	151	60%
CO_2 Price [$/ton]	-	8		-	151	
CO_2 Emissions Rate [tons/MWh]	0.163	0.161	-1%	0.341	0.194	-43%
Import-only CO_2 Rate [tons/MWh]	0.464	0.464	0%	0.464	0.464	0%

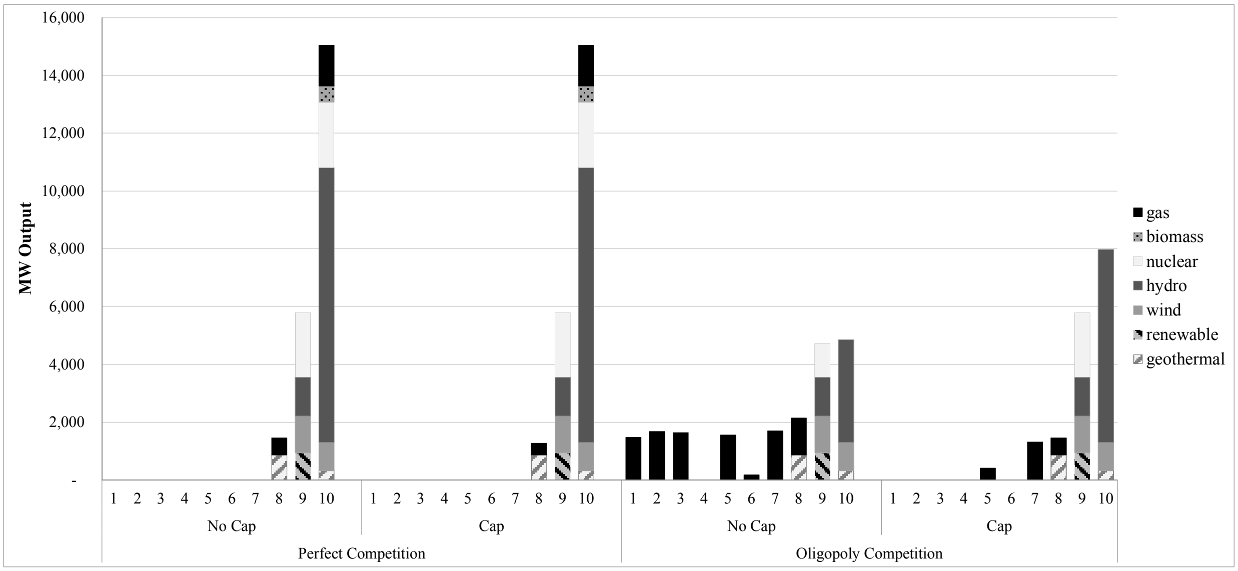
under the perfect competition. Had the reduction been lower than 20%, the permit price would be more aligned with actual market outcomes. As mentioned before, we intended to examine a stringent cap in order to understand the impact of the C&T policy on producers' responses and market outcomes.

Interestingly however, the impact of the cap is more pronounced in the oligopoly scenario when compared with the perfect competition scenario. In the oligopoly scenario with transmission constraints (Table 2.9), the average LMP is 64% (=(154-94)/94) higher; energy consumption declines 12% (=(25,040-28,567)/28,567); and emissions rate is 14% higher (=(0.195-0.171)/0.171), relative to the results of the perfect competition scenario. In an oligopoly market, the strategic withholding by dominant firms allows other polluting (higher-cost) competitors to increasingly fulfill demands and set higher LMPs. Because the dominant firms in this case possess a significant share of clean facilities, the permit market is indirectly influenced by strategic withholding. Had firms been allowed to exercise market power in the permit market, we would expect to see a greater impact of strategic withholding on permit prices. The incentive for the clean firms in such a case is to increase demand for permits and make them more valuable while they incur little, if not zero, emissions costs, thereby raising surpluses for their infra-marginal units.

One example illustrating how a dominant firm withholds its output and indirectly raises permit market prices is summarized as follows. When there is no carbon regulation, the



(a) With Transmission Constraints



(b) Without Transmission Constraints

Figure 2.4: Equilibrium results for outputs by firm

dominant firm 10 withholds hydroelectric power and completely restricts its nuclear power in equilibrium, as illustrated in Figure 2.4(a). Once the carbon cap is imposed, firm 10 then operates more of the non-polluting facilities by increasing hydroelectric power. Nonetheless, firm 10 still withholds more than 30% of its generation relative to what it would generate in the perfectly-competitive market. Not only the firm withholds competitive gas-fired generation—as compared to the perfect competition scenario, but it also withholds a large portion of non-polluting capacity. This same behavior is also observed at firm 9. With this strategy, the carbon permits are indirectly used as an instrument to increase other competitors' marginal costs as they seek more permits, making some of the competitors uncompetitive and raising marginal prices. Figure 2.4(a) shows that a number of firms found it economically undesirable to generate electricity when the cap is implemented.

Under the C&T regulation, these differential effects of market outcomes between perfect competition and oligopoly are magnified if transmission constraints are not enforced. In the oligopoly scenario without transmission constraints (Table 2.10), the average LMP is 170% (=(151-56)/56) higher; energy consumption is reduced by 17% (=(25,170-30,286)/30,286); and emissions rate is 21% higher (=(0.194-0.161)/0.161), relative to the results of the perfect competition scenario. The permit price in the congested oligopoly market (155 $/ton) is approximately the same as in the non-congested oligopoly market (151 $/ton), as opposed to a much lower price in the non-congested perfectly competitive market (8 $/ton). In particular, the absence of transmission constraints could enhance the outcomes of the perfectly-competitive market by making the market more accessible, increasing social surplus. Such market enhancements are less significant in the oligopoly scenario in this case, in part because the congestion level ($ 84k) is not as high as in perfect competition scenario ($ 379k), as shown in Table 2.11. Without congestion in the oligopoly market, firm 10 operates slightly more of its hydroelectric power to fulfill firm 3's generation that is no longer competitive in the non-congested market (see Figure 2.4). Without the cap, firm 3 is competitive regardless of the presence of congestion. This result suggests the importance of network congestion effects on potential abuse of market power that may interact with the C&T policy.

As reported in Tables 2.11 and 2.12, the social surpluses remain relatively unchanged after the cap is imposed, while consumers generally suffer from higher LMPs. Consumers are most affected in the congested oligopoly market. Under the C&T, the producer surplus is the highest in the non-congested oligopoly market and the lowest in the non-congested perfectly-competitive market. Assuming a competitive market, the California market under the 20% emission-reduction target will be subjected to at least 50% increase in the costs of energy imports due to the rising LMPs, as a result of increased CO_2 costs.

Finally, as shown in Figure 2.5, the emission reduction is mainly a result of the reduction in generation from polluting facilities if the market is perfectly competitive. In the oligopoly market, the emission reduction is, however, a simultaneous change in outputs from both polluting and non-polluting facilities. Unlike firms in a perfectly-competitive market, dominant firms in the oligopoly market are likely to withhold outputs from lower-marginal-cost facilities that are also less polluting. Once the cap is imposed, firms in the perfectly-competitive market may avoid carbon charges in the short run only by reducing outputs from polluting facilities as non-polluting resources have already operated at full capacity.

Table 2.11: Economic results (with transmission constraints)

	Perfect Competition			Oligopoly		
	No Cap	Cap	Change	No Cap	Cap	Change
In thousands of $						
Social Surplus	10,386	10,348	0%	9,899	9,968	1%
Consumer Surplus	8,945	7,905	-12%	7,839	6,320	-19%
Producer Surplus	1,243	1,701	37%	2,038	2,804	38%
Congestion Revenues	198	379	91%	22	84	285%
Total Carbon Value	-	364		-	760	
In-State Fuel Costs	347	245	-29%	663	215	-68%
Import Costs	440	673	53%	804	1,209	50%

Table 2.12: Economic results (without transmission constraints)

	Perfect Competition			Oligopoly		
	No Cap	Cap	Change	No Cap	Cap	Change
In thousands of $						
Social Surplus	10,511	10,510	0%	9,923	9,988	1%
Consumer Surplus	9,135	9,033	-1%	7,906	6,400	-19%
Producer Surplus	1,376	1,437	4%	2,017	2,849	41%
Congestion Revenues	-	-		-	-	
Total Carbon Value	-	40		-	738	
In-State Fuel Costs	235	225	-4%	651	216	-67%
Import Costs	433	460	6%	779	1,241	59%

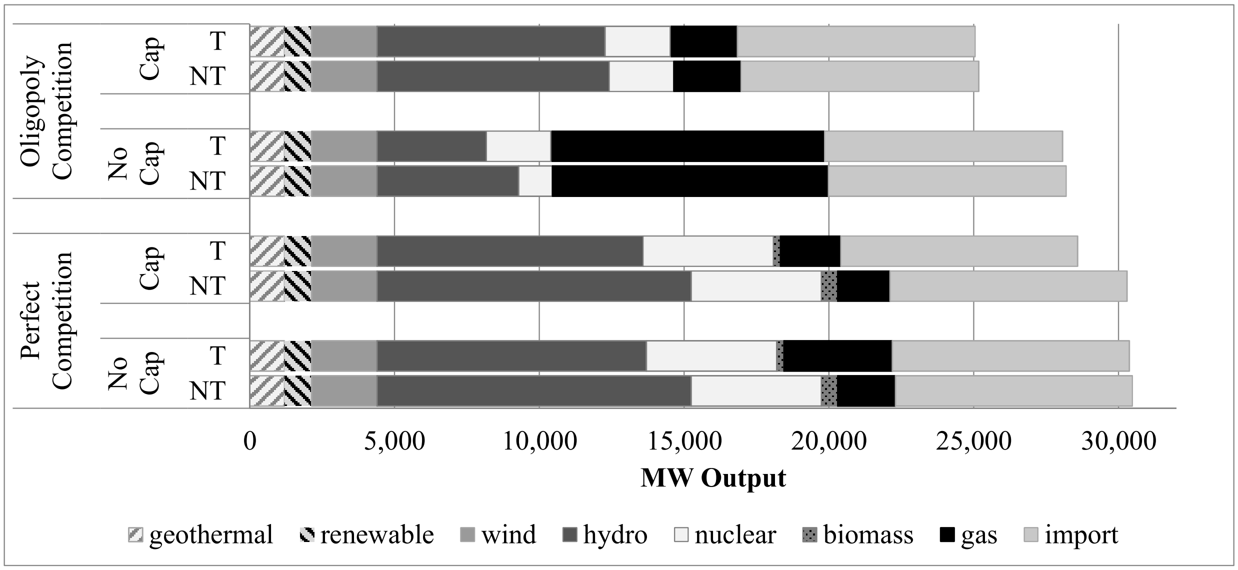


Figure 2.5: Comparison of total equilibrium outputs by technology (T indicates the transmission-constrained network, and vice versa.)

Chapter 3

The Impact of Imperfect Competition in Emission Permits Trading on Oligopolistic Electricity Markets

In the recent years, growing concerns around the issue of climate change have led to numerous transformations in the electric power industry. These changes are partly driven by regulatory policies such as renewable portfolio standard and emission trading programs that rely on market-based mechanisms to mitigate emissions and/or promote renewable energy. One concern over the implications of these regulations is the possibility that some firms in the market posses market power in both permit and electricity markets. Such market power may manifest itself when a dominant firm can deliberately consume permits in order to raise other firms' production cost or it can withhold its capacity to drive up electricity prices. There is substantial empirical evidence that market power is a relevant issue in both permit and electricity markets.[1]

Since the onset of California electricity crisis, the presence of market power, even within the electricity markets alone, has drawn considerable attention. This is mainly because the complexity of market rules and regulations in the electricity markets have made the markets fundamentally different from other commodity markets. In such a scenario, where the issue arises from the existence of market power, a Nash-Cournot game is commonly applied to model an electricity market. Such models can be justified by empirical evidence suggesting that the performance of several U.S. regional electricity markets, e.g., Pennsylvania, New Jersey, and Maryland (PJM), New England, and California, is consistent with Nash-Cournot market outcomes (Bushnell et al., 2008). Nevertheless, finding Nash-Cournot oligopoly equilibria could be complicated by the presence of a congestion-prone transmission network. For example, Neuhoff et al. (2005) showed that the inclusion of transmission constraints into

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[1] See e.g., Borenstein et al., 2002; Joskow & Kahn, 2002; Mansur, 2007; Puller, 2007 on market power in electricity market. And see Kolstad & Wolak, 2003 on permit market).

the strategic models, used in the analysis of impacts of regulatory mechanisms, can result in unexpected equilibria. Cardell et al. (1997) and Borenstein et al. (2000) also demonstrated the effect of transmission congestion on firms' strategic behavior. The introduction of any emission regulation to a transmission-constrained electricity market can lead to some unintended consequences for market outcomes when transmission congestion occurs (see e.g., Downward, 2010; Limpaitoon et al., 2011). These studies highlight the importance of incorporating transmission network into strategic models used in the analysis of market power in electricity markets.

As mentioned earlier, a market for trading emission permits has also faced concerns over potential market power. Studies have shown that dominant firms are able to employ manipulative strategies in order to move prices in their favor. For instance, Kolstad and Wolak (2003) provided empirical evidence that firms used permit prices to justify higher costs of electricity produced, and for raising electricity prices. The earliest work on market power in the permit markets was introduced by Hahn (1984). He considered one dominant polluting firm and other price-taking firms in a static model. Sartzetakis (1997) studied a two-stage duopoly model, where the leader sets the permit price in the first stage and both firms' output and abatement decisions are made in the second stage. Resende and Sanin (2009) studied a three-stage model. This differs from Sartzetakis (1997) in that the follower in the permit market can anticipate the strategic response from its rival in the output market in the third stage, when deciding the optimal permit quantity in the second stage. Montero (2009) extended Hahn's model to accommodate the more contemporary market settings such as permit auctions. Tanaka and Chen (2011) considered a model for electricity market in which permit prices can be manipulated through fringe producers.

Although existing models consider imperfect competition in permit markets, most have not taken into account neither transmission network nor realistic network scale. The exception is the work by Chen and Hobbs (2005) who considered electricity and permit markets with a realistic, yet coarse, scale of transmission network. Our work differs from those existing models in that we examine *simultaneous* interactions, instead of a multi-stage model, of oligopoly competition between multiple players of transmission-constrained electricity market participating in a carbon permit market at a more realistic scale. Our approach takes into account essential market characteristics such as electrical loopflow, resource ownership, and transmission constraints based on thermal ratings. To account for the transmission network, we employ a direct current (DC) approximation, which is a common approach to analyze the impact of market power because of its tractability (Wei & Smeers, 1999; Pang et al., 2001).

In modeling market power in the permit market, we propose a conjectural variation approach, whereby the conjectural variation parameters are derived "empirically" through simulations.[2] The approach allows us to estimate conjectural variations under different per-

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[2] Conjectural variation approach generalizes Cournot model (Perry, 1982) and is widely used in both empirical studies and modeling of imperfect output markets (see e.g., Mansur, 2001; Ehrhart et al., 2008).

mit endowments because our conjectural variation parameters are estimated endogenously, whereas the parameters derived in Chen and Hobbs (2005) are based on historical emissions. Our model is especially useful when a regulatory agency wants to examine the extent of market power, if exists, in *joint* electricity and permit markets. Furthermore, the proposed model is readily extended to account for other economy sectors participating in the permit market.

The model is applied to a reduced 225-bus representation of the Western Electricity Coordinating Council (WECC) 225-bus network system for two reasons.[3] First, evidence has shown that the California market is among the least competitive restructured US electricity markets.[4] Second, California has recently implemented a cap-and-trade program (C&T) under AB 32, where market power is a concern.[5] As for the issues of permit allocation[6], this chapter is primarily focused on characterizing the equilibrium when initial emission permits are freely allocated to generation firms. This is because permits allocation in California under AB 32 is intended for various reasons other than efficiency and equity (e.g., mitigating price impact). Our main interest is to understand the potential strategies taken by firms, when they are given different permit endowments. A sensitivity analysis of permit endowments of firms may shed light on how firms strategically plan their permit positions. This is relevant to the issue of "holding limit" of emission permits that is currently under discussion by the California Air Resource Board in Resolution 11-32. We also look at various market scenario assumptions in attempt to investigate the extent to which simultaneous exercises of market power in both electricity and permit markets impact market outcomes.

Our analysis shows that when an efficient firm (less polluting and low production cost) is "grandfathered" a substantial number of permits, it tends to strategically withhold the "unused" permits in order to place upward pressure on permit price, therefore driving up electricity prices. The degree to which firms strategically withhold permits may be lessened, when a stringent cap is imposed, a situation in which permit prices tend to be relatively expensive. Also, the effect of the degree of competition in the permit market on social welfare is ambiguous and depends on the cap level. Finally, patterns of transmission congestion can be influenced by trading activities in the permit market. However, given that the scope of a C&T policy covers more than one sector, the case study may underestimate the price elasticity of emission permits, therefore inflating permit prices. Along with the adoption of other complementary measures to mitigate potential for market power, the possible market outcomes, as we argue, are likely bounded by our simulation results.

This chapter is organized as follows. Section 3.1 describes an equilibrium model that

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[3] The WECC 225-bus system was also implemented in Yu et al. (2010) under an agent-based framework.

[4] See, for example, Mansur (2007), Puller (2007), and Bushnell et al. (2008).

[5] As directed by Resolution 11-32, the California Air Resource Board has established a market simulation group to identify situations that might lead to market disruptions. These include market power, market manipulation, and non-strategic market frictions.

[6] Issues such as allowance distribution can greatly influence market incentives. For example, Eshel (2005) studied how permits should be initially allocated in order for the efficiency of permit market to be maximized.

includes optimization problems and market equilibrium conditions. The concept of conjectural variation in the context of permit market is also introduced. Section 3.2 describes a case study of the California market through the WECC 225-bus network in conjunction with a C&T program. In the section we simulate various market scenarios, propose the estimation procedure for conjectural variations, and discuss the economic implications of a C&T program on the electricity market in the light of market power in the joint markets.

3.1 Model

We extend the model proposed by Limpaitoon et al. (2011) to account for market power in an emission permits market via conjectural variations. In particular, instead of having the permit price being determined endogenously within a perfectly-competitive equilibrium framework using a complementarity constraint[7], imperfect competition in the permit market, herein, assumes that each firm makes a conjecture about other firms' demand for permits. Each firm's decision regarding the number of permits to hold at equilibrium is, therefore, based on its perceived residual supply of permits. A firm's conjectured price response in the permit market—which relates the price and quantity of permits that the other firms are willing and able to purchase—is represented by a downward-sloping demand curve. These curves are constructed from the simulation results of a Nash-Cournot game of an electricity market and a perfectly-competitive permit market by varying levels of emission cap. The simulation of joint markets yields the demand for permits, resulting from electricity producers' unabated emissions as they behave à la Cournot in the electricity market but behave as price-takers in the permit market. This may introduce inconsistency concerning firms' behaviors in the permit market and the resulting residual permit supply function will be less price-responsive at equilibrium, thereby biasing the extent of market power upward.

In the proposed model, the electricity market consists of an Independent System Operator (ISO), producers, and consumers in an electricity market. The ISO maximizes social welfare. The producers are Cournot players who own multiple power plants (or electric power generation facilities) competing to sell energy at different locations in a locational marginal price (LMP)-based market[8], where prices are set by the ISO. As Cournot players in the electricity market, producers maximize their profits by adjusting production levels given their respective residual demand, while behaving as price takers with regard to locational congestion markups that are set by the ISO. Consumers at each location are assumed to be price-takers, and their demand is represented by a linear price-responsive demand function.

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[7] A complementarity constraint is defined as follows: $x \geq 0$, $f(x) \geq 0$, and $f(x)^T x = 0$, where $x \in R^n$ and the function $f : R^n \rightarrow R^n$ are given (Cottle et al., 1992). In this chapter, the orthogonality condition is denoted by $\perp$.

[8] For computational ease, a virtual location (bus) is created for each additional power plant at those locations with multiple plants. These virtual locations are connected to their corresponding original location through a line with unlimited thermal capacities. Each location then has at most one plant.

To account for transmission constraints, the equilibrium model is based on a lossless DC load flow model where electric power flows on transmission lines are constrained by thermal capacities of the lines. The flows in the system are governed by the Kirchhoff's laws through the Power Transfer Distribution Factors (PTDFs).

In what follows, we first introduce notations used in the model and subsequently present the equilibrium model that consists of all Karush-Kuhn-Tucker (KKT) conditions of the optimization problems faced by all entities in both electricity and permit markets.

Let N denote the set of buses (or locations) and L be the set of transmission lines whose elements are ordered pairs of distinct buses. Let G be the set of firms, and $N_g \subset N$ be the set of buses where power plants owned by firm $g \in G$ are located. Let i and l be the elements in N and L, respectively. By construction, each i refers to bus i and also refers to the plant located at bus i, if a plant exists. The fuel cost of plant $C_i(q)$ is assumed to be a quadratic function of megawatt (MW) power output q defined as $C_i(q) = \frac{1}{2}s_i q^2 + c_i q$, $\forall i \in N$. The amount of emissions from power plants is given by $F_i(q) = e_i q$, $\forall i \in N$, where e_i is the emission rate of plant i.[9] Consumers in each location i are represented by the inverse demand function $P_i(q) = a_i - b_i q$, where a_i and b_i are location-specific constants, $\forall i \in N$.

3.1.1 ISO's Problem

The welfare-maximizing problem faced by the ISO is described by the ISO's optimization problem. The variables in parentheses next to the constraints are the Lagrange multipliers corresponding to those constraints. The KKT conditions of the ISO's optimization problem are also summarized.

ISO's Optimization Problem

$$\max_{r_i : i \in N} \quad \sum_{i \in N} \int_0^{r_i + q_i} P_i(q)dq - C_i(q_i) \tag{3.1}$$

$$\text{s.t.} \quad \sum_{i \in N} r_i = 0 \qquad (p) \tag{3.2}$$

$$-K_l \le \sum_{i \in N} D_{l,i} r_i \le K_l, \qquad (\kappa_l^-, \kappa_l^+) \quad \forall l \in L \tag{3.3}$$

$$-\sum_{l \in L} h_{s,l} \sum_{i \in N} D_{l,i} r_i \le T_s \qquad (\tau_s) \quad \forall s \in S \tag{3.4}$$

$$r_i + q_i \ge 0, \qquad (\xi_i) \quad \forall i \in N \tag{3.5}$$

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[9] For greenhouse gas such as CO_2, the constant emission rate is commonly used in modeling energy policies, e.g., the Integrated Planning Model (IPM) used by U.S. Environmental Protection Agency ([EPA], 2012). In contrast, strong nonlinearity associated with output level for other air pollutants, e.g., NO_x (nitrogen oxides), is observed from a dataset provided by Continuous Emission Monitoring System (EPA, 2007). If the CO_2 emission rate was modeled as proportional to the quadratic fuel cost, it would discourage power plants from producing at a higher level since they would incur higher carbon costs.

The ISO is assumed to maximize welfare (3.1)—taking into account the MW output decisions of the firms—subject to the lossless energy-balance constraint in the network (3.2), transmission-related constraints (3.3, 3.4), and the non-negativity constraint (3.5).

The ISO manages congestion by controlling electric power imports/exports r_i, which is positive for imports into location i. The Lagrange multiplier p of (3.2) is the system marginal energy cost or price at the reference location. Electric power flows on the transmission lines are simply a function of the import/export at all locations. That is, the MW flow on line l resulting from a MW transfer from location i to the reference location is measured by the PTDF, $D_{l,i}$. The flow on each transmission line l is constrained by its thermal limit K_l measured in MW in DC models, where κ_l^+ and κ_l^- correspond to the Lagrange multiplier of the upper and lower transmission limits in (3.3). The load, $q_i + r_i$, must be non-negative because electricity is non-storable, and ξ is the multiplier assigned to this non-negative constraint (3.5).

In addition to the thermal limits already accounted for by (3.3), the ISO may enforce a list of additional transmission constraints, often referred to as "bubble constraint", to ensure reliable operation in the case of unpredictable generation contingencies in so-called "load pockets." The purpose of such constraints is to enable emergency imports into the load pocket. The list includes several groups of transmission lines (branch groups). Let S be the set of branch groups and L_s be the set of lines included in group $s \in S$. The constraints for these branch groups are then accounted for by (3.4), where T_s is the power transfer limit of group s; τ_s is the corresponding Lagrange multiplier; and

$$h_{s,l} = \begin{cases} 1 & \text{if } l \in L_s \text{ and } l \text{ is defined in the same direction,} \\ -1 & \text{if } l \in L_s \text{ and } l \text{ is defined in the opposite direction,} \\ 0 & \text{if } l \notin L_s. \end{cases}$$

KKT Conditions

$$\varphi_i = \sum_{l \in L} (\kappa_l^+ - \kappa_l^-) D_{l,i} - \xi_i - \sum_{s \in S} \sum_{l \in L} \tau_s h_{s,l} D_{l,i}, \qquad \forall i \in N \tag{3.6}$$

$$P_i(r_i + q_i) - p - \varphi_i = 0, \qquad \forall i \in N \tag{3.7}$$

$$\sum_{i \in N} r_i = 0, \tag{3.8}$$

$$0 \le \xi_i \perp r_i + q_i \ge 0, \qquad \forall i \in N \tag{3.9}$$

$$0 \le \kappa_l^- \perp \sum_{i \in N} D_{l,i} r_i + K_l \ge 0, \qquad \forall l \in L \tag{3.10}$$

$$0 \le \kappa_l^+ \perp K_l - \sum_{i \in N} D_{l,i} r_i \ge 0, \qquad \forall l \in L \tag{3.11}$$

$$0 \le \tau_s \perp T_s + \sum_{l \in L} h_{s,l} \sum_{i \in N} D_{l,i} r_i \ge 0, \qquad \forall s \in S \tag{3.12}$$

The above formulation is the KKT conditions for the ISO's optimization problem. φ_i in (3.6) is introduced to represent the sum of difference of κ_l^+ and κ_l^- over all the lines l weighted by the i-th row of the PTDF matrix minus ξ_i and $\sum_{s\in S}\sum_{l\in L}\tau_s h_{s,l}D_{l,i}$. In a sense, φ_i is the marginal congestion cost associated with bus i, which reflects the cost contributions of the various transmission elements experiencing congestion, measured between bus i and the reference bus. The last term of (3.6) reflects the additional cost of the branch groups experiencing congestion. The ISO uses congestion markup φ_i as a price signal corresponding to transmission congestion to control line flows. Reflected by (3.7), the market clearing LMP at bus i is then $p+\varphi_i$, where the demand at location i is equal to the MW power generated by plant i plus the MW import, expressed by $q_i + r_i$. (3.8) is the energy-balance constraint and (3.9)-(3.12) are the complementarity conditions.

3.1.2 Firms' Problem

The profit-maximization problem faced by each generation firm is described by the firms' optimization problem. The KKT conditions of the firms' optimization problem imply the set of equilibrium conditions for each firm g.

Firms' Optimization Problem

$$\max_{\substack{q_i:i\in N_g,p\\ x_g,\mu}} \quad \sum_{i\in N_g}\left\{(p+\varphi_i)q_i - C_i(q_i)\right\} - \mu(x_g - x_g^0) \tag{3.13}$$

$$\text{s.t.} \quad \sum_{i\in N_g} q_i = \sum_{i\in N}(P_i)^{-1}(p+\varphi_i) - \sum_{i\in N\setminus N_g} q_i \quad (\beta_g) \tag{3.14}$$

$$\underline{q}_i \le q_i \le \bar{q}_i, \quad (\rho_i^-, \rho_i^+) \quad \forall i \in N_g \tag{3.15}$$

$$x_g = M - y(\mu) - x_{-g}(\mu) \quad (\alpha_g) \tag{3.16}$$

$$x_g - \sum_{i\in N_g} F_i(q_i) \ge 0 \quad (\eta_g) \tag{3.17}$$

Each firm seeks to maximize profits (3.13)—in response to price signals φ_i from the ISO—subject to the firm's residual demand curve in the electricity market (3.14), the limits of electric power generation at plants owned by the firm (3.15), the firm's residual supply curve regarding the permit market (3.16), and the minimum permits constraint (3.17).

In the electricity market, each firm g considers the output of all other firms and optimally sets its own output q_i, $\forall i \in N_g$, so as to maximize its profits, expressed in (3.13). Firm g earns $p+\varphi_i$ for each unit of power output sold at location i as competing outputs from all firms simultaneously determine the reference-bus marginal energy cost p, while treating the locational congestion markup φ_i, determined by the ISO, as exogenous. This assumption implies bounded rationality of firms and is credible when the network is not radial (Neuhoff et al., 2005), as is the case for most LMP-based market such as the California market. Firm

g incurs the fuel costs $\sum_{i \in N_g} C_i(q_i)$ as its power plants generate outputs. In order to comply with the cap-and-trade regulation, firm g may engage in permit trading. The firm optimally decides on the number of permits x_g it needs to acquire to cover its unabated emissions. Because firm g is initially allocated emission permits of x_g^0, $x_g > x_g^0$ implies that the firm purchases more permits (than initially allocated) from the permit market and incur the opportunity cost of permit price μ for each unit of emission. On the other hand, if $x_g < x_g^0$, firm g sells permits to the market and receives μ for each permit sold.

All firms exhibit a Cournot-like behavior by optimizing their profit with respect to their output level against their residual demand curve in the electricity market, expressed in (3.14), treating sales from other firms as fixed. Outputs from power plants are constrained by minimum operating limit ($\underline{q}_i$) and maximum operating limit ($\bar{q}_i$) in (3.15) so as to abstract from representing the startup, shut-down, ramping, and other non-convex costs that are typically considered in unit-commitment models.[10] The corresponding Lagrange multipliers ρ_l^- and ρ_l^+ reflect the shadow prices corresponding to the lower and upper limits in (3.15).

Our approach to modeling an imperfect permit market follows the notion of conjectural variations where strategic firms conjecture aggregate permits demanded by other firms. The approach is needed because the aggregate permit quantity is fixed (i.e., inelastic) and the supply elasticity for permits faced by any firm is endogenously determined by the price response of other firms participating in the permit market. The conjectural variation approach is incorporated into the model by (3.16). In response to changes in permit price μ, firm g conjectures changes in the aggregate number of permits demanded by all firms other than g that compete in the electricity market, denoted as x_{-g}, and the number of permits demanded by other sectors of economy, denoted as y. That is, x_{-g} and y are written as a function of μ in (3.16). Firm g optimally decides its own x_g—*concurrently* with making the output decisions—as if it is facing a residual supply curve (the right-hand side of (3.16)), which is equal to the total emission cap M less the sum of $y(\mu)$ and $x_{-g}(\mu)$. In addition, (3.17) requires that each firm is obligated to cover its unabated emissions $\sum_{i \in N_g} F_i(q_i)$ by holding corresponding number of permits. It is important to note here that the Lagrange multiplier of (3.17), η_g, reflects the marginal abatement cost of firm g for the emissions abated through changes in the firm's MW outputs. By means of the conjectural variation approach through (3.16), firms are no longer price-takers in the permit market as they anticipate changes in permits demanded as a result of changes in the permit price.

Modeling the firms' problem this way allows us to explore strategic interaction of firms as generation facilities of each firm are best responding to others throughout both electricity and permit markets simultaneously.

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[10] This implies that our approach of modeling fixed minimum production limits without possibilities of decommitment may overestimate the emissions from these generation units for which such limits are imposed.

KKT Conditions

$$p + \varphi_i - \beta_g + \rho_i^- - \rho_i^+ - \frac{dC_i(q_i)}{dq_i} - \eta_g \frac{dF_i(q_i)}{dq_i} = 0 \qquad \forall i \in N_g \tag{3.18}$$

$$\beta_g \sum_{i \in N} \frac{d}{dp}(P_i)^{-1}(p + \varphi_i) + \sum_{i \in N_g} q_i = 0 \tag{3.19}$$

$$-\mu - \alpha_g + \eta_g = 0 \tag{3.20}$$

$$-\alpha_g \left(\frac{dx_{-g}}{d\mu} + \frac{dy}{d\mu} \right) - (x_g - x_g^0) = 0 \tag{3.21}$$

$$\sum_{i \in N} q_i = \sum_{i \in N} (P_i)^{-1}(p + \varphi_i) \tag{3.22}$$

$$x_g + x_{-g} + y = M \tag{3.23}$$

$$0 \le \eta_g \perp x_g - \sum_{i \in N_g} F_i(q_i) \ge 0 \tag{3.24}$$

$$0 \le \rho_i^- \perp q_i - \underline{q}_i \ge 0, \qquad \forall i \in N_g \tag{3.25}$$

$$0 \le \rho_i^+ \perp \bar{q}_i - q_i \ge 0, \qquad \forall i \in N_g \tag{3.26}$$

The preceding formulation is the KKT conditions for firm g's optimization problem. Equations (3.18)–(3.21) are the first-order conditions, (3.22) and (3.23) are equality constraints, and (3.24)–(3.26) are the complementarity constraints. Note that the residual demand curve in (3.14) can also be viewed as the market clearing condition for the electricity market (3.22) in which the reference price p is implied by the joint production decisions of all power plants in the same way as the price in a conventional Cournot model. Similarly, the residual supply curve in (3.16) implies the market clearing condition for the permit market (3.23)—or equivalently, by construction,

$$y + \sum_{g \in G} x_g = M, \tag{3.27}$$

where the total demand of permits equals the total supply of permits. At equilibrium, given the demand function y, the permit price μ is therefore determined by concurring decisions on x_g, $\forall g \in G$.

Plugging (3.20) into (3.21) and rearrange the terms, we obtain

$$-(\frac{dy}{d\mu} + \frac{dx_{-g}}{d\mu})(\eta_g - \mu) = x_g - x_g^0. \tag{3.28}$$

This condition presents the relationship between marginal abatement cost η_g and permit quantity x_g, associating permit price μ with the firm's permit endowment x_g^0. In particular, firm g has an incentive to use the initially allocated permits to exert a favorable influence upon the permit price through its strategic decision on x_g. For instance, when more permits are demanded by other market participants as μ decreases, distributing *more* permits ex ante to firm g than it needs at equilibrium ($x_g - x_g^0 < 0$) will yield $\eta_g - \mu < 0$. In such a case, any further increase in x_g^0 would likely drive further the wedge between its marginal abatement cost η_g and permit price μ. The extent to which a strategic firm can manipulate the permit price, however, is influenced by several intricately intertwined forces. First, the extent of market power by firms in the electricity market is lessened by the extent of which other economy sectors participate in the permit market. Second, the strategic behavior is influenced directly by the firm's market power in the permit market. The model captures this aspect by means of conjectural variations. The third is the firm's ability to abate emissions at lower costs, i.e., whether or not the firm has lower marginal abatement cost curve compared to other firms, which is reflected by η_g in the model. Importantly, as the firm abates emissions through changes in outputs among its power plants, the abatement costs are further complicated by transmission congestion. Lastly, the firm's joint competitiveness in the electricity market, reflected by β_g, can largely affect outcomes in the permit market, as β_g is related to η_g in (3.18).

3.1.3 Equilibrium Conditions

All KKT conditions for the ISO's and the firms' problems ($\forall g \in G$) represent the market equilibrium conditions that constitute a mixed nonlinear complementarity problem in general. When the presence of market power in the permit market is ignored, the complementarity problem can be written in a linear form (LCP) if the marginal cost functions and the inverse demand functions are linear (see Yao et al., 2008; Limpaitoon et al., 2011). By extending the model to account for the market power—of which the market clearing condition for the permit market is (3.27)—our market equilibrium conditions remain LCP given that the emission functions and the demand curves for permits are linear.

At equilibrium, the reference price p is determined simultaneously by all firms' decision on outputs. Equations (3.7) and (3.8) in the ISO's KKT conditions imply the market clearing conditions (3.14) and thereby (3.22). Nevertheless, including (3.14) in the firms' problem implies oligopoly behavior where the producers account for the effect of their joint decision on the reference price, as reflected by (3.19).

Similarly, condition (3.16) (thereby (3.23)) is simply the market clearing condition for the permit market (3.27). Including (3.16) in the firms' problem, however, allows firms to conjecture the effect of their permit demand on permit price. At equilibrium, permit price μ is therefore determined by concurring decisions on x_g, $\forall g \in G$, while taking y as exogenous. As incorporating other sectors into the permit market requires information concerning the residual permit demand curve y, we focus our attention on an isolated C&T market that targets the electricity market alone in the case study. That is, $y \equiv 0$ hereafter. In the case of perfect competition used in the simulation, the equilibrium conditions for both markets are modified as follows.

A Perfectly Competitive Electricity Market. All firms behave as price takers with respect to both the reference price and the locational congestion markups; thus, (3.14) and thereby (3.22) are removed, while (3.19) is replaced with $\beta_g = 0$, $\forall g \in G$. This modification yields the same result as a cost-minimizing dispatch model with fixed demand when emission is not regulated.

A Perfectly Competitive Permit Market. Firms are prevented from conjecturing about other firms' demand for permits and behave as price takers in the permit market. Therefore, (3.16) and thereby (3.23) are removed, while (3.21) is replaced with $\alpha_g = 0$, $\forall g \in G$. In effect, the firm-specific marginal abatement cost η_g equates across all firms and is equal to permit price μ, as implied by (3.20) when $\alpha_g = 0$.

3.2 Case Study

In this section, we perform an equilibrium simulation for a reduced 225-bus WECC network model with actual heat rate and load data, based on the equilibrium model introduced in Section 3.1. We aim to investigate the impact of market power on economic outcome and system operation. In the following subsections, we will first describe some important characteristics of the 225-bus system. Then, we discuss the assumption of market scenarios, elaborate on the estimation procedure of conjectural variation parameters, and subsequently proceed to the economic analysis.

3.2.1 Characteristics of the WECC 225-Bus System

This subsection is duplicated from Subsection 2.4.1 to provide completeness within this chapter so that it can stand alone. The WECC 225-bus system model represents the California ISO (CAISO) area and is composed of 293 transmission lines and 225 buses. Figure 3.1 depicts the network topology of the system. Bubble constraints are represented by the curved lines and circles, cutting across transmission lines. These bubble constraints help ensure reliable operation under system contingencies that may be caused by failures of generation or transmission. There are 23 aggregated thermal generators, 2 nuclear facilities, and a total of 15 aggregated hydroelectric and other renewable energy generators. Because gas is the predominant fuel, the aggregated thermal generators grouped as "gas" accounts for the largest share of total capacity of the WECC system. The gas technology has the highest average marginal cost, which is 70 \$/MWh. All technologies, except for gas, have zero carbon emission. Table 3.1 summarizes the resource mix of this system.

The net imports into the CAISO area are aggregated to several import points (dark circle nodes in Figure 3.1), i.e. Adelanto, El Dorado, Malin, Palo Verde, and Sylmar LA. To account for emissions, the state average CO_2 emission rates are used for imports (1,219

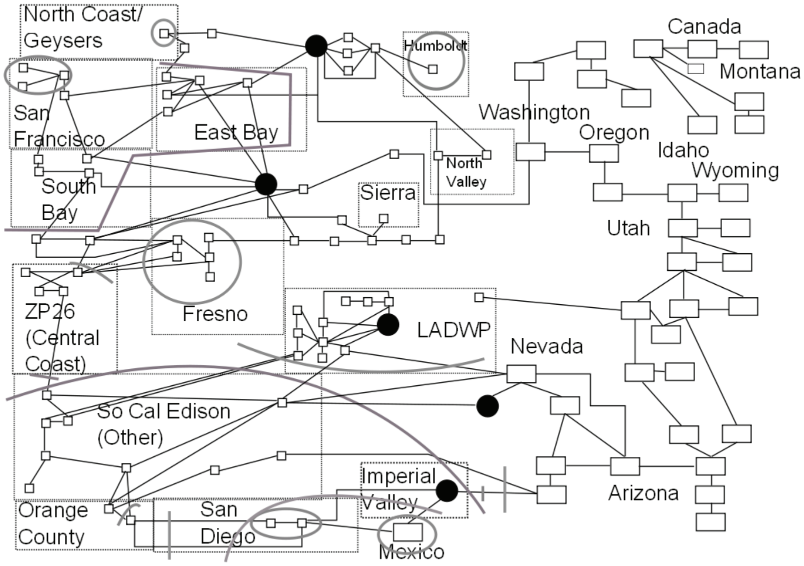

Figure 3.1: A schematic diagram of the WECC 225-bus model. Reprinted from *Coupling renewable energy supply with deferrable demand* (Doctoral dissertation, p. 57), by A. Papavasiliou, 2011, University of California, Berkeley.

Table 3.1: Resource mix of the WECC 225-bus system

Fuel Type	Avg. MC ($/MWh)	Avg. CO_2 (lbs/MWh)	# of units	Total MW
Gas	70	1,281	23	26,979
Biomass	25	0	3	558
Nuclear	9	0	2	4,499
Hydro	7	0	6	10,842
Wind	0	0	3	2,256
Renewable	0	0	1	946
Geothermal	0	0	2	1,193

lbs/MWh for Arizona; 1,573 for Nevada; 456 for Oregon).[11] The net exports to the Sacramento Municipal Utility District (SMUD)—a separate control area surrounded by the CAISO control area—are assumed to be electrical loads (electricity consumers).

The owners and fuel types include aggregations of some owners and fuel types within each zone. The biggest non-investor-owned utility (non-IOU) owners are retained, while the others are grouped into the IOUs' portfolio since many of them would actually be under contracts with the IOUs. In total, there are 10 aggregated owners (firms) and a competitive fringe that represents imports into the CAISO. As shown in Figure 3.2, there is a great disparity of resource mix between the firms. Clearly, not only firms 9 and 10 dominate the market with

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[11] Source: eGRID2006 V2.1, April 2007

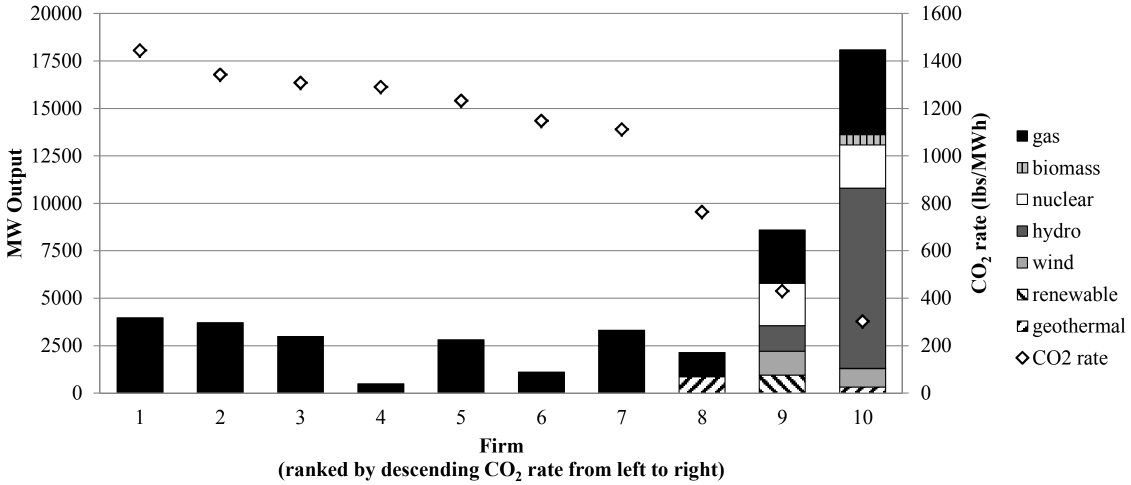

Figure 3.2: Generation mix and average carbon emissions rate by firm

their greater shares of generation capacity, but both firms also possess technologies that are much less polluting on average, depicted by their lower capacity-weighted average emission rate (CO_2 rate).

3.2.2 Scenario Assumptions

Three market scenarios are considered. The first scenario, denoted by OG, is oligopoly equilibria in the electricity market with perfectly competitive permit market. The second scenario, denoted by OG-MP, is oligopoly equilibria in the electricity market with market power in the permit market. The third scenario, denoted by PC-MP, is perfectly competitive equilibria in the electricity market with market power in the permit market. Although PC-MP scenario is less likely in the real world, this scenario will be used for the purpose of comparison. All these scenarios are the same as the ones used in Montero (2009), whose work analyzes theoretically the impact of market power in permit market under a Stackelberg setting. The OG scenario, while being "socially efficient" in the permit market, is not so in the electricity marketand, therefore, serves as a benchmark for the comparison with OG-MP scenarios.

Our simulated hour is the median of the total hourly system load to represent the typical system condition. In the real setting, the permit price is determined by the supply and demand conditions over an extended time period, typically a one-year compliance period. Nevertheless, by focusing on the median-hour analysis, it allows us to explore the market outcomes when producers respond to the C&T more aggressively.[12] The emissions target

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[12] Had the model been extended to an annual simulation, the permit price would be more elastic as producers are capable of coordinating their production decisions over extended periods. In fact, the model can be modified to account for annual simulations. For example, Chen and Hobbs (2005) presented a similar

Table 3.2: Baseline allocation scheme: proportions for initial permit allocation

Firm	1	2	3	4	5	6	7	8	9	10	import fringe
Emission (tons)	874	951	1157	48	995	245	862	821	0	0	3814
Percent share	9%	10%	12%	0%	10%	3%	9%	8%	0%	0%	39%

is set at 15% (the cap of 8,301 tons) and 30% (the cap of 6,836 tons) reduction from the oligopoly equilibrium of electricity market without any emissions trading. The 15% and 30% targets, hereafter, are referred to as a loose cap and a tight cap, respectively. For scenarios where the electricity market structure is oligopoly, an emission target at a level greater than the tight cap would simply result in a number of firms being outcompeted because the carbon costs are too high. With these emission targets, we can compare economic outcomes meaningfully across all market scenarios.

Unless noted otherwise, permits are freely allocated to firms in proportion to their emissions resulted from a scenario in which these firms were to compete in an oligopolistic electricity market in the absence of C&T. Such initial allocations henceforth are referred to as the “baseline” scheme. Table 3.2 reports emission results used as the basis for the baseline allocation scheme. A notable observation is that firms 4, 9, and 10 emit no carbon pollution under such a circumstance for different reasons. Firms 9 and 10 do so as they withhold their thermal generators at equilibrium to place an upward pressure on LMPs. On the other hand, firm 4 is an exception as it is outcompeted at equilibrium. As a result, firms 4, 9 and 10 are not allocated any free permit ex ante, whereas firms 2, 3 and 5 each receive at least 10 percent of the total permits.

The inverse demand function at each location is assumed to be linear with a price elasticity of -0.1, sloping through its corresponding competitive equilibrium solution of an electricity market without any permit trading. Although short-run elasticities are nearly zero, this level of elasticity is consistent with empirical studies (Azevedo et al., 2011). For computational purposes, we assume the existence of price-responsive demand at all locations, and hence the demand curve at a location with no load is set as almost vertical with the intercept on the x-axis being a very small positive number.

The import supplies are assumed to represent a competitive fringe with a price-responsive supply curve, which can be constructed using the same approach that generates the demand curves. The price-responsive supply functions for imports into California are assumed to be linear with supply elasticity of 0.005 (Tsao et al., 2010). The import supplies are also assumed to be a competitive fringe with regard to the permit market.

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framework that allows the price of $\mathrm{NO_x}$ emission permits to be determined endogenously. However, coupling multiple periods would likely complicate our analyses with limited additional insights unless permit banking and borrowing are also taken into account.

3.2.3 Estimating Conjectural Variation and Its Consistency

Because oligopoly equilibria empirically describe electricity markets (Bushnell et al., 2008), OG scenario is used as the benchmark for comparing market outcomes that may deviate from a perfectly competitive permit market if market power exists in the permit market. Such market power is captured by conjectural variations. As our study is confined to the permit market in which only electricity sector is included, $y \equiv 0$. The procedure in which conjectural variations are estimated is illustrated in Figure 3.3. The conjectural variation of firm g is derived from a linearized relationship, in a small neighborhood ϵ of an emission cap M, between the equilibrium permit price and the number of permits held at equilibrium by all other firms. At cap level M, for instance, we initially simulate the OG scenario with the cap set at $M - \epsilon$ and obtain x_{-g} and μ at equilibrium. This is point A in Figure 3.3. We then change the cap level to $M + \epsilon$ and obtain the corresponding equilibrium point B. The inverted slope of the line passing through both A and B, equal to ${}^{\triangle x_{-g}}/_{\triangle\mu}$, is served as an initial estimate of ${}^{dx_{-g}}/_{d\mu}$ in (3.28).[13] In order to obtain "consistent" conjectural variations that are equivalent to what is defined by Perry (1982), we re-evaluate ${}^{\triangle x_{-g}}/_{\triangle\mu}$ through repeated simulations of the OGMP scenario, using the same procedure at the cap M, until the sequence $[{}^{\triangle x_{-g}}/_{\triangle\mu}]_n$ converges.[14] Finally, the converged parameter estimates are used to

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[13] Our approach can be related to the definition commonly used in the standard literature on industrial organization theory (Tirole 1988) as follows. Let us define the conjectural variation parameters commonly used as

$$\delta_g \equiv \frac{dx_{-g}}{dx_g},$$

reflecting firm g's conjectured change in the number of permits demanded by other firms in response to its demand for permits. Since it is convenient for our model to work with ${}^{dx_{-g}}/_{d\mu}$ in (3.28), the following derivation will relate the derivative term with δ_g. We approximate a linear relationship between permit price and quantity locally at the emission cap of interest. Formally, let the price function of permit quantities in small neighborhood ϵ of cap level M be approximated linearly by $\mu \equiv P^M(Q) = a^M - b^M Q$, where $Q \in (M - \epsilon, M + \epsilon)$ and $Q = x_g + x_{-g}$. a^M and b^M are positive constants. Rewrite $\mu = a^M - b^M(x_g + x_{-g})$ and take the derivative with respect to μ on both sides to obtain

$$1 \quad = \quad -b^M\left(\frac{dx_g}{dx_{-g}} \cdot \frac{dx_{-g}}{d\mu} + \frac{dx_{-g}}{d\mu}\right)$$

Under the assumption that firm g is not a price taker ($\delta_g > -1$), we can rearrange the preceding equation and obtain the relation between ${}^{dx_{-g}}/_{d\mu}$ and δ_g as follows:

$$\frac{dx_{-g}}{d\mu} = -\left(\frac{\delta_g}{\delta_g + 1}\right) \cdot \frac{1}{b^M}$$

[14] Perry (1982) defined "a conjectural variation is consistent if it is equivalent to the optimal response of the other firms at equilibrium defined by that conjecture." If sequence $[{}^{\triangle x_{-g}}/_{\triangle\mu}]_n$ converges for all $g \in G$, each firm is best responding to the other firms at equilibrium. Therefore, all conjectural variations are consistent when the sequence converges. To deconstruct δ_g from the relation derived above, we use the convergence

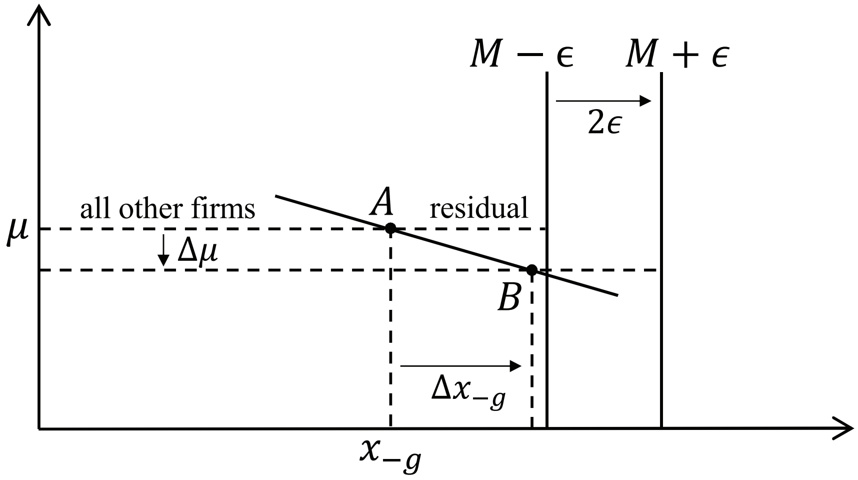

Figure 3.3: Estimation procedure of conjectural variations

produce further results in all market scenarios. In particular, the sensitivity analyses that follow apply the same converged estimates obtained from the baseline allocation scheme across all different endowments.

3.2.4 Economic Analysis

This subsection is divided into two parts: a sensitivity analysis of permit endowments and a comparative analysis of market scenarios. The sensitivity analysis allows us to examine strategies in which firms of different technologies exercise market power, while the comparative analysis provides insights into the extent of market power as well as the impact on social welfare under different assumptions on market competition in the joint markets.

Sensitivity Analysis of Permit Endowments

Figures 3.4 and 3.5 show the sensitivity analysis under the tight- and the loose-cap cases, respectively. Panels (a) and (b) plot the average sale-weighted LMP and permit price under varying initial allocations. Panels (c) and (d) plot the number of permits held by firms at equilibrium (x_g) and marginal abatement costs (n_g) under varying initial allocations. The parameter θ_g is defined as a fraction of the total number of permits that is first allocated to firm g, while allocating the remaining permits (1-θ_g) to the rest of the market, based on the proportions shown in Table 3.2. For example, $\theta_3 = 0.2$ means that 20 percent of the total number of permits is allocated to firm 3 and then the remaining 80 percent is allocated

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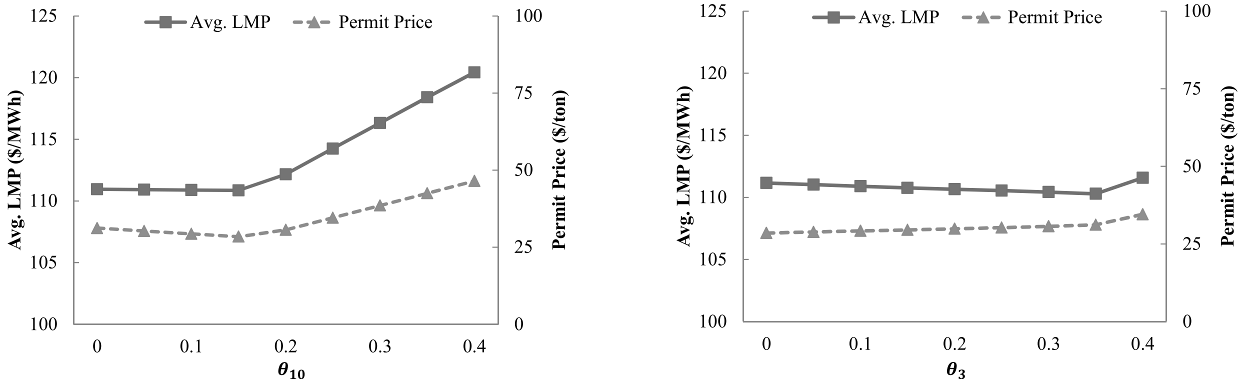
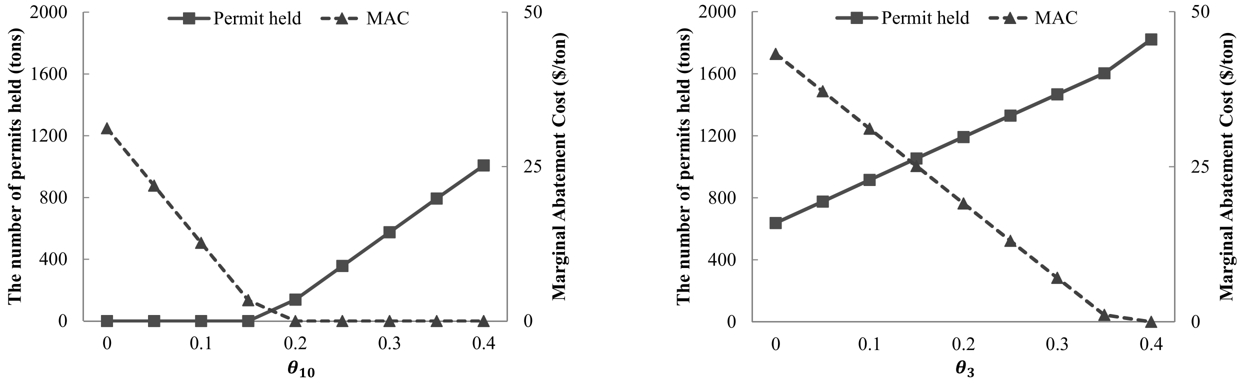
limit of $[\triangle x_{-g}/\triangle\mu]_n$, and b^M is equal to $|\triangle\mu/2\epsilon|$ as sequence $\left|\triangle P^M(Q)/\triangle Q\right|_n$ converges. The sequences may not necessarily converge, however.



(a) Electricity price and permit price under varying share of firm 10's permit endowment

(b) Electricity price and permit price under varying share of firm 3's permit endowment



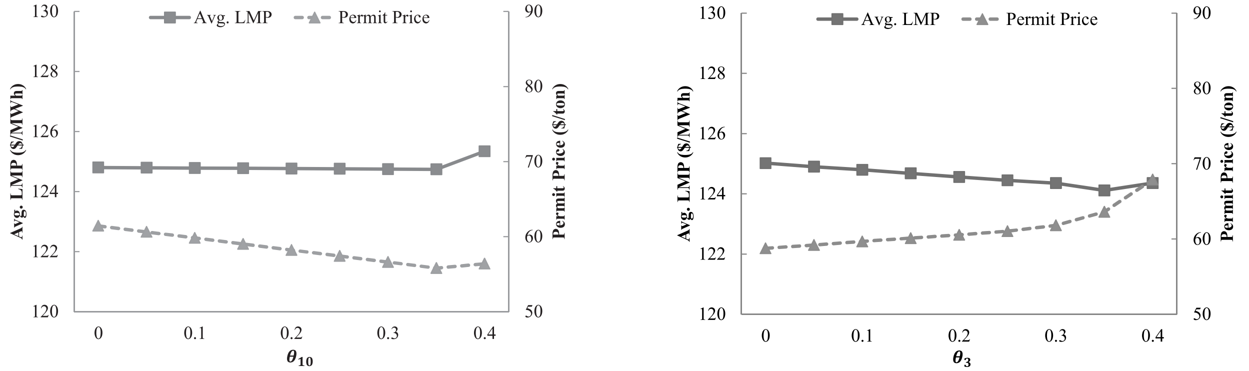
(c) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 10's permit endowment

(d) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 3's permit endowment

Figure 3.4: Sensitivity results for loose cap

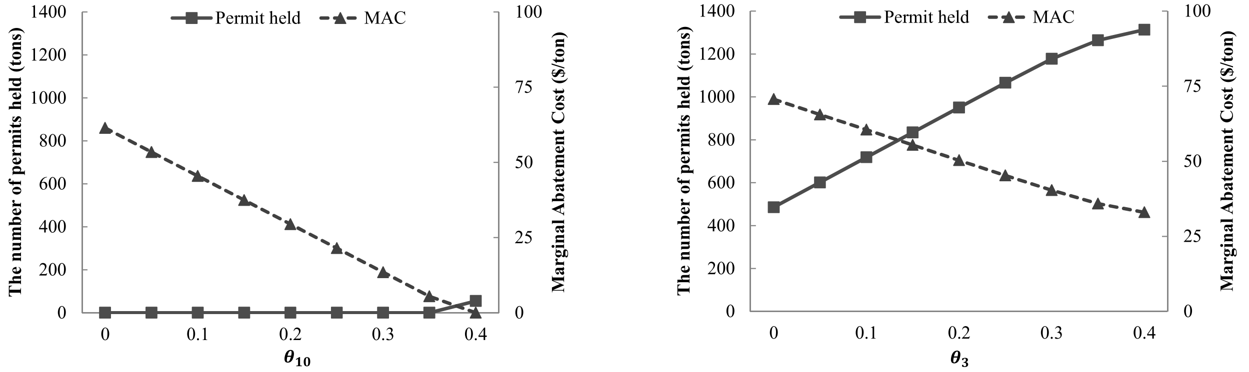
to the rest of the market in proportions according to the recalculated percent shares that discard firm 3 from the table.

Firms 3 and 10 are chosen to perform the sensitivity analysis of permit endowments for two reasons. First, a "dirty" firm can be characterized by firm 3 as it has on average high emission intensity of available resources; a "clean" firm can be characterized by firm 10 as it has on average low emission intensity (see Figure 3.2). Second, among firms with relatively high emission rate, firm 3 produces relatively more outputs in OG scenario. Under the baseline allocation scheme, firm 3 therefore receives the highest number of the permits allocated, whereas firm 10 receives none. Since it is of our particular interest in this chapter to investigate strategies taken by firms with different technologies, and these two firms offer such contrast in technologies, firms 3 and 10 are chosen as examples to illustrate possible strategies taken by other firms of similar characteristics.



(a) Electricity price and permit price under varying share of firm 10's permit endowment

(b) Electricity price and permit price under varying share of firm 3's permit endowment



(c) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 10's permit endowment

(d) Equilibrium number of permits and marginal abatement cost (MAC) under varying share of firm 3's permit endowment

Figure 3.5: Sensitivity results for tight cap

LMP and Permit Price. Figures 3.4 and 3.5 suggest that firms' optimal strategies for permit trading can be greatly influenced by permit endowments. We summarize three main observations as follows. First, whether a firm is more or less polluting, once it is granted substantial permit endowments above and beyond its ex post needs, it can potentially exert unilateral market power to increase prices. In such a case, a firm tends to place upward pressure on the permit price, thereby driving up the average LMP. This is implied by a sharp kink that bends the price curves upward for both LMP and permits, plotted in (a) and (b) of Figures 3.4 and 3.5. This kink is indeed found to occur at a threshold in which a firm's marginal abatement cost reaches zero.[15] At this point, any marginal increase in

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[15] We assume all firms are not able to modify their technologies in the short term; therefore, firms can only abate their emissions through a change in outputs and/or the use of permits. What the zero marginal abatement cost means, within the caveat of this assumption, is that firms do not incur any incremental cost

emissions by such firm, as a result of changes in outputs, is fully subsidized ex ante, thereby leaving to the firm an excess number of permits. One can refer to the complementarity condition (3.24) in the firms' problem. As they are given more endowment, both firms 3 and 10 increasingly withhold the "unused" permits—except for firm 3 under the tight-cap case—because its private marginal abatement cost remains zero after the threshold, a point at which any further withholding of permits would increase the permit price and the LMP. But the extent to which they withhold the number of unused permits is clearly much greater in the case of firm 10, as depicted by steeper bends when comparing (c) and (d) of Figures 3.4 and 3.5. For firm 3, any increase in permit allocations would rather be used in order to expand its share of output in the electricity market. Nonetheless, when further allocations to the firm render zero marginal abatement cost, it will employ the same strategic withholding as firm 10 does.

Although this result does not depend on the cap level, such a threshold is relatively higher (in absolute value) for the tight-cap case. For instance, the threshold for firm 10 under the loose cap is approximately 1,660 (=0.2 × 8,301) tons of permit allowances, which is much lower than the threshold of 2,734 (=0.4 × 6,836) tons under the tight cap. This is simply because marginal abatement costs are significantly higher in the tight-cap case, implying that permit prices are at least 20% higher. At such prices, firm 10 would be better off selling its permits, rather than withholding them. Similarly, firm 3 would likely use all the permits for its unabated outputs, instead of holding some of them unused, unless they are allocated an enormous number of permits.

Therefore, a substantial subsidy for emission costs, in terms of permit allocation that far exceeds such a threshold described previously, would potentially lead to a situation in which firms substantially withhold unused permits. The degree of such withholding at equilibrium is negatively correlated to the permits supply in the market; firms tend to withhold fewer unused permits because they can significantly profit from selling permits at high prices when the permits are scarce. In general, where permit banking is allowed, this situation could be thought of as a dominant firm purchasing a lot of permits at low prices within one compliance period in attempt to place an upward pressure on prices in both permit and electricity markets in the subsequent period.

Second, the strategic withholding of unused permits pursued by firm 10 can exert a higher upward pressure on LMPs than the strategy of firm 3 does. That is, the effect of market power in terms of LMP tends to be greater in the case of firm 10. In the loose-cap case (referring to (a)-(b) in Figure 3.4), the slope of the LMP curve (after the kink) of firm 10 (0.005 \$/MWh-ton in 3.4(a)) is steeper than that of firm 3 (0.003 \$/MWh-ton in 3.4(b)). By employing the strategic withholding, firm 10 can effectively create shortage in permits supply, thereby raising its rivals' abatement costs. Such scenario can potentially force some polluting units to be outcompeted in the electricity market and raise the LMPs,

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for their marginal change in emissions at equilibrium when they ex ante receive substantial allocations for free.

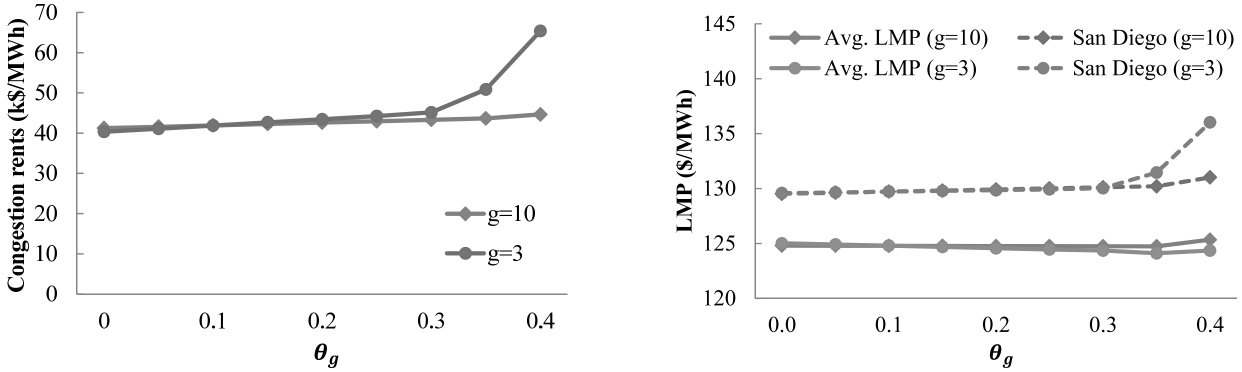
while leaving firm 10's non-polluting inframarginal outputs largely unaffected. While firm 3 can also induce a short supply of permits, if granted substantial permits initially, it does so at a lesser extent because of its need for permits.

Third, although LMPs and permit prices are often thought to be positively correlated in light of cost-raising strategies, as illustrated in the first two observations, we found that 1) the increase in permit prices does not necessarily give rise to the increase in LMPs; and 2) the LMP may remain unchanged even when there is a decline in permit price. The first result involves the situation where a relatively polluting firm receives disproportionately higher endowment for its emissions. Figure 3.4(b) shows a slight decline in LMP with increasing permit price as a result of more permits, of up to 35 percent of total permits, being allocated to firm 3. When firm 3 is increasingly being subsidized for its emissions, it can increase its output, thereby lowering LMP as shown in Figure 3.4(d). Despite being more polluting, the firm's generation units with lower marginal cost can become more competitive in the electricity market, resulting in the lower LMPs. The same result holds in the case of tight cap shown in Figure 3.5(b).

The latter result occurs in our analysis when a greater permit endowment is given to a less-polluting firm 10. In particular, as the share of initial allocation increases from zero to the thresholds (in Figures 3.4(a) and 3.5(a)), firm 10 is a net seller as it sells of all permit endowment, which can be seen from Figures 3.4(c) and 3.5(c) where the firm's equilibrium number of permits is zero. When firm 10's permit endowment is less than those at thresholds, the firm would become better off if it sells all of its permits. Not only can the firm sustain the level of LMP that allows itself to maintain the profit from inframarginal units, but the firm can also retrieve similar profit from selling all permits, even at slightly lower permit prices.

Network Congestion. Figure 3.6 shows the impact of initial allocations on the system network under the tight-cap scenarios. We omit the results of loose-cap scenarios because the same general conclusion can be drawn. Figure 3.6(a) shows congestion rents (i.e., ISO revenues) which indicate the overall congestion level under varying initial allocations of both firms 3 and 10, whereas Figure 3.6(b) shows average LMPs and zonal prices. We conclude that market power in the permit market can influence system operation as follows.

We observe that more permits allocated to a specific firm can induce a higher level of transmission congestion, especially in the case of firm 3. The increase in congestion, shown in Figure 3.6(a), mainly arises from the increased power import into the San Diego area. Such increase in congestion is relatively higher in the case of firm 3. The Miguel transmission corridor connecting Miguel, which is located in the San Diego area, to Imperial Valley (referred to Figure 3.1) experiences higher level of congestion because gas-fired generation units in San Diego area, owned by firms 5 and 7, become less competitive and lower their outputs when permit price rises. This situation increases energy imports from Imperial Valley which further draws more energy imports from Palo Verde, causing congestion on



(a) Congestion rents under varying share of firm g's permit endowment

(b) Avg. LMPs and zonal prices (San Diego) under varying share of firm g's permit endowment

Figure 3.6: Congestion rents and zonal prices

the Arizona-to-Imperial Valley corridor. As a result, the zonal LMP of the San Diego area rises in both cases—as shown in Figure 3.6(b)—but higher in the case of firm 3. Since this phenomenon results from an aggregate effect of interactions in the network, it is difficult to trace its root cause or deduce any specific conclusion as to whether market power induces higher congestion level or not. Rather, this highlights the interaction of market power in the permits market and system operations that can alter the level and pattern of transmission congestion.

Comparative Analysis of Market Scenarios

Table 3.3 reports the total CO_2 emission, total energy consumption, average sale-weighted LMP, permit price, average output-weighted emission rate, social welfare, consumer surplus, producer surplus, and congestion rents for all market scenarios. In the table, we present the results of $\theta_g = 0.4$ in order to make distinct comparison with the baseline allocation scheme.

Impact on Oligopoly Equilibria. Table 3.3 shows that there is no difference in LMP between OG and OG-MP (baseline). In contrast, there is a noticeable increase in LMPs between OG and the other OG-MP scenarios where firm 3 is given a significant permit endowment that places an upward pressure on permit price. This is evidenced by at least 20 percent higher permit prices in the θ_3 scenarios, i.e., from 29 \$/ton to 35 \$/ton in the loose-cap case, and from 55 \$/ton to 68 \$/ton in the tight-cap case. The average emission rates tend to be lowest when firm 10 is granted a substantial number of permits. In the loose-cap case, the emission rate of OG-MP (when $\theta_{10} = 0.4$) is 0.272 tons/MWh, which is much lower than 0.304 of OG; in the tight-cap case, the emission rate of OG-MP is 0.255, which is slightly lower than 0.257 of OG. Firm 10 can increase its less-polluting outputs at the expense of other firms' polluting outputs when the permit price rises partly due to

Table 3.3: Economic results

	Loose Cap (15%)					Tight Cap (30%)				
	OG	OG-MP			PC-MP	OG	OG-MP			PC-MP
		baseline	θ_{10}=0.4	θ_3=0.4			baseline	θ_{10}=0.4	θ_3=0.4	
Total CO_2 emission [tons]	8301	8301	7293	8155	6075	6836	6836	6782	6836	6086
Energy consumption [MWh]	27343	27324	26819	27292	30275	26615	26584	26556	26619	30269
Avg. LMP [$/MWh]	111	111	120	112	61	124	125	125	124	61
Permit price [$/ton]	29	31	46	35	3	55	61	56	68	7
Emission rate [ton/MWh]	0.304	0.304	0.272	0.299	0.201	0.257	0.257	0.255	0.257	0.201
Social welfare [K$]	9957	9957	9985	9963	10385	9997	9996	9997	10000	10383
Consumer surplus [K$]	7467	7457	7201	7440	8896	7099	7084	7069	7096	8893
Producer surplus [K$]	2462	2471	2745	2489	1275	2857	2871	2883	2839	1277
Congestion rents [K$]	28	28	39	34	214	42	41	45	65	213

the strategic withholding of permits. As a result, the actual emission of 7,293 tons in the OG-MP is approximately 12% lower than the cap of 8,301 tons under the loose cap. The firm can do so to a lesser extent when the cap is more stringent.

Economic Surplus. When permits are allocated highly disproportionately to a few firms, such firms can reap the economic benefits, as is this case for firm 3 or firm 10. The cost of permits would rise because of the strategic withholding of unused permits. In addition, the overall producer surplus may rise at the expense of consumers as the LMP is higher. Although lessened competition in the permit market can lead to the decrease in energy consumption, its effect on social welfare is ambiguous. Table 3.3 illustrates that the loose cap results in a slightly improved welfare in OG-MP relative to OG, due largely to skewed allocations of permits. In contrast, the social welfare is slightly lower for OG-MP (baseline) relative to OG in the tight-cap case.

Despite the decrease in energy consumption under the loose-cap case (from $27,343k to $26,819k), efficient firms (e.g., firms 9 and 10) can increase their outputs at the expense of the other less-efficient firms, leading to a slight increase in the social welfare (from $9,957k to $9,985k). This is consistent with the conclusion by Sartzetakis (1997). Nonetheless, under the tight-cap case, the welfare remains unchanged even with decreased outputs when the permit market is no longer perfectly competitive. In particular, "grandfathering" more permits to an efficient firm than to a less efficient firm may result in higher welfare when the permit market is relatively less stringent. This highlights that the cap level (or the availability of permits) may also play a role in the welfare effect in the presence of market power in joint permit and electricity markets.

The PC-MP scenario, where the electricity market is assumed to be perfectly competitive, results in a drop in the average LMP from 111 $/MWh to 61 $/MWh under the loose-cap case and from 124 $/MWh to 61 $/MWh under the tight-cap case, as shown in Table 3.3.

Consequently, the drop in prices leads to the increase in energy consumption. If firm 10 were to compete in PC-MP, its equilibrium output would have been higher than in OG and in OG-MP. The sharp output differentials are mainly caused by the strategic withholding of outputs by firm 10. This leads to a significant drop in the permit prices because the demand for permits falls when non-polluting resources do not pursue strategic withholding in the electricity market and increase their outputs. This result implies that the permit price can be greatly influenced by the level of competition in electricity market. Furthermore, the highest social welfare and the highest consumer surplus in PC-MP imply that the degree of competition in the electricity market itself can affect economic outcomes of the market to a greater extent than the presence of market power in the permit market.

Chapter 4

Conclusions

4.1 Summary

In this dissertation, I study firms' strategic interactions in a transmission-constrained electricity network under pollution regulation. The thesis focuses on carbon cap-and-trade programs as the regulatory mechanism. There are two parts to this study. The first part, described in Chapter 2, presents a model to analyze the joint interaction between electricity and permit markets. It also examines the economic impacts on electricity markets where the permit market is perfectly competitive. The second part, described in Chapter 3, also presents an extended model to analyze the joint market interactions; the only modeling difference lies in the assumption that the permit market is instead imperfect. The proposed approaches are proven useful as a tool for market monitoring purposes in the short run from the perspective of a system operator, whose responsibility has become indirectly intertwined with a cap-and-trade regulation. Both parts apply the model to an electricity market that can closely represent the California's electric power system. The findings of each part are summarized below.

In Chapter 2, I identify a potential gaming opportunity for a non-polluting generator that supplies power to a load pocket that has a limited access to alternative generators. The example raises concerns about inefficient transmission line utilization and suggests that efficient pollution regulation will require strict regulatory oversight. This is especially relevant to a state like California, where it is independently investing in in-state clean generation and largely relying on energy imports from fossil fuel generators in the neighboring states. A short-term equilibrium analysis of a cap-and-trade program in the transmissions-constrained electricity markets reveals that the ownership structure of producers may play a vital role in determining the economic and emissions outcomes. Here, I show that while a tightened cap may effectively constrain the total CO_2 emissions, resource ownership concentration could adversely interact with emissions policy and transmission constraints, leading to some unintended outcomes. Our main findings from the two analyses are summarized as follows. First, under a tighter emission cap and a higher degree of concentration of non-polluting electricity supplies, the electric power market is subject to potential abuses of market power. Second, a higher level of market competition, together with a tight cap, affects the distribution of producer surpluses among producers. Third, if clean resources are geographically concentrated in a transmission-constrained market, can lead to the potential abuses of market power in the procurement of clean energy through the permit market.

In Chapter 3, a short-term equilibrium analysis of the joint markets in the presence of market power reveals that strategic permit trading can play a vital role in determining economic outcomes in the electricity market. Following is the summary of our main findings. First, when less polluting electricity suppliers are allocated a "substantial" number of permits, these suppliers are more likely than the more polluting ones to strategically withhold of permits in order to place upward pressure on permit price and to drive up the electricity price. The extent to which firms employ such strategic withholding to influence the electricity price is likely to be diminished with a stringent emission target. To mitigate the excessive accumulation of permits, one possible modification to the C&T policy is to limit the number of permits a firm is allowed to hold.[1] Alternatively, firms may be required to surrender some portion of permits on a regulated time basis. Second, the effect of the degree of competition in the permit market on social welfare is ambiguous and may depend on the cap level. Third, strategic permit trading can influence patterns of transmission congestion. This might create a potential gaming opportunity in congestion revenue rights (CRR) market, where a firm may participate in a strategic permit trading in order to induce a certain pattern of congestion that is favorable to their CRR positions. Nonetheless, given that the scope of a C&T policy includes economy sectors other than electricity, the case study may underestimate the price elasticity of emission permits, therefore inflating permit prices. Along with the adoption of other complementary measures to mitigate potential for market power, the possible market outcomes, as we argue, are likely bounded by our simulation results.

In summary, I have identified some counter-intuitive results that vary with respect to the network topology and ownership. Some outcomes are indeed related to the specifics regarding plant locations and technology types. However, the challenge faced by the government is that environmental regulation and market surveillance are subject to different regulatory entities—Environmental Protection Agency (EPA) and Federal Energy Regulatory Commission (FERC)—and, therefore, horizontal coordination among government agencies is needed to prevent abuse of market power from occurring. The strengths of the current framework include its flexibility to answer what-if type of questions by formulating various counterfactual scenarios.

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[1] In fact, "holding limits" has been considered by CARB (see Chapter 1).

4.2 Future Work

The approaches described in this dissertation, however, are subject to limitations. The models do not take into consideration neither permit banking and borrowing nor intertemporal demands. The permit price should be determined by the supply and demand conditions over an extended time period, such as a typical compliance period of one year, or over a longer period if banking and borrowing over multiple periods are considered. One possible remedy is to extend the models to a multi-period setting in which firms take into account seasonal electricity demand in making the decision on permits banking and borrowing under the cap that declines over time. Although some features such as holding limits can be incorporated into the present model through sensitivity analysis, such extended modeling with banking can further investigate potential market issues associated with timing and compliance as well as implications of holding limits in the context of intertemporal trading. In addition, issues of safety valves can be analyzed.

Although one of the proposed models is readily extended to include other sectors covered under the C&T program, the analyses are focused on an isolated C&T market that targets the electricity market alone. Given that the scope of a C&T policy could cover more than one sector, our approach may underestimate the price elasticity of emission permits, therefore inflating permit prices. One possible remedy is to incorporate a residual permit demand curve in our model. However, this will require information concerning the marginal abatement cost curves from other sectors.

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