ABSTRACT

Title of Document: SUSTAINABLE INFRASTRUCTURE MODELING AND POLICY ANALYSES: CONSTRUCTION, ENERGY AND TRANSPORTATION INDUSTRIES

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Sustainable infrastructure operation assumes consideration of interrelated elements and problems within interacting industries in which the decisions made for one industry may affect those in interrelated industries. Problems related to global climate change and resource scarcity are main concerns for a society trying to build a sustainable infrastructure. These problems are targeted from many perspectives, including government-enforced policies and regulations that call for energy efficiency and transportation efficiency to build a sustainable infrastructure.

There is a growing interest among engineers in accounting for sustainability under the impact of climate change policies that limit the amount of pollutants being released from projects and facilities. While specific problems can be targeted by

specialists in each industry or field, an optimal sustainable solution will be very difficult to find if considered separately.

Despite that directions for improvement are defined, the methods and techniques for reaching these specified goals are not yet well developed. Decision-makers do not have the necessary models to evaluate the impact of proposed carbon policies supporting sustainable infrastructure development. Yet, it is important to analyze the problem in a systematic fashion to find cost-efficient, technically well-designed and constructed and sustainable solutions.

In this dissertation, an interdisciplinary approach is used with the aim of analyzing programs geared at reducing emissions and costs, and determining optimal allocation of resources along with profit maximization by developing and employing optimization, regression and game-theoretic models for the construction, energy and transportation industries. These models can be used by national, state, local and private agencies for assessing carbon-mitigation policies and low-cost carbon policy developments.

Concepts from integer programming, multi-objective decision-making, bi-level programming, simulation and regression are employed in the development of models to support informed decision-making and policy analyses in the construction, transportation and energy sectors. The models incorporate industry-specific details covering engineering, economic and environmental aspects of sustainable practices. The application of these models to real-world case studies provides insights that will allow defined specific goals to be achieved in a cost-efficient way. Results of case studies were optimal and most importantly not intuitive.

SUSTAINABLE INFRASTRUCTURE MODELING AND POLICY ANALYSES: CONSTRUCTION, ENERGY AND TRANSPORTATION INDUSTRIES

By

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Dissertation submitted to the Faculty of the Graduate School of the
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DEDICATION

This dissertation is dedicated to my love,

Annette,

Parents, Gevorg and Marine, brother Misak's family, and sister, Arpie,

For their unconditional love, inspiration, and support

Making my academic journey a success

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CHAPTER 1: INTRODUCTION

This chapter provides background information about sustainability and the industries considered in this dissertation. It also illustrates related problems encountered in each of these industries, provides brief information about the defined solution approaches and the findings. Specifically, the rest of this chapter is structured as follows: Section 1.1 presents background information about the importance of sustainability and how the considered industries in this dissertation are interrelated. Section 1.2 describes the importance and significance of the construction industry, provides details of identified problems and describes the developed approaches for solving the problems. Section 1.3 describes the natural gas industry where the importance of strategic investments for supply network is presented followed by Section 1.4 for transportation sector, with similar structural organization. Section 1.5 uses the same structure as the previous three sections and provides information about carbon cost pricing policy analysis on the natural gas industry. Section 1.6 summarizes the contributions and possible extensions.

1.1 Background

Sustainability is an important concept given depleting natural resources in both developed and developing countries. Establishing and maintaining sustainability of a given industry is a complex problem that includes decisions for both current and future time periods. Sustainability assumes the most optimal resource usage with minimum pollution levels. Sustainable development as defined by the World Commission on Environment and Development (1987) is: *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

This means that if present decisions for optimal operation of infrastructure are made sustainably, then the current environment will be cleaner and also can provide better conditions for future generations. Therefore, there is a need for further research in the area of sustainability that may help in informed decision-making for optimal resource allocation/usage and minimization of emissions.

The implementation of sustainability practices is a subject that is of interest to many people, but it is particularly of interest to members of firms and industries that are polluting the environment (Avetisyan 2008). To help decision-makers analyze possible outcomes of certain developments and make informed decisions, there is a need for decision-support models. In this dissertation, decision-support models are developed for selected sectors of the economy, namely, construction, natural gas, and on-road transportation. These industries are interrelated and interdependent. For instance, the construction industry is important for building the infrastructure of almost any industry, including the transportation and the energy sectors, but it cannot operate by itself if energy supply is not provided or resources are not transported. Likewise, the transportation sector may not operate efficiently without the infrastructure of roads or the energy supplied. A similar dependence also exists in the energy industry that may not exist or operate without the construction industry that builds its facilities and transportation sector that supplies the necessary combination of fuels and other supplies. Figure 1-1 schematically illustrates the relation and dependence among these three sectors of the economy. The figure shows that the decisions in one industry may affect the operation of other industries.

Since one of the important aspects of sustainability is the amount of released greenhouse gases (GHGs), the developed models treat GHGs in these units and their costs as major components in decision-making. The developed optimization and regression models in this dissertation minimize and estimate the amount of released emissions by analyzing carbon cost effects for informed decision-making in addition to cost minimization or profit maximization.

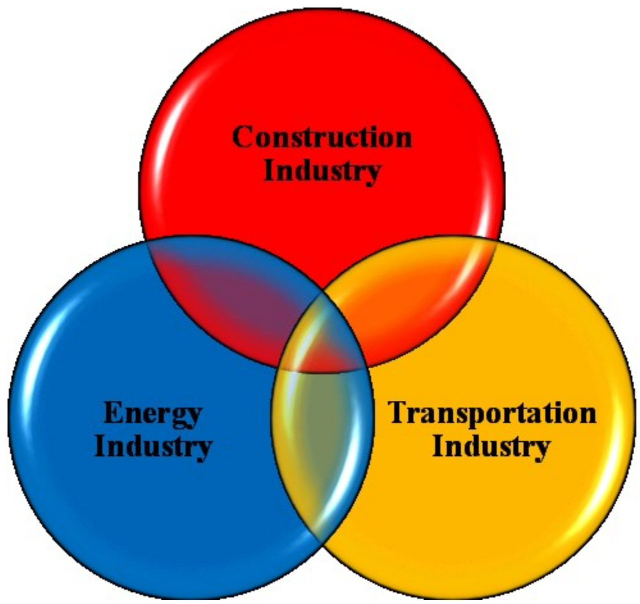

Figure 1-1: Relation and dependence between considered industries

While these three industries are closely related, a scenario justifying the connection among those industries can be considered. For instance a continuous economic growth creates the necessity for more energy supply to satisfy the needs of the society. A growing economy requires transporting more people through existing and yet-to-be-built roadways and needs new facilities for normal operation of the society. It also follows that the number of vehicles will grow on the roads increasing energy usage, and accordingly generating more emissions. This also means that a construction projects would be carried over to build the facilities and roads, and allow economic growth. So, none of these can be accomplished if any of the considered industries fail to provide services for others. More specifically, when a construction project (for example, an energy supply network expansion) interacts or passes by an existing road, the traffic on that road might be affected. Such instances may increase the chances of traffic incidents and road blockages. In general, this example indicates that the construction industry is interconnected with the energy industry, and the projects interact with the transportation sector. Finding a low-cost and environmentally friendly approach for each of these three industries is a complex problem that is regulated by a variety of carbon policies that tax, cap or grant allowance for related emissions. Since the regulatory platform for environmental policies is still in its development stage, further research that may help in the policy-making process would benefit all these industries.

The following problems for each industry were considered for further analyses. In the construction industry, emissions and cost minimization from construction equipment was chosen to comply with project-level requirements. This is due to the fact that the largest portion of emissions from construction activities is related to the construction equipment usage that burns large amounts of fuel. In the energy industry, the natural gas sector was chosen, since natural gas is the most environmentally friendly fossil fuel, which gradually replaces or complements other fossil fuels used by society. In this sector, the problem selected for further analyses was the development of a model for strategic investment decisions regarding gas supply network expansions. The supply network expansions are directly related to the optimal usage of resources and investments, while minimizing the adverse impact of those projects on the environment. Since the goal is to make environmentally sound decisions, the impact of shared carbon costs between suppliers and consumers of natural gas was also investigated. This approach may help in informed policy-making and assessing the impact of policies on the natural gas market. For the transportation sector, the problem chosen for further analysis is the emission estimation from on-road traffic for which a set of regression models were developed.

The following sections present the details about importance of each industry, the identified problem and developed solution approach for each selected industry.

1.2 Construction Industry

1.2.1 Importance and Significance of the Construction Industry

The construction industry is a vital part of any country, since without it no economy can progress. Until recently the process of construction did not consider any of the concerns related to sustainability, but was directed to profit maximization by having the job completed on time and within the budget, sometimes even sacrificing the quality due to time pressure and financial obligations. Construction firms began to consider some aspects of sustainability within the last two decades (USGBC 2003). Some companies are pioneers in sustainable practices, while others only try to comply with regulations and requirements by state or federal agencies, such as the Environmental Protection Agency (EPA) (CFR 2013).

1.2.2 The Problem

A significant portion of construction-related emissions is related to the operation of construction equipment. Even though there are more environmentally-friendly equipment pieces available in the market, which produce fewer emissions per unit of work, the cost-benefit ratio does not seem to be favorable for contractors purchasing completely new equipment fleets or retrofitting existing equipment. A variety of programs exist to support efforts to produce such emission reductions. Additional strategies have been proposed for reducing emissions from equipment use and materials production. Moreover, a number of calculators have been developed for assessing emissions from construction projects. However, it appears that no tools exist to aid contractors in making optimal construction management plans with the goal of reducing emissions while minimizing the impact on costs.

1.2.3 The Developed Approach

An optimization-based methodology was developed to allow a construction firm or a decision-maker to assess equipment needs for a project, while taking into account the GHG emissions resulting from equipment use. The problem of limiting the amount of emissions from construction equipment is regulated by a variety of policies and regulations. These policies are being improved continuously, but the existing models do not allow for analyses that may reflect the impact of policies and regulations at a project level. The developed decision-support model seeks to fill this gap and allows for informed decision-making. The developed model may also help policy makers to set carbon prices, caps and penalties for noncompliance. More specifically, the problem of optimal selection of construction equipment for project completion and simultaneous minimization of emissions and project costs (given project duration, workload, compatibility, working conditions, equipment availability and regulatory constraints) is formulated as a multi-period, bi-objective, mixed integer program (MIP).

Details of this analysis including model development and its application to a case study are presented in Chapter 2. The next section describes the development of the strategic investment decision-support model for the natural gas supply network expansion projects.

1.3 Energy Industry (natural gas)

1.3.1 Importance and Significance of the Natural Gas Industry

Similar to the construction industry, the energy sector is a vital part of the modern world. Since the beginning of the 20th century (BC), people have started using energy sources other than sun and wood, and have been dependent on these for making stronger tools and cooking food (Need 2011). Nowadays, the dependence is much higher and can even trigger energy wars (McKillop 2008). This means that decisions made for or within this industry are of strategic importance. In particular, since natural gas is the cleanest fossil fuel, it is frequently cited as a bridging fuel for future renewable energy sources. Natural gas emits less carbon than any other fossil fuel, and, hence, environmentally it is more attractive to industries that have a built infrastructure that allows switching from other fossil fuels to natural gas. More important, when environmental or sustainability regulations are considered, (such as described in "US Clean Air Act Amendments 1990," "US EPA NOX SIP Call," "US EPA Clean Air Interstate Rule" (Dewees 2008) or "Effluent Guidelines: Iron and Steel – Regulations" (EPA 2002) and others) the largest consumers of highly polluting energy sources such as coal try to comply with regulations and prefer cleaner energy options. Therefore, decision-support models for strategic investment decisions are important for decision-makers.

1.3.2 The Problem

Since natural gas is expanding its share in global energy markets, the gas supply network needs to be expanded and updated for efficiency reasons. Therefore, there is a need for huge financial investments with strategic importance.

In natural gas markets, some suppliers have better geographic and political positions (i.e. they may force their political power and will into decisions made for the market, which makes them leaders and the rest of the market followers). The leader-follower structure is more important when the decisions are related to investments for supply capacity expansions. Varieties of models, such as the World Gas Model (WGM) (Gabriel et al. 2005a, 2005b), GASMOD and GASTALE (Gabriel et al. 2010; Holz et al. 2006; Lise and Hobbs 2009), AMIGA (Huntington 2005), and EUGAS (Perner and Seeliger 2003) to name a few, were developed to help in the decision-making for the natural gas industry. These models mostly analyze the market for maximizing profits or minimizing costs, while meeting the demand in the market, considering social welfare or looking into the detailed engineering aspects of the problem. These models have endogenous data for capacity expansions, but none take into account the bi-level leader-follower approach for capacity expansion analyses, where the leader may decide on its capacity expansions and supply levels by taking into account the followers' market behavior. The developed model seeks to fill this gap. The bi-level approach in decision-making focuses on the leader-follower interaction, where the leader decides on its actions and followers move according to the leader's decision. This structure is not used for natural gas supply network expansions and as shown by case studies may provide a great benefit for both suppliers and consumers. Since the leader can practice its political will on the followers as well as on the consumers, the decisions also consider security of the gas supply. It should be mentioned that previous studies did not consider the security of supplies in the natural gas industry. The developed two-level leader-follower model seeks to fill this gap.

1.3.3 The Developed Approach

A decision-support model for strategic investments for the natural gas network capacity expansions was developed as a two-level leader-follower problem known as a Stackelberg game (von Stackelberg 2011). In this model, the lower level is an equilibrium problem, which when combined with the upper-level problem is known as a mathematical program with equilibrium constraints (MPEC). Stackelberg games are used for analyses of regulations of the economy or a particular industry (Dimitriou et al. 2008; Bard, 1998). The model developed in this dissertation decides on natural gas supply network capacity expansions and supply levels for the leader's profit maximization. In most cases, the leader represents the private sector that might have a power in decision-making in the given market, compared to other players representing the followers.

A novel feature of the proposed Stackelberg model is the consumers' dependence on suppliers and their willingness to accept a maximum supply share from different suppliers. In the current global market, where decisions go beyond cost effectiveness, supply security plays a significant role in identifying the most preferable solution from the leader's perspective. In addition, the model considers costs from GHG emissions due to capacity expansions and from the gas supply.

Details of this analysis including model development and case scenarios are presented in Chapter 3. The next section presents the work related to the on-road transportation sector.

1.4 Transportation Industry (on-road transportation)

1.4.1 Importance and Significance of the Transportation Industry

The transportation industry is another important sector providing mobility to people around the world. Like the energy sector in some parts of the world it is expanding at an increasing rate. At the same time, due to its expanding nature, the transportation industry became one of the most polluting industries. As of 2011, in the U.S., the on-road transportation sector was responsible for 28% of total greenhouse gas emissions (DOT 2011).

The transportation industry consists of a variety of transportation modes and the mode that is highly integrated into people's everyday life is the on-road transportation. Factors including speed, acceleration, frequent stop-and-go driving conditions, congestion, and driving behavior impact the amount of emissions generated from vehicles operating on a road network.

1.4.2 The Problem

Continued economic growth around the world is expanding the transportation network and consequently the miles traveled are increasing. In some countries such as the U.S., the road network is not expanding much, but the increase in emissions still occurs due to increasing number of vehicles. Following this growth, the amount of emissions increases, and, therefore, there is a need to estimate the amount of generated emissions for further informed decision-making for on-road traffic emissions reductions. There are many assessment tools that measure the amount of emissions by using the output of traffic micro-simulation platforms. The simulation and design of roads on simulation platforms is a resource intensive and computationally expensive process.

When the regular traffic flow is altered by road congestion resulting from rush hour, incidents, and work zones, the impact on emissions becomes much more noticeable when serving the same number of vehicles on the roads. To reduce emissions, the government agencies provide incentives that tend to improve vehicular composition on roads by supporting a purchase of much "cleaner and greener" vehicles. Since congestion might be caused by construction activities, it is thought that the contractor or project owner should be held responsible for compensating some or all of the incentives helping to minimize the adverse impact on the environment from their projects or be incentivized for scheduling its activities in a timely manner that generates lower emissions. Analyses capturing all mentioned specifics of the problem require considerable efforts on traffic micro-simulation platforms, which is time intensive and expensive process. It is known that the amount of emissions is related to the vehicle type, age, engine power, road type, road grade and many other factors, and, therefore, the decision-makers would benefit from the development of quick decision-support models that disclose expected impact from congestion causing activities, namely: traffic incidents and construction activities.

A set of regression models was developed that can help analyze the necessary changes in vehicular composition to minimize the released amount of emissions and hence help in deciding on the magnitude of financial support for incentives. The models can also help analyze impact of road blockage duration due to work zones and traffic incidents. Existing methods do not allow such analysis from emission mitigation incentive perspectives, and therefore such models are necessary for informed decision-making or quick analysis of given road traffic conditions.

1.4.3 The Developed Approach

To provide decision-makers with a set of models for major road types, analyses of emission estimation were conducted for freeway and arterial roadways located in Montgomery County, Maryland. The VISSIM traffic micro-simulation platform was used for scenario analyses. Scenarios consider systematic changes in vehicular composition and volume, incident and work zone related road blockage and blockage durations. The data was later used in an emission estimation tool ORSEEM. The output from ORSEEM was used for development of regression models for on-road traffic emissions estimation.

Details of this analysis including model development, extension and case scenarios are presented in Chapter 4. The next section presents the CO_2e pricing analyses for the gas industry.

1.5 Carbon Dioxide Pricing Analyses for the Global Natural Gas Industry

1.5.1 Importance and Significance of Carbon Pricing

Carbon pricing is considered an efficient measure for environmental assessment from a GHG emissions perspective. Carbon dioxide equivalents (CO_2e) are selected for measuring the variety of GHGs as one unit of measure allowing carbon taxation, allowances or caps to be applicable to most polluting sectors. The impact of carbon pricing might have severe results for some market players in any industry, while others would still be able to continue their operation and generate profits. The issue of environmental taxation is aimed at reducing negative externalities or external costs. From an economic perspective such costs can be considered as economic rents, which do not change the production-related industry decisions. The negative impact of such taxation is the increased overall price for the consumer that may minimize the suppliers' profits (Pigou 1920). This effect is true for any industry. The emissions tax or the Pigouvian tax is discussed in many areas of modern economics. It can be shown that if the tax is applied to the amount of emissions generated by a plant, then there is an incentive for the producer to reduce the production of goods. If the tax is applied as a percentage of emissions per unit of produced good, then there would be an incentive for the supplier to improve the technologies. Baumol (1972) stated that the impact of any externality is difficult to measure and hence there is a need for further analysis to understand the impact of carbon policies.

Since GHG emissions in the construction and transportation sectors are extensively related to the use of energy, the carbon pricing analyses allowing both the suppliers and consumers to be responsible for carbon costs are conducted directly in the energy sector (i.e. the natural gas sector). Specifically, the natural gas sector is selected, since it is the least polluting of all the fossil fuels (relative to CO_2e) and hence likely to expand its market share more than other hydrocarbon-based fuels when CO_2e-type regulations are imposed nationally or regionally. The market expansion is related not only to direct preferences by major consumers, such as electricity producers or cement and steel manufacturers, but also to gradual and steady technological changes, such as switching to compressed natural gas-fueled vehicles. Since there are not many choices available for efficient emissions reduction from burning fuels (due to the scale of users), where the supplier might be held responsible for the related emissions, the carbon cost is applied to the amount of emissions generated from the use of one unit of natural gas.

1.5.2 The Problem

As energy consumption increases, environmental concerns rise. To minimize the impact of GHG policies, carbon taxes, and cap and trade, and emission allowances have been proposed. These policies aim to act as incentives for consumers switching to cleaner energy sources and improved technologies. As stated earlier, the impact of carbon pricing might have severe results for some market players in any industry, while others might still be able to continue their operation and generate profits. The existing decision-support models do not provide such choices for analysis and, therefore, there is a need to develop techniques that will support analysis of the dynamics of the natural gas market under carbon policies.

1.5.3 The Developed Approach

An extension of an already well-designed World Gas Model is selected to analyze the impact of carbon pricing policies. The World Gas Model is a long-term, game-theoretic model of global gas markets with representation of the Nash-Cournot market power originally based on a North American version of the model (Gabriel et al. 2005a, b) and eventually extended to a global version (Gabriel et al. 2012). Analyses were conducted in accordance to carbon policy scenarios suggested by the Global Change Assessment Model (GCAM), a multi-industry general equilibrium model (developed by the Joint Global Change Research Institute) that was specifically developed for large-scale analyses of industries all over the world with consideration of carbon policies and other economic factors.

Details of this analysis including model extension formulation and case scenarios are presented in Chapter 5.

1.6 Summary of Contributions and Organization of the Dissertation

1.6.1 Summary of Contributions

Contributions derived from this dissertation are summarized below.

1. The construction equipment selection decision-support model provides solution from multiple perspectives, including the minimization of construction equipment-related costs and emissions, and the completion of projects in a timely manner.
2. The strategic investment model for the natural gas supply network expansion leader-follower formulation is given for the leader's profit maximization, but with consideration of emissions associated with construction activities and the combustion of supplied natural gas. The security of energy supplies is also included, which is a major factor not considered in other decision-support models for such decisions.
3. A set of on-road traffic-related emissions estimation regression models was developed allowing consideration of vehicular and road parameters (such as road grade that affect the amount of emissions) during analyses. A post-run comparison of results obtained from the regression models supports cost-benefit analyses of impacts from vehicular composition and volume changes along with lane blockage durations, emissions savings and insights for policy development.

4. The impact of application of carbon pricing on suppliers and consumers was analyzed. The extended version of the existing World Gas Model was used, which made it a more powerful model for analyzing the impact of carbon policies in the global gas market. This improvement in the model allows analyses of detailed policy implications, which also allow consideration of shared responsibility for emissions generated from the use of natural gas. Contribution to this extension of the World Gas Model was done gradually; first, analyzing the impact of carbon cost on the supply side, and, then, on the consumer side. At the final stage, the combination of both supplier and consumer sides was considered.

Overall, this dissertation provides a set of optimization and regression models that allow industry-wide (construction, natural gas, transportation) analyses for sustainability with consideration of carbon dioxide equivalent emissions and their pricing impacts.

1.6.2 Organization of the Dissertation

The first chapter of the dissertation is dedicated to the details relating the considered industries to each other and why the decisions need to be made considering sustainability. Each section in the first chapter indicated the importance of the considered industry, discussed why selected problems are important and why there is a need for further analyses, and also presented the solution developed for identified problems.

The next chapter introduces the details of the problem identified and solved for the construction industry. The chapter starts with a short description of the defined problem, considered solution approach and general results. This is followed by an extensive presentation of the model development. The chapter also presents a case study and the overall benefits of using the developed model.

Chapter 3 and succeeding Chapters 4 and 5 follow the same structure as Chapter 2 for consistency. Chapter 6 summarizes conclusions, contributions along with possible extensions of developed models. The Bibliography section follows these chapters.

CHAPTER 2: DECISION MODELS TO SUPPORT GREENHOUSE GAS EMISSIONS REDUCTION FROM TRANSPORTATION CONSTRUCTION PROJECTS

Abstract

In this chapter, an optimization-based methodology is proposed to permit a construction firm to assess its equipment needs while accounting for the GHG emissions resulting from equipment use and policy makers to set carbon price, caps and penalties for noncompliance. Specifically, the problem of optimally selecting equipment for project tasks so as to simultaneously minimize emissions and project costs given project duration, workload, compatibility, working conditions, equipment availability and regulatory constraints is formulated as a multi-period, bi-objective, mixed integer program (MIP). Two techniques are considered for its solution: a weighting technique, which seeks to create the Pareto-frontier, and a constraint approach whereby costs are minimized while maintaining an emissions cap. Off-the-shelf MIP solvers, such as CPLEX, can be used to provide solutions once the model input data and parameters are specified for a particular application. These techniques are applied on a case study involving construction of a roadway in Maryland. The developed approach[1] is generic and can be applied over varying geographic locations, site elevations, soil properties and other factors that affect equipment operation and productivity.

[1] The analysis and results of this study have been published in Hakob Avetisyan, Elise Miller-Hooks, Suvish Melanta "Decision Models to Support Greenhouse Gas Emissions Reduction from Transportation Construction Projects" ASCE Journal of Construction Engineering and Management, Vol. 138, No. 5, pp. 631-641.

2.1 Introduction

It is known that Greenhouse Gases (GHG) are vital for maintaining the earth's temperature, however, excessive presence of these gases can be harmful. In recent years, national and international support has grown for reducing the activities that cause climate change and, thus, many restrictions have been imposed to minimize carbon footprint on the earth (IPCC 2007).

The construction sector plays a significant role in GHG emissions in the U.S. According to the U.S. Environmental Protection Agency (EPA), approximately 1.7% of U.S. GHG production (as of 2003), or 6% of total U.S. industrial-related GHG emissions, can be attributed to this sector, placing the construction industry in the list of top emitters in the country (EPA 2009a). While each project may not produce large quantities of GHGs compared with operations in other sectors, because there are consistently a large number of on-going construction projects, the aggregate product of these projects is large. Given that the U.S. produced 5,839.3 million metric tons (MTs) of CO_2 in 2008 from fossil fuel usage (EIA 2009), one can estimate that this sector produces on the order of 100 million MTs of CO_2 per year. In fact, the construction industry is the third largest GHG emitter, following only the oil/gas and chemical industries (Truitt 2009). In addition, the construction industry ranks third for its CO_2 emissions per unit of energy used as input. Cement and steel production industries are first and second (Amano and Ebihara 2005) and these industries supply construction projects with needed materials.

The construction industry's contribution to GHG emissions is, in large part, like on-road traffic, due to its dependence on fossil fuel for energy required to operate heavy equipment. The burning of fossil fuel generates carbon, which when combined with oxygen from the atmosphere yields CO_2, the most abundant of the GHGs. However, the average rate of production of emissions is much greater for construction equipment (i.e. non-road vehicles) as compared to passenger vehicles (see Report MS-12 1997 for more detail) due to differences in fuel type (i.e. diesel versus gasoline), engine technology, and horse power. With continuing demand for fossil fuel, sustained increase in GHG emissions is predicted (EPA 2009a).

To foster mitigation efforts to reduce industrial and construction-related environmental impact associated with GHG emissions, improvements in technologies to aid in monitoring, and methods to encourage individual and institutional accountability towards emissions reductions, are being developed (ARB 2010a). Construction equipment manufacturers are working to improve engine efficiency, and many construction companies have switched to the use of low-sulfur diesel, reducing the amount of sulfur-oxides produced (Lewis 2009). Additionally, governments are considering instituting limitations, in the form of caps, on carbon emissions. Such caps, once enforced, will require companies to either comply with national or regional regulations, and/or pay a penalty for noncompliance or excessive GHG emissions production. While carbon markets that permit the buying and selling of carbon allowances between companies, industries and countries exist internationally, the establishment of such markets in the U.S. is likely to have a significant effect on all sectors of the economy (ARB 2010a).

Within construction projects in the transportation sector, the operation of equipment on-site accounts for the majority of project emissions. Equipment categorization, age, and horsepower, as well as the type of fuel used, can greatly affect rates of emissions. For example, backhoes, bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders produce significantly more emissions than other construction equipment pieces per hour of use (Lewis 2009). However, such projects often offer flexibility in the choice of equipment assigned for each task. Thus, it may be possible to reduce project emissions through careful assignment of equipment from a pool of available equipment for specific jobs. This can be accomplished with little or no increase in project costs. In this chapter, an optimization-based methodology is proposed to aid construction firms in making profitable decisions in terms of equipment choice and usage while minimizing project emissions or satisfying emissions cap requirements. Specifically, the problem of optimally selecting equipment for project tasks so as to simultaneously minimize emissions and project costs given project duration, workload, compatibility, working conditions, equipment availability and regulatory constraints is formulated as a multi-period, bi-objective, mixed integer program (MIP) and is referred to as the Optimal Equipment Selection Problem (*OESP*). Two techniques are considered for its solution: a weighting technique, which seeks to create the Pareto-frontier, and a constraint approach whereby costs are minimized while maintaining an emissions cap. The proposed approach as developed is generic and can be applied over varying geographic locations, site elevations, soil properties and other factors that affect equipment operation and productivity.

The application and benefits of using the developed methodology is demonstrated on a case study involving construction of a major new roadway facility, a 7.2-mile portion of Maryland's InterCounty Connector (ICC) (ICC 2010). The developed approach is also applicable for designing an equipment usage plan for roadway maintenance projects.

Agencies, such as state departments of transportation (DOTs), manage and fund enormous construction projects. Contractors compete for these projects based on estimated costs, project duration and reputation. Given the high cost of new, more efficient equipment, older, more emissive equipment is often used on construction jobs. In fact, off-road diesel equipment have a lifespan of 20 to 30 years, or even longer. To encourage construction contractors to improve their fleet mix, new jobs often require that the equipment mix meet EPA Non-road Diesel Tier System requirements, and suggest the limitation of the number of older, less efficient equipment on a job site during specified periods of time. The developed approach permits a construction firm to optimize its equipment usage so as to minimize resulting GHG emissions or meet a GHG cap and, thus, compete for the project based not only on cost, but also on environmental stewardship.

The main contribution of this work is an optimization-based methodology to permit a construction firm to assess its equipment needs while accounting for the GHG emissions resulting from equipment use and policy makers to set carbon price, caps and penalties for noncompliance. While many works in the literature promote the need for construction firms to reduce their impact on the environment, few provide tools to enable such reduction. This chapter seeks to aid in filling this gap.

2.2 Related Works in the Literature

2.2.1 Emissions Reduction in Construction

Numerous works proclaim the need for emissions reduction in the transportation construction sector. Toenjes (2010), for example, recognizes the need for construction firms to prepare for changes in local and national clean-air regulations. The U.S. EPA and many related state agencies not only espouse the need for environmental consciousness, but offer incentives to promote emissions reduction from this sector. For example, incentives are offered for retrofitting equipment with exhaust after-treatment devices, repowering (engine replacement), engine repairs and rebuilds, scrapping and replacing of older equipment, and use of alternative fuels to maximize performance. The Voluntary Diesel Retrofit Program (Bailey 2005) is an example of such an incentive program. Such programs recognize that even as more stringent emissions standards are created for new equipment, it will take years until older equipment are phased out. Another program, the Carl Moyer Program, funds efforts to reduce nitrogen oxides (NOx) emissions with a goal of reducing such emissions by 5,100 MTs per year (ARB 2010b). A related effort to reduce emissions from diesel fueled vehicles is the Texas Emissions Reduction Plan, which allocates approximately 33% of its funds to reduce emissions from construction equipment (TERP 2010).

A number of papers and reports suggest low-cost emission reduction strategies, including, for example: reducing equipment idling time and power usage; preventative maintenance; operator training; use of ultra-low sulfur diesel, biodiesel or other low-emitting fuel sources; mechanical changes to the equipment engine or engine upgrade; and electrification of equipment (Bailey 2005; EPA 2007; Toenjes 2010; ARB 2010b; TERP 2010). These suggested reduction strategies are often expensive and simpler actions (e.g., reducing idle time) may not result in significant improvements. Other works (e.g., EPA 2008a) recommend minimizing construction-related emissions through the use of alternative materials, such as fly ash produced by coal-fired power plants and supplementary bonding materials in concrete and asphalt manufacturing, in construction. The use of waste products is especially beneficial and can be a win-win for all involved industries (ACAA 2010).

Several tools have been developed to estimate GHG emissions and air pollutants from construction equipment use. These tools include the NONROAD model developed by the EPA in 2005 and updated in 2008 (EPA 2009), the OFFROAD model developed by the California Air Resources Board (ARB 2007), the Road Construction Emissions Model (Lewis 2009), the URBEMIS2007 model for general land development projects (Rimpo 2007; Lewis 2009), and the Carbon Footprint Estimation Tool (CFET) (Melanta et al. 2013). CFET takes a more holistic approach than the earlier tools, accounting for not only emissions from equipment use, but also emissions from materials, the impact of deforestation, and potential offsets due to reforestation efforts. These tools provide an estimate of GHG emissions for a given input. They are not intended for use in equipment choice.

To obtain an optimal equipment choice using such a tool, one would need to consider every possible, feasible combination of inputs and then choose the combination which results in a best compromise solution in terms of emissions and cost. The tool would be applied only to measure the emissions that would be produced for any given combination. Enormous computational effort would be required to enumerate all combinations. Consider the case study discussed in the Practical Application Section herein. With 26 time periods, 55 work activities, and between 4 and 44 pieces of equipment that can be assigned to each activity, there would be 39,000 initial combinations and the factorial of 39,000 solutions that would need to be considered. This number of potential solutions is so large that it cannot even be computed on a calculator, let along generated. Moreover, the feasibility of each of these solutions would need to be evaluated and each feasible solution would need to be entered as input to such a tool to produce an estimate of emissions production for the given input. The cost of the option would be evaluated separately. Trade-offs between options could be assessed manually. The methodology proposed herein eliminates the need for such a complete and unfathomable enumeration and manual manipulation of output.

2.2.2 Equipment Selection in Construction

Selection of equipment is typically made by matching equipment in a fleet with tasks. Such matching accounts for equipment productivity, equipment capacity and cost (see Glansberg et al. 2006, for example). More sophisticated decision tools that rely on optimization methodologies for equipment selection have been proposed in the literature since the 1970s. An overview of such techniques can be found in (Glansberg et al. 2006).

Optimization models have been proposed for equipment selection for specific construction activities. For example, Peurifoy (2002) proposed a mathematical model that seeks an equipment selection for hauling loads that maximizes equipment productivity at a given point in time. Phelps (1977) similarly considered productivity maximization in the context of cut and fill; although, Phelps considered decision-making over a time duration. Shapira and Goldenberg (2005) proposed the use of the analytical hierarchy process (AHP) to capture human preferences in construction equipment selection. Similar AHP-based approaches have been suggested in (Cheung et al. 2001; Hastak and Halpin 2000; and Skibniewski and Chao 1992). While optimization has also been employed in equipment purchasing or replacement, the authors know of no works in the literature that propose decision support through optimization in equipment selection over an entire construction project. Such an optimization approach supports efficient and objective decision-making. Neither could any prior work that considers emissions in equipment selection be found. This chapter seeks to fill this gap.

There is agreement about the need to reduce emissions from construction efforts (EPA 2005b). A myriad of programs exist to support efforts to make such reductions, and additional strategies have been proposed for reducing emissions from equipment use and materials production. Moreover, a host of calculators have been developed for assessing emissions from construction projects. However, it appears that no tools exist to aid contractors in making optimal construction management plans with the goal of reducing emissions while minimizing the impact on costs.

2.3 Mathematical Model and Solution

A multi-period, bi-objective, linear, integer program is presented for the *OESP*. The objective is to choose equipment from a pool of available equipment for each stage of a construction project so as to meet task, regulatory and temporal requirements while minimizing the total cost of equipment from ownership and operation, rental, lease or purchase and emissions abatement over the project's duration. The construction period is considered at a set S of discrete times $t=\{t_0+n\Delta\}$, where $n=0,1,2,\ldots,I$. Δ may be any increment of time, e.g., one minute, hour, day, week, or even longer. It should be noted that the number of selected pieces of equipment should be based on the specified amount of work that needs to be completed in each period t.

Many states have begun to require contractors working on large state roadway construction projects to ensure their equipment fleet follow the EPA's Non-road Diesel

Engine Tier System. The designation of a tier to a particular piece of equipment is a function of fuel-usage type, engine efficiency (horse power and year of production), and whether or not the equipment has been retrofitted to reduce emissions. Also, many federal projects recommend guidelines for construction fleets, based on the EPA Tier System classification, to encourage emissions reduction from equipment usage. For example, Maryland's requirements associated with the ICC case study described in the next section (herein referred to as the Tier System Guidelines) specify that no more than a small percentage of all equipment present on the construction site fall under one of several tiers associated with high rates of emissions. The mix given as a percentage of equipment located on site at any point in time permitted within each predesignated tier is described in Table 2-1, where the highest tier, Tier 3, includes the least emissive equipment. These Tier System requirements are included within the proposed model. For other locations these percentages can be modified according to EPA guidelines or based on any other policies or regulations.

Table 2-1. Maryland's Tier System Guidelines for Equipment on Construction Sites

EPA Tier	**Equipment limitations by percentage on site**
Tier 0	must not exceed 10%
Tier 1	must not exceed 70% (combined with Tier 0)
Tier 2	must not exceed 90% (combined with Tiers 0 and 1)
Tier 3	must be no less than 10%

2.4 The Model

Notation

Additional notation employed in the mathematical formulation of the *OESP* are defined next.

A = set of activities, i, to be completed

X = $\{0,1,2,3\}$, the set of tier levels

Y = set of equipment types (e.g., excavators, tractors, loaders)

Y_i = subset of equipment in Y that can be used for activity $i \in$A, $Y_i \subseteq Y$.

Y_i^C = subset of equipment in Y compatible with equipment in Y_i, $i \in$A, $Y_i^C \subseteq Y$.

N_t = number of pieces of equipment permitted on site in each period $t \in$ S.

c_{xy} = cost of operating (renting, leasing or owning) each type of equipment $y \in Y$ in tier $x \in X$.

V_{it} = amount of work (in terms distance, surface area, volume, or weight, depending on the activity) associated with task $i \in$A, that must be completed in period t

w_t = number of working days in period $t \in$S

v_y = daily capacity of work that can be completed by equipment type $y \in Y$, computed as a function of cycle time (time period required by piece of equipment to complete task and return to its original position).

D_{it} = calculated or assigned duration of task $i \in$A, in period $t \in$S

g_{xy} = GHG emissions rate for equipment type $y \in Y$, in tier $x \in X$, expressed in CO_2e

P_{xyt} = quantity of available equipment of type $y \in Y$, belonging to tier $x \in X$, in period $t \in$S

f = leniency factor for each N_t assumed constant over all $t \in$S

q = adjustment factor for equipment compatibility, limits differences in capacities of equipment that must operate together for any task

β_t = discounting factor for inflation by period $t \in S$

Decision variables

α_{xyt} = quantity of equipment of type y, $y \in Y$, belonging to tier x, $x \in X$, to be used during period $t \in S$

Formulation OESP

$$Minimize \quad Z(\alpha_{xyt}) = [Z_1(\alpha_{xyt}), Z_2(\alpha_{xyt})] \qquad (2\text{-}1)$$

where:

$$Z_1 = Min \sum_{t \in S} \left[\sum_{x \in X} \sum_{y \in Y} c_{xy} \cdot \alpha_{xyt} \right] \cdot \beta_t \qquad (2\text{-}1a)$$

$$Z_2 = Min \sum_{t \in S} \left[\sum_{x \in X} \sum_{y \in Y} w_t \cdot g_{xy} \cdot \alpha_{xyt} \right] \qquad (2\text{-}1b)$$

subject to:

$$\alpha_{xyt} \le P_{xyt} \qquad \forall t \in S, x \in X, y \in Y \qquad (2\text{-}2)$$

$$w_t \cdot \sum_{x \in X} \sum_{y \in Y_i} v_y \cdot \alpha_{xyt} \ge V_{it} \qquad \forall t \in S, \quad i \in A \qquad (2\text{-}3)$$

$$\frac{V_{it}}{\sum_{x \in X} \sum_{y = Yi} v_y \cdot \alpha_{xyt}} \le D_{it} \qquad \forall t \in S, \quad i \in A \qquad (2\text{-}4)$$

$$q \cdot \sum_{x \in X} \sum_{y \in Y_i} v_y \cdot \alpha_{xyt} \ge \sum_{x \in X} \sum_{y \in Y_i^c} v_y \cdot \alpha_{xyt} \qquad \forall t \in S, i \in A \qquad (2\text{-}5)$$

$$\sum_{x \in X} \sum_{y \in Y_i} v_y \cdot \alpha_{xyt} \le q \cdot \sum_{x \in X} \sum_{y \in Y_i^c} v_y \cdot \alpha_{xyt} \qquad \forall t \in S, i \in A \qquad (2\text{-}6)$$

$$\sum_{x \in X} \sum_{y \in Y} \alpha_{xyt} \leq f \cdot N_t \qquad \forall t \in S \qquad (2\text{-}7)$$

$$\sum_{y \in Y} \alpha_{0yt} \leq 0.1 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{xyt} \qquad \forall t \in S \qquad (2\text{-}8)$$

$$\sum_{y \in Y} \alpha_{0yt} + \sum_{y \in Y} \alpha_{1yt} \leq 0.7 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{xyt} \qquad \forall t \in S \qquad (2\text{-}9)$$

$$\sum_{y \in Y} \alpha_{0yt} + \sum_{y \in Y} \alpha_{1yt} + \sum_{y \in Y} \alpha_{2yt} \leq 0.9 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{xyt} \qquad \forall t \in S \qquad (2\text{-}10)$$

$$\sum_{y \in Y} \alpha_{3yt} \geq 0.1 \cdot \sum_{x \in X} \sum_{y \in Y} \alpha_{xyt} \qquad \forall t \in S \qquad (2\text{-}11)$$

$$\alpha_{xyt} \in Z^{+} \qquad \forall t \in S, x \in X, y \in Y \qquad (2\text{-}12)$$

The *OESP* contains two objectives. The first, objective (2-1a), seeks the selection of equipment so as to minimize the total cost associated with completing the construction tasks over the construction period. The second, objective (2-1b), aims to minimize emissions in terms of CO_2e released during the construction's duration. The functional constraints of the model fall into two general categories: those that address construction activity requirements and those that address emissions regulations.

Equipment availability for project use through a construction firm's fleet or local rental or leasing office stocks is enforced through constraints (2-2). Workload requirements are enforced through constraints (2-3) and (2-4). Constraints (2-3) ensure that equipment is selected for a given period so as to guarantee that all work required for the given activities can be completed. To illustrate, consider a specific task involving cut and fill that requires soil compaction. Thus, the equipment to be assigned to complete this work must be chosen so that the total capacity of the equipment in terms of an ability to cover the required surface area exceeds the amount of work associated with the compaction activity for the period. Constraints (2-4) ensure that selected equipment can efficiently handle the activities to be accomplished in a specified duration. Note that each piece of equipment has its own work rate (productivity rate) that is a function of its horsepower and other technical characteristics, as well as conditions associated with the site, including soil type, elevation, and weather. Constraints (2-5) and (2-6) ensure compatibility between chosen equipment pieces in terms of productivity and ability that are paired for the completion of specific tasks. These constraints limit the difference in the capacities of equipment to be operated together. They apply, for example, where a loader is paired with a truck: a loader to move dirt or other materials into a vessel and a truck to act as the vessel to move the material within or off the site. The effect of cycle time difference between such paired equipment must be considered and is handled in the constraints accordingly. The total number of pieces of equipment in the construction site during a given period must be restricted so as to permit sufficient working space within a construction site. This restriction is satisfied through the inclusion of constraints (2-7). A leniency factor f allows for a small increase in N_t for any $t \in S$ and is set to a value greater than one as desired. Constraints (2-8) through (2-11) apply the Tier System Guidelines. Integrality constraints are given in (2-12).

Ideally, a single solution would simultaneously satisfy the cost and emissions objectives of the *OESP*. However, as these objectives are conflicting in nature, it is not likely that such an ideal solution will exist. Thus, the set of non-inferior solutions can be generated, where no solution exists that is better than a non-inferior solution in terms of both objectives simultaneously. This set of non-inferior solutions is often referred to as the set of Pareto-optimal solutions and can be plotted on a graph with x-y coordinates corresponding to each objective to show the Pareto-frontier.

Numerous methods exist to generate the Pareto-frontier. In this chapter, a weighting method is employed whereby the objectives are combined (and weighted) so as to reduce the problem to a single objective MIP that can be solved using off-the-shelf optimization software. Specifically, objectives (2-1a) and (2-1b) are replaced by new objective (2-1').

$$Min \sum_{t \in S} \left[\sum_{x \in X} \sum_{y \in Y} (\Omega \cdot c_{xy} + (1-\Omega) \cdot cc_t \cdot w_t \cdot g_{xy}) \cdot \alpha_{xyt} \right] \cdot \beta_t \,. \qquad (2\text{-}1')$$

Since objectives (2-1a) and (2-1b) are not in common units, a conversion factor, cc_t is applied to change emissions to a monetary value[2]. cc_t is an assumed value for the price set for one MT of carbon in time period t in a carbon market. Objective (2-1') assumes a linear preference function. Each component is weighted by Ω (or $1-\Omega$), where $0 \le \Omega \le 1$. When Ω is set to 1, only the cost objective is considered. Likewise, when it is set to zero, only the emissions objective is active. By varying the value of Ω over its range and solving the resulting MIPs, the Pareto-frontier can be identified. Alternatively, a decision-maker can set Ω as a function of preference for one component over the other and solve the MIP only once to generate a preferred solution. Generation of the entire frontier aids decision-makers in evaluating trade-offs between the objectives. This can also be particularly helpful when a decision-maker is uncertain as to how to set the weights either due to lack of certainty in preference for one objective over the other or how to set the weights so as to reflect his/her preference.

In generating the Pareto-frontier by a weighting method, an appropriate increment

[2] The cost term is added in the emissions minimization objective to allow cost tradeoff analyses between objectives, where one cost increases if another cost is lowered, as suggested by WebFinance (2013) and Flanagan (2010).

for adjusting Ω from one run to the next must be chosen. In applying this technique herein, solutions are plotted as they are derived and the increment is adjusted so as to fill in voids such that the Pareto-frontier is fully visualized. Thus, some portions of the curve may be developed through coarser analyses, while other portions may be developed from very fine increments.

A second method is considered for approaching the *OESP* in which only the cost objective (2-1a) is included and the emissions objective (2-1b) is reformulated as a constraint. The objective here is merely to minimize cost from the selection of equipment, while an emissions cap is imposed (constraints 2-13).

$$w_t \cdot \sum_{x \in X} \sum_{y \in Y} g_{xy} \cdot \alpha_{xyt} \leq G_t, \qquad \forall t \in S, \qquad (2\text{-}13)$$

where G_t is a cap on GHG emissions expressed in CO_2 equivalents (CO_2e) for period *t*, $t \in S$. The use of CO_2 equivalents is aligned with recommendations of the International Panel of Climate Change. 100 year global warming potentials (GWPs) were employed herein for expressing individual GHGs in this common metric (IPCC, 2007; EPA, 2005a for more information on GWPs). Such a cap would be set to be consistent with existing emissions regulations (e.g., a carbon cap) or policies. Thus, (2-1) is replaced by its component (2-1a) and constraints (2-13) are added to create the constrained-version of formulation (*OESP*): $Min \sum_{t \in S} \left[\sum_{x \in X} \sum_{y \in Y} c_{xy} \cdot \alpha_{xyt} \right] \cdot \beta_t$ subject to constraints (2-2)-(2-13). This constrained-version of formulation (*OESP*) (i.e. constrained-*OESP*) can be solved directly. Alternatively, one might consider generating solutions over a wide array of values of G_t. A comparison of solutions in which constraints (2-13) are binding for one or more time periods can provide additional insight.

In summary, the proposed decision models require input related to the amount of work for each type of activity, daily capacity of available equipment pieces, list of construction equipment available for use on the project, time duration available for each activity, equipment compatibility, equipment suitability for tasks, operational and maintenance costs by equipment type and tier, and specifications to enable assignment of equipment to tier-level. The emission rate per equipment piece must be obtained next. As described in the following section, these rates can be computed (formulae (2-14) and (2-15)). These data can be stored in a spreadsheet. The models can be replicated for the specific application in an off-the-shelf optimization software product, such as CPLEX or Xpress, and runs can be conducted as necessary to produce the Pareto-frontier. Description of this procedure and the process of choosing from among Pareto-optimal solutions, as demonstrated on a real-world case study, is provided in the following section.

2.5 Practical Application

2.5.1 Case Study Design

The proposed problem formulation and solution approach is illustrated on a case study involving a 7.2-mile segment (known as Contract A) of an 18-mile roadway named the ICC. The case study is designed to demonstrate the utility and potential benefits of the proposed methodology.

Contract A broke ground in November of 2007. Data from the period of November of 2007 through January of 2010 was provided for use in this study. The time period was broken into one-month intervals for $|S|=26$. A list of data provided by the contractor for conducting the case study analysis is given in Table 2-2.

Table 2-2. Information Provided by Contractor

Data Type	Details of Included Information
Gantt chart:	Percent completion and duration of tasks
Quantities of materials used:	Provided data was categorized by structure type such as: substructure, bridge girder and superstructure concrete; graded aggregate base course; miscellaneous aggregate hot mix asphalt pavement; steel girders and reinforcing steel; pipes
On-site equipment list:	List of equipment present on construction site over given time intervals
Equipment assignment to tasks:	The equipment assignment for major tasks completion were specified by general categories, such as articulated trucks, crawler loaders, wheel loaders, excavators, cranes, compactors, etc.
Major tasks:	Clearing and grubbing; earthwork cut and fill; installation of piles and retaining walls; placement of substructure concrete, steel/concrete bridge girders, superstructure concrete, and reinforcing steel, culverts, culvert wing-walls/headwalls, water/sewer pipes, drainage pipes, structures, and noise walls

In addition to the information supplied by Contract A, numerous calculations and assumptions were required. Specifically, equipment cycle times and, thus, the amount of work each piece of available equipment could complete in a given day were estimated from equipment specifications assuming 75% “duty days” and eight-hour workdays. The amount of work to be completed in each work category was calculated from provided total work estimates prior knowledge of construction processes, categories of equipment assigned to task, and equipment productivity. The productivity of each piece of equipment when employed on a particular task depends in part on its cycle time, which is a function of its speed and the distance over which it must work. Equipment cycle times are subject to many factors, such as soil properties, water content, geographic location, and rolling resistance. Since this information was not provided by the contractors, estimates were made. Estimation of the work required to complete cut and fill tasks illustrates the procedures used. Articulated trucks, excavators, smooth drum rollers, track loaders, compactors, dozers, and scrapers were assigned to this task in Contract A. It was presumed that the articulated trucks are used to move the entire volume of soil from cut areas to fill areas. Excavators and loaders are employed in loosening and loading soil, respectively. Assuming that the quantity of soil to be cut is equivalent to the quantity to be filled, the amount of work supported by compactors and rollers in this stage of the project is assumed to be half of the surface area of the project. Given the local terrain and its impact on maneuverability, scrapers were assumed to conduct their work over 40% of the project area. Dozers serve in leveling the project area and loosening the soil for loaders. It was assumed that half of the cut volume of soil is handled by dozers. Thus, the amount of soil to be moved, the types of equipment involved in completing the move, and the area over which the activity takes place are predicted. With this knowledge and information pertaining to the characteristics of available equipment, cycle times and ultimately productivity can be estimated.

Similar estimates were made to capture other activities on the construction site. For example, the number of trees that needed removal during the clearing and grubbing phase was discerned from information available through the U.S. Department of Agriculture (Zhu 1994), where the average forest density mapping is provided by region. An average tree diameter was assumed based on the forest type and age. Tonnage of trees to be removed was thus assessed from forest density and expected tree weights. Work (in terms of volume) required to cut and move these trees was approximated based on presumed types of equipment that would be involved in these processes.

In an application of the proposed methodology to such a construction project, more accurate information pertaining to the required amount of work for each task is typically obtained through field measurements and such measurements are routinely taken.

The types of equipment that can be used for a given task were specified based on field experience. Work completed by each piece of equipment will produce emissions. To estimate daily emissions of CO, CO_2, CH_4, NOx, and SOx by equipment piece, the EPA's formula (2-14) for emissions calculation was used.

$$Emissions_{GHG} = AF \times Power \times Load\ Factor \times Activity\ hours\ per\ day \times Emission\ Factor_{GHG}, \quad \text{for GHG} \in \{CO, CO_2, CH_4, NO_x, SO_x\}, \quad (2\text{-}14)$$

where

AF:	adjustment factor
Power:	by equipment, in horsepower
Load Factor:	measure of equipment efficiency
Activity hours:	assumed to be 6 hours per day
Emission Factor:	Amount in emissions in grams per horsepower per hour; sources: EPA 2001; DieselNet 2010; Lewis 2009

An adjustment factor of 0.85 is employed here to account for inaccuracies in load factor and fuel type. This value was chosen so as to reflect recent reductions in the sulfur content of diesel fuel and inaccuracies in estimates of load factors. The load factors were obtained from (EPA 2004); however, more accurate values can be obtained from the manufacturer. Likewise, Contract A uses low-sulfur diesel only; however, formula (2-14) presumes the use of more emissive regular diesel. Emission data collected from equipment use in prior projects or from information supplied in equipment performance handbooks can be employed in daily emissions estimation for equipment usage and emission factor setting.

For CO, CH_4, NOx, and SOx, the emission factors were obtained directly from the EPA (2004). An emission factor is not provided in relation to CO_2; however, a formula (2-15) for its computation, based on brake-specific fuel consumption (BSFC), is provided in (EPA, 2005a). One will note that hydrocarbon (HC) emissions are removed to avoid their being double counted, as they include CH_4.

$$\text{Emission Factor}_{CO2} = (\text{BSFC}\times 453.6\text{-HC})\times 0.87\times(44/12), \qquad (2\text{-}15)$$

where

BSFC:	fuel consumption in lb/hp-hr
453.6:	conversion factor from pounds to grams
HC:	in-use adjusted hydrocarbon emissions in g/hp-hr
0.87:	carbon mass fraction of gasoline and diesel fuel
44/12:	ratio of CO_2 mass to carbon mass

To illustrate, consider a Tier 2 excavator with 128 horsepower manufactured by Caterpillar (model 320CL). To determine the total emissions in terms of CO_2e per workday using one such excavator, the following computations can be made. The Cat Performance Handbook indicates that this equipment model consumes five gallons of fuel per hour of medium-level work. The EPA NONROAD suggests using a BSFC equal to 0.367 (EPA 2005a) for a power rating between 100 and 175 horsepower. Alternatively, one can calculate the BSFC (NASA 2008) specific to this piece of equipment. Assuming each gallon of fuel weighs seven pounds, the BSFC is calculated as 5×7/128 = 0.2734. The HC value for non-road engines can be set to 0.15 g/hp-hr (DieselNet 2010). By equation (2-15), using the exact calculation for BSFC, Emission Factor $_{CO2}$ is 395.2 g/hp-h for this equipment model. Equation (2-14) can then be applied to obtain the total emissions of CO_2. This equation involves an adjustment factor, AF, which is assumed to be 85% based on the relative emission rates of the three most likely used fuels (petroleum gasoline, petroleum diesel and soybean biodiesel) and a 4% safety factor (AFDC 2011). With this information, along with a 0.59 load factor for this piece of equipment (EPA 2004) and an assumed six hour duty day (75% duty day of eight hour workday), $Emissions_{CO_2}$ is estimated at 0.15 tons per day. Similar computations can be completed to obtain the total amount of emissions of other GHGs for a six hour duty day of this equipment model. $Emissions_{CO}$ of 0.0014 tons/day, (with Emission $Factor_{CO}$ = 3.7 g/hp-h), $Emissions_{CH_4}$ of 0.000058 tons/day (with Emission $Factor_{CH_4}$ = 0.15 g/hp-h), and $Emissions_{NO_x}$ of 0.001 tons/day (with Emission $Factor_{NO_x}$ = 2.85 g/hp-h) are found. SOx emissions are negligible and are omitted. Given global warming potentials for CO of 3, CH_4 of 21 and NO_x of 310, the total CO_2e emissions sums to 0.498 tons/day. Similar calculations must be computed for each equipment model.

Other categories for which calculations were made or approximation schemes were devised are listed in Table 2-3.

Table 2-3. Additional Information Used as Model Input Not Provided by Contractor

Data Type	Details of Information
Amount of work to be completed by each type of equipment:	Based on assignment of equipment types to task types and construction stages for each task.
Assignment of specific equipment to tasks:	Based on assignment of equipment types to task types and specific capabilities of equipment.
Compatibility of equipment:	This is a daily capacity difference between coupled equipment that need to be operated together for task completion which is set to be less than 10%.
Cost for equipment by tier:	For a given piece of equipment, the cost of equipment falling within Tiers 0, 1 and 3 are assumed to be 15% less expensive, 10% less expensive and 20% more expensive than the same equipment falling within Tier 2 (in which the majority of the contractor's equipment fall).

Emission Caps:	G_t for each $t \in S$ is set such that $\sum_{t \in S} G_t = 160{,}000$. G_t is set for each period to vary over the construction period according to a beta distribution, ~β(A, B, p, q) (p>0,q>0, A<B), with p=2, q=1.2, A=0, and B=1.2.
Total number of equipment pieces allowed on site simultaneously:	This value was set based on actual number of pieces on site in each period.
Equipment productivity:	Set based on known capacities and estimated cycle times, where cycle time estimates are based on the roadway profile where appropriate and equipment characteristics; an average productivity was computed over all time periods based on required travel distances per period.

As it is possible for the contractor to use equipment from his/her own fleet or to purchase, rent or lease equipment externally, it was assumed that all equipment listed on the supplied list of on-site equipment was available for every tier level. Ownership and operating expenses for equipment were set based on information available from the U.S. Army Corps of Engineers for Region II (Hill 2009).

The price for CO_2e (i.e. carbon credit) used herein is based loosely on the carbon price on the Chicago Climate Exchange, one of the best organized carbon markets in the U.S. The price ranges between pennies and a few dollars per MT of carbon credit. Carbon price on this market reflects the amount a company or individual might be willing to pay on a voluntary basis, since carbon allowances are not currently imposed within the U.S. Assuming that once carbon allowances are enforced the carbon price will rise steeply, and given that the price is close to $30/MT in Europe where carbon allowances exist in certain sectors, in this case study, three values are used for the price of carbon on a carbon market: $5/MT, $30/MT and $50/MT. $50/MT is considered because economists estimate that this price is required to pay for 65% emission reductions to be reached by 2030 in developing countries (World Bank 2010).

2.5.2 Case Study Results and Analysis

The problem once formulated was solved with EXPRESS-MP running on a desktop with 2.27 GHz Intel Duo Core CPU P8400, 3.00 GB of RAM on a 32 bit Windows 7 operating system. Ω was set between 0 and 1 in 5% increments, generating 25 problem instances. The component objective function values were plotted against each other to produce the Pareto-frontier. Typical runs of EXPRESS required approximately 35 minutes in real-time. Problem instances contained approximately 12,000 variables. An optimality gap of 0.35% was permitted, consistent with recommendations to solve to within 5% of optimality. The resulting Pareto-frontier is visualized in Figures 2-1 (left) and 2 for each setting of the cost of one MT of carbon credit.

It can be seen from the figures that significant reductions in emissions are expected through intelligent selection of construction equipment for use in completing project tasks. Figure 2-1 (left) shows that at a cost of \$5 per MT of CO_2e, a dramatic improvement in emissions can result from a modest increase in equipment usage costs. For instance, when Ω is decreased from 0.1 to 0.08, the equipment cost increases by just over \$312,000 (approximately 4.7%). For this increase in equipment cost, a reduction by 28% in emissions (and its associated cost) can be obtained. Similar efficiencies are noted when the price per MT of CO_2e is set to \$30 (Figure 2-2 (left)) and \$50 (Figure 2-2 (right)).

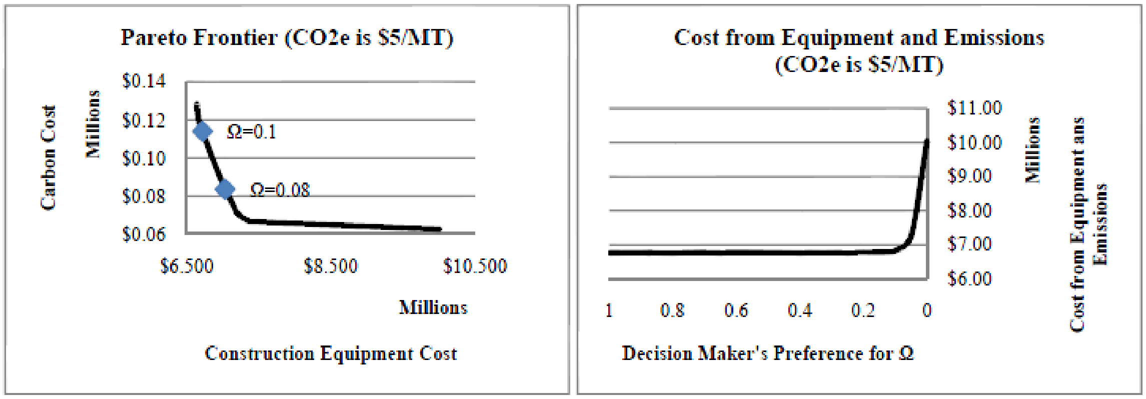

Figure 2-1: Pareto-Frontier (left) and Cost from Equipment and Emissions (right) for CO_2e at $5/MT

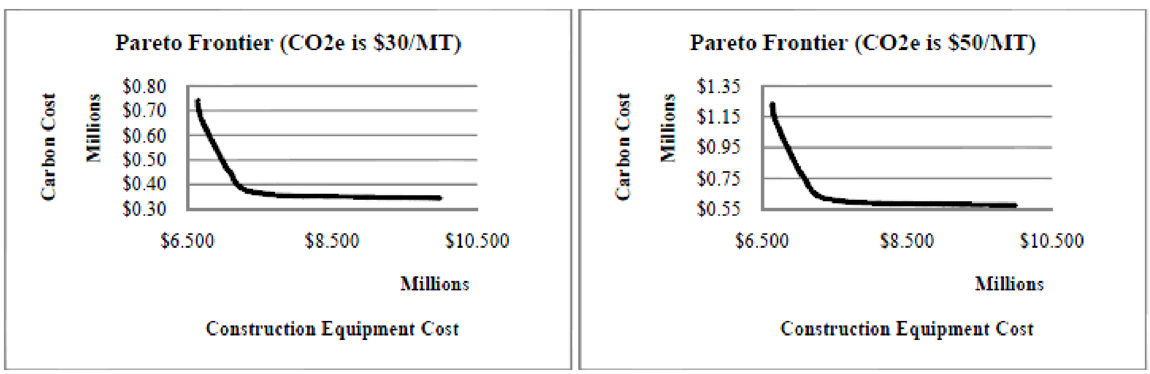

Figure 2-2: Pareto-Frontier for CO_2e at $30/MT (left) and for CO_2e at $50/MT (right)

Figure 2-1 (right) depicts the relationship between the Ω setting and objective function value. Little if any change in the objective function occurs between Ω = 1 and Ω = 0.1. This implies that there is little if any change in the solution for Ω in this range. As Ω is reduced below 0.1 (the cost of emissions is given more weight), there is a steep change in curvature of the line, indicating a significant change in equipment selection.

An estimate of emissions at 160,000 MTs of CO_2e produced from equipment use in Contract A over the study period was made based on the number of days each piece of equipment in the on-site equipment list spent on site, number of assumed working hours per day and emissions rate per equipment type. This estimate was used to create the initial settings for G_t for each $t \in S$ in (2-13) of the (*constrained-OESP*) formulation. Solution of this formulation was obtained and the objective function value (i.e. equipment cost) was plotted against a reduced $\sum_{t \in S} G_t$. That is, to show how more restrictive cap values affect the optimal solution, the value of the sum of G_t over all $t \in S$ was reduced from its initial value, assumed at 160,000 MTs over the entire time horizon. The resulting cost from equipment is plotted against the reduced values of $\sum_{t \in S} G_t$. This is depicted in Figure 2-3, where the x-axis indicates the relative value (in terms of percentage decrease) of $\sum_{t \in S} G_t$ with respect to its initial value. X% on the x-axis refers to an X% reduction in $\sum_{t \in S} G_t$ from the initial $\sum_{t \in S} G_t$ of 160,000 MTs. A percentage emissions reduction of 80%, for example, corresponds with a value for $\sum_{t \in S} G_t$ of 32,000 MTs (a reduction of 128,000 MTs). As indicated in the figure, $\sum_{t \in S} G_t$ can be reduced substantially before a notable increase in equipment cost arises. This confirms that constraints (2-13) are not binding at the initial $\sum_{t \in S} G_t$ value. In fact, if constraint (2-13) is binding for any particular time period t, when the associated G_t is reduced, the problem will be infeasible. At approximately 78% of the initial $\sum_{t \in S} G_t$ value, equipment cost begins to rise sharply to comply with this constraint. When set even lower, it becomes difficult to comply with the constraint at any cost, as indicated by the nearly vertical line beginning at an x-axis value of approximately 89%.

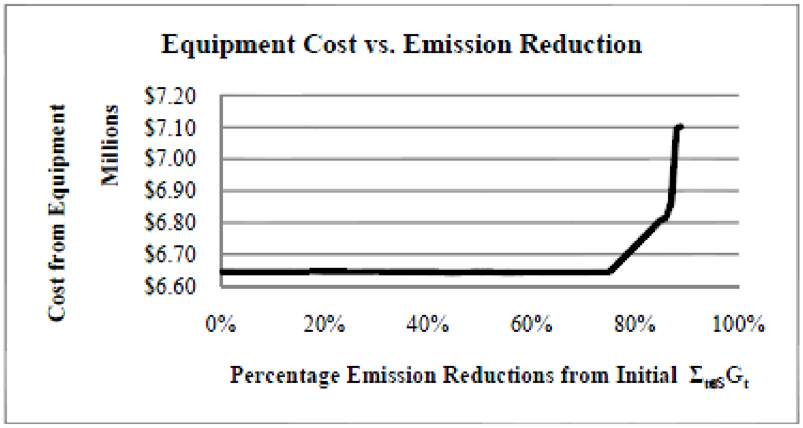

Figure 2-3: Impact on Equipment Cost of Reduced Emissions Cap

Figure 2-3 also shows how an industry might set a reasonable cap for a given project. In the case of the ICC, the cap might be set in the range of 80-85% of the initial $\sum_{t \in S} G_t$ value. Moreover, if the estimated initial $\sum_{t \in S} G_t$ value accurately reflects emissions as a result of equipment use in the project (recall that it was assumed that equipment on site was in use 6 hours per day, 7 days per week), one will note that for a very small equipment cost increase, a very significant improvement in emissions reductions can be achieved.

To illustrate the potential impact in terms of emissions prevented and choice of equipment that results from the use of the proposed methodology, equipment plans generated through solution of the *OESP* with Ω = 1, 0.9, 0.1, and 0 are compared for cc_t of \$5 at a single select time interval, t = 21. These results are compared in Tables 2-4 through 2-6.

Results given in Table 2-4 indicate that when cost is the only consideration (i.e. Ω=1), few pieces of equipment from the top tier are selected, i.e. the minimum required to meet Tier System constraints (2-8 to 2-11). When emissions are the only consideration (i.e. Ω=0), and cost is of no consequence, all equipment are chosen to be in the top tier

(Tier 3). While little difference in number of equipment pieces in each tier level is noted for Ω at 0.1 as at 1, there are changes in equipment within a category as shown in Table 2-5. For example, within the Off-Highway Trucks category, there is a change from 14 "ArtA335D" selected when Ω=1 to 13 "Art730s" and three "ArtA35Ds" when Ω=0.1. These fall under the same tier level. Additionally, there are changes in tier level, as is the case in the Dozers category. 11 Tier 1 equipment pieces are selected when Ω=1, while 11 similar pieces of equipment that fall under Tiers 2 and 3 are selected when Ω=0.1. Appendix provides information associated with t=21 that supports these conclusions.

Table 2-4. Number of Equipment Pieces Assigned by Tier for t=21and varying objective function weights (Ω)

Tier	**Ω=1**	**Ω=0.9**	**Ω=0.1**	**Ω=0**
0	7	7	7	0
1	43	43	44	0
2	14	14	15	0
3	8	8	8	77
Total	**72**	**72**	**74**	**77**

Table 2-5. Number of Equipment Pieces Assigned by Equipment Type and Category for t= 21 by varying objective function weights (Ω)

Equipment Category	**Equipment ID**	**Ω=1**	**Ω=0.9**	**Ω=0.1**	**Ω=0**
Off-Highway Trucks:	ArtA35D	14	14	3	0
	ArtT730	0	0	13	17
Graders:	Com815F	1	1	1	1
Cranes:	Cr165TN	3	3	3	3
Dozers:	DozD65	0	0	0	11
	Doz650J	1	1	0	0
	DozD5GLGP	2	2	3	0
	DozD6N	7	7	7	0
	Ex315CL	1	1	1	1
Excavators:	Ex330CL	0	0	0	5
	Ex345CL	4	4	4	0
	Ex325DL	0	0	0	1
Forklifts:	Fork10054	6	6	6	6
Tractors/Loaders/Backhoes:	L410J	2	2	2	2
	L644G	4	4	4	4
	Rol50	2	2	2	0
	Rol66	0	0	0	11

Rollers:	RolSD100D	11	11	11	0
	RolSD110D	0	0	0	1
Scrapers:	Scrap621G	9	9	9	9
Skid Steer Loaders:	Skid460D	1	1	1	1
Other Construction Equipment:	ConcF4800	1	1	1	1
Other Material Handling Equipment:	FB643J	1	1	1	1
	HB260HP	1	1	1	1
Other General Industrial Equipment:	TGrind6600	1	1	1	1
Total		72	72	74	77

From Table 2-6 it can be seen that at a carbon price of \$5/MT, over \$3 million (a 50% increase) is incurred in excess costs in selecting the optimal equipment with consideration only for emissions (i.e. Ω = 0). A more modest increase (of a bit over \$64,000) is incurred when cost is given small weight, i.e. when Ω = 0.1. It can also be noted that when funds are expended on more efficient (high tier) equipment, the cost from emissions in the objective function decreases.

Table 2-6. Cost Comparison for varying objective function weight (Ω) for a Carbon Price of \$5/MT

Weight Ω	Equipment Cost	Emissions Cost	Total
Ω=1	\$6,641,602	\$123,384	\$6,764,986
Ω=0.9	\$6,642,333	\$123,196	\$6,765,529
Ω=0.1	\$6,720,404	\$108,946	\$6,829,351
Ω=0	\$10,008,880	\$57,449	\$10,066,329
Ω=0.9 vs. Ω=1	\$731	\$(187)	\$543
Ω=0.1 vs. Ω=1	\$78,802	\$(14,437)	\$64,365
Ω=0 vs. Ω=1	\$3,367,277	\$(65,935)	\$3,301,343

The percentage increase in cost and reduction in estimated actual emissions that result from considering the cost of emissions in the objective function can also be derived from the results. For a 0.95% increase in total cost from equipment, a savings of 12% in emissions can be achieved given Ω set to 0.1. Likewise, for a 51% increase in equipment cost, a reduction in emissions by 53% can be achieved given Ω set to 0.

To demonstrate that the model produces feasible assignments of equipment to time periods, a quick validation of some of the computations is completed. Consider cut and fill activities in time period 21. The data supplied by the contractor indicates that there is a need for a total of 216,731 cubic yards of earthwork. This activity requires cutting of the soil so that it can be moved. This task is undertaken by dozers. Solution of the mathematical program for $\Omega = 1$ as given in Table 2-5 indicates that 10 dozers of three different types (Doz650J, DozD5GLGP and DozD6N) should be assigned to this task. The first of these dozer types has a productivity rate of 524 cubic yards/day, while the second and third types have rates of 551 cubic yards/day and 1008 cubic yards/day. These rates are computed from cycle times and blade sizes. Consider period 21 with duration of one month or 25 working days. The total work that can be completed by these 10 dozers is 217,035 cubic yards. This exceeds the required 216,731 cubic yards.

Similar computations for different settings of Ω result in similarly satisfactory equipment choices. For example, when Ω is set to 0.1, the model selects 10 dozers of types: DozD5GLGP and DozD6N. This selection of dozers can support an estimated 217,710 cubic yards of work in the one month period. When Ω is set to 0, 11 dozers of type DozD65 with daily productivity rates of 796 cubic yards/day are selected, enabling completion of 218,790 cubic yards of work in the given month.

Note from Table 2-A that for $\Omega = 1$ or 0.1, all selected dozers fall into Tier 1; however, for $\Omega = 0$ (i.e. the objective is to choose the most environmentally favorable equipment), Tier 3 dozers were selected. Again, to assess the validity of decisions suggested by the model, consider the emissions rates of these equipment pieces. Doz650J and DozD5GLGP produce 0.7 tons/day. DozD6N produces 1.16 tons/day. Finally, DozD65 produces 0.25 tons/day. Costs per month for these pieces are: $4,724/month, $5,129/month $8,922/month and $10,800/month, respectively. Note that as the emissions rates decrease, the monthly cost for use of the equipment increases. With decreasing Ω, we see the contribution to emissions due to dozer use decreases from 128.98 tons/month to 69.41 tons/month, while the cost increases from $77,436/month to $158,400/month. As there are 70 different equipment pieces available for use in this construction project, and each piece is unique in terms of its tier ranking, cost of use, and productivity, the selection of the optimal set of equipment for use in each period is complicated. The proposed solution methodology provides an automated and efficient approach to equipment selection.

2.6 Conclusions

Solution of the proposed mathematical formulation provides an optimal choice of equipment to be used in each period of a construction project. It further aids a contractor in deciding whether to buy, lease or rent equipment for the project. It relies on data that is readily available for any moderate to large construction job. Output of the model can help contractors in quantifying the potential value in terms of costs to meet environmental standards or identify requirements for investment in new equipment to reduce project emissions. Also, by including equipment that can be rented or leased in the pool of possible equipment for selection, the tool aids in decisions related to augmentation of an equipment fleet through renting or leasing. Costs considered in the objective function of formulation (*OESP*) can account for changes in cost as a function of purchase price, depreciation, terms of lease, rental prices, and tax regulations.

Delays in task completion may result as a consequence of unforeseeable circumstances, such as inclement weather. Such delays adversely affect project length. Through solution of the mathematical formulation using updated task durations, the proposed methodology provides optimal equipment selection for future time periods so as to reduce the impact of the delays. The viability (and cost) of shortening the project's duration so as to obtain a bonus for early completion can also be evaluated.

While all bids must show that designated requirements regarding the environment in the call for proposals are met, rarely is environmental impact considered in choosing the winning bid. The proposed decision tool permits a contractor to develop an equipment-usage plan that adheres to current and future environmental regulations that might affect construction, including the EPA's Non-road Diesel Engine Tier System, and possible establishment of a carbon tax or cap and trade programs. Moreover, it aids contractors in trading off project cost, duration and resulting emissions in the development and proposal of construction bids, allowing green construction decisions. The tool will, likewise, enable state agencies to consider emissions in addition to project costs and duration in assessing bids.

The proposed methodology can aid construction firms in maintaining profitability in a carbon regulated future by facilitating decisions aimed at meeting new regulations or reducing environmental impacts by making changes to its equipment fleet. This can also aid in better positioning a construction firm to receive government-provided incentives for environmental stewardship. Consideration of solutions to the *OESP* for a select project generated by setting Ω to its extreme values (i.e. 0 and 1) will provide policy makers with reasonable estimates of achievable emissions reductions, and an understanding of costs associated with emissions abatement. Likewise, in an emissions regulated future, solution of the (*constrained-OESP*) can facilitate a construction firm in determining the amount of money in terms of an acceptable carbon price for expanding its carbon allowance through either the purchase of surplus carbon credits or by paying penalties for noncompliance. It may also be possible to profit from selling surplus allowances. Additional costs associated with producing such a surplus through equipment selection can also be assessed. Furthermore, this feature facilitates policy makers or contracting agencies in setting a reasonable cap for a given project.

As public sentiment for reducing our carbon footprint continues to increase in popularity, it may be possible for companies employing environmentally friendly decision-making processes to attract and retain environmentally conscious clients. Thus, it can be profitable to meet or even surpass expectations of emissions regulations. Moreover, as new regulations are adopted, these companies will be poised to take a larger share of the market, as their less earth-friendly competitors are driven out of business.

The optimization-based methodology proposed herein, therefore, aids the construction sector in adapting to a carbon regulated future.

Appendix 2-A

Table 2-A provides a list of selected equipment given by solution of the *OESP* with the given Ω. The number that precedes the equipment name indicates the equipment tier level.

Table 2-A. Selected Equipment Quantities for t=21 for selected objective function weights (Ω)

Ω=1 (and Ω=0.9)		Ω=0.1		Ω=0	
Tier. ID	Quant.	Tier. ID	Quant.	Tier. ID	Quant.
0.ArtA35D	3	0.ArtA35D	3	-	
0.Cr165TN	3	0.Cr165TN	3	-	
0.TGrind6600	1	0.TGrind6600	1	3.ArtT730	17
1.ArtA35D	11	1.ArtT730	13	3.Com815F	1
1.Com815F	1	1.ConcF4800	1	3.ConcF4800	1
1.ConcF4800	1	1.DozD5GLGP	3	3.Cr165TN	3
1.Doz650J	1	1.DozD6N	7	3.DozD65	11
1.DozD5GLGP	2	1.Ex315CL	1	3.Ex315CL	1
1.DozD6N	7	1.FB643J	1	3.Ex325DL	1
1.Ex315CL	1	1.L410J	2	3.Ex330CL	5
1.Ex345CL	4	1.L644G	4	3.FB643J	1
1.FB643J	1	1.Rol50	2	3.Fork10054	6
1.L644G	4	1.Scrap621G	9	3.HB260HP	1
1.Scrap621G	9	1.Skid460D	1	3.L410J	2
1.Skid460D	1	2.Com815F	1	3.L644G	4
2.HB260HP	1	2.Ex345CL	4	3.Rol66	11
2.L410J	2	2.HB260HP	1	3.RolSD110D	1
2.RolSD100D	11	2.RolSD100D	9	3.Scrap621G	9
3.Fork10054	6	3.Fork10054	6	3.Skid648G	1
3.Rol50	2	3.RolSD100D	2	3.TGrind6600	1

CHAPTER 3: STRATEGIC INVESTMENTS FOR NATURAL GAS PIPELINE AND LNG SUPPLY NETWORK EXPANSIONS USING A TWO-LEVEL MARKET MODEL

Abstract

Natural gas, the most environmentally friendly fossil fuel, is expanding its market globally. To satisfy the growing demand for energy, the supply network of natural gas needs to be expanded. Network expansion requires huge financial investments. These are strategic investments and need a careful analysis. In natural gas markets some suppliers have better geographic and political positions than others, which makes them leaders and the rest of the market followers. In this chapter a decision-support model for strategic investments in natural gas network capacity expansions as a two-level leader-follower problem known as a Stackelberg game is developed, in which the lower-level is an equilibrium problem, which when combined with the upper-level problem is known as a mathematical program with equilibrium constraints (MPEC). Stackelberg games are widely used for analyses of regulations for an economy or a particular industry (Abou-Kandil and Bertrand 1987; Bard 1998; Dimitriou et al. 2008; Jain et al. 2008). To illustrate the use of the model, a case study of a proposed natural gas supply pipeline from Russia to China is considered. Findings of the study suggest that current prices and market characteristics are not favorable for Russia (as a Stackelberg leader) to invest in the proposed capacity expansion and that higher supply prices would be needed.

3.1 Introduction

Natural gas is the most environmentally friendly fossil fuel, which is expanding its share of consumption in global markets growing from 15% in 1965 to 24% in 2010. In terms of trillion cubic feet (Tcf), this is an increase from 23 Tcf to 104 Tcf (MIT 2010). Forecasts indicate further growth of demand in North American, Eurasian and Middle Eastern energy markets (Figure 3-1) (AGA 2008; EIA 2010a; MIT 2010). While pipeline infrastructure is aging and the need for energy in the world is growing, there is worldwide need for new pipelines and capacity expansions for existing pipelines and liquefied natural gas (LNG) plants with supporting transportation vessels (ANL 2007; MIT 2010). Decision-making for these types of investment projects is challenging and sometimes includes issues of not only technical and financial feasibility, but also factors of political orientation and preferences (von Hirschhausen et al. 2005).

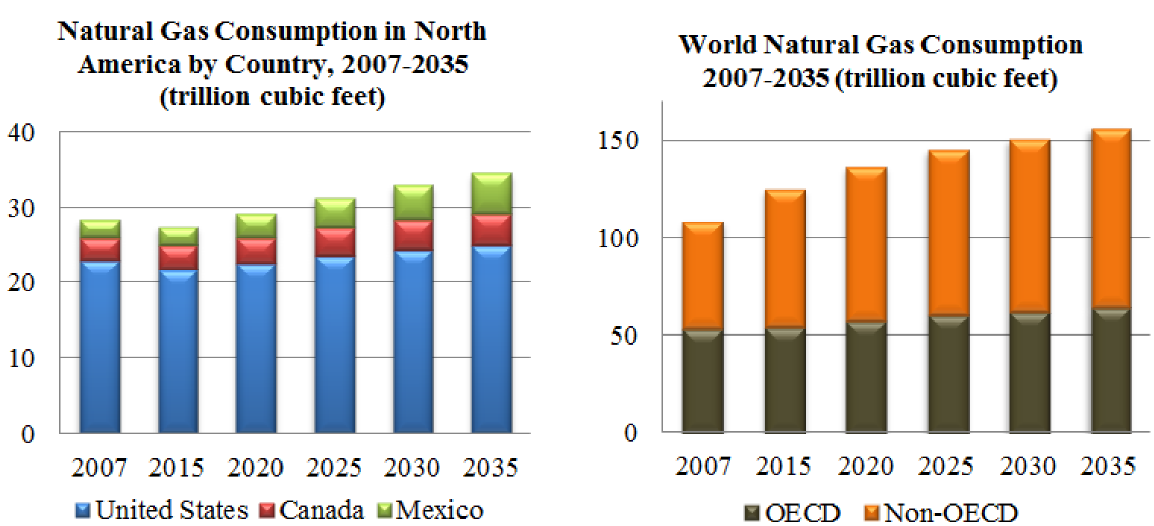

Figure 3-1: North American (left) and Total World (right) Natural Gas Consumption.

According to projections in the U.S. and Canada alone the range of investment varies between \$133 and \$210 billion in infrastructure over the next 20 years. This is primarily based on increased domestic natural gas production from unconventional shale basins along with tight sands and the need to connect those to the existing pipeline network (Brown et al. 2010; Levell 2010; INGAA 2009). Studies in the area of the natural gas industry analyze the market from various perspectives such as maximizing profits or minimizing costs while meeting the demand in the market, or considering social welfare in addition to those analyses. In particular the World Gas Model (WGM) is a long-term, game theoretic model of global gas markets that has been used in such studies. The original model was developed for the North American market only (Gabriel et al. 2005a, 2005b), which later was extended to a global version (Gabriel et al. 2012). WGM has a "Cournot coefficient" which allows having more sophisticated analyses by assigning market power to a particular player/s. Similar to WGM other widely recognized models related to natural gas market analysis that have some type of market power are GASMOD and GASTALE (Gabriel et al. 2010). GASMOD is a European gas market-based game theoretic two-stage model where local producers decide how much to produce after exporters outside of Europe decide how much to import gas to Europe (Holz et al. 2006). GASTALE is also an equilibrium model for the European gas market that includes producers, transporters, storage, and consumers of natural gas where under Nash-Cournot equilibrium (Cournot competition) producers maximize their profits assuming that other regions will not affect their sales in consuming regions (Lise and Hobbs 2009). These specified models have endogenous data for capacity expansions, but none of these models takes into account the bi-level leader-follower approach for capacity expansion analyses, where the leader may decide on its capacity expansions and supply levels by taking into account the followers' market behavior.

The model AMIGA, developed at Argonne National Laboratory and DePaul University, makes use of Lagrange multipliers, but does not include a leader-follower formulation so may not be appropriate to represent players in the model (Huntington 2005). The model EUGAS depicts the European gas market while providing prices also for electricity generation (Perner and Seeliger 2003; Huntington 2005). It provides information about investments for the industry. This model is geographically specific and similar to other models discussed above, but does not supply information on a leader-follower basis. The model GASCOM is a game theoretic model which provides specific information about the timing of pipeline construction. It is mostly limited to the area of Former Soviet Union (Huntington 2005). GASCOM is an equilibrium-based model and may not necessarily maximize a leader's profits and is not formulated as such. Rice University developed a model for gas trade with large spatial coverage, but does not provide specific information about network expansion and moreover it is not formulated as a leader-follower problem and may not be used for leader's profit maximization purposes (Huntington 2005). FRISBEE is another gas market model that provides information about gas prices including LNG. FRISBEE is not formulated to maximize a leader's profits either (Aune et al. 2009). The U.S. Energy Information Administration developed the National Energy Modeling System (NEMS) and SAGE models, which are used to produce the output for the Annual Energy Outlook report, but these models do not provide information about strategic investments from the leader's perspective and do not maximize the leader's profits (Huntington 2005). ICF developed the NANGAS model, which is a dynamic, linear program and provides information about pipeline expansion and also provides information about carbon prices, but does not allow for market power (Gabriel et al. 2003; Huntington 2005). The equilibrium approach needs to be considered when modeling the natural gas industry (Huntington 2005). GaMMES model developed at Electricité de France (2011) is a generalized Nash-Cournot equilibrium model calibrated for the European gas market and considers the shale gas availability for European producers, but does not take into account the effect of the leader-follower relationship (Abada et al. 2011).

Some studies had been conducted in electric power market analyses using an MPEC formulation. For instance, the decisions of an energy-producing leader firm for expansion investments were investigated while considering the stochastic production levels of follower firms (Wogrin et al. 2011). MPEC applications were applied to the energy market not only for network or capacity expansion purposes, but also for a pricing and bidding purposes. In that problem each firm submits bids to an ISO for profit maximization by taking into account decisions made by rival firms (Hobbs et al. 2000). This is an important aspect for strategic investment analyses that allows for considering the effect of leader's decision on the rest of the gas market. Kazempour et al. (2011) used an MPEC approach for strategic investment decision making for electricity generation. Murphy and Smeers (2005) used various approaches including MPEC formulation for investment decisions for electricity generation where the first stage considered investments for expansion and the second stage of the problem was a production level analysis (Murphy and Smeers 2005). Fortuny-Amat and McCarl (1981) discussed solution methods for MPECs using the disjunctive nature of complementarily slackness conditions (Fortuny-Amat and McCarl 1981). Other MPEC models for the power sector were formulated by Gabriel et al. (2009) where the authors described a Benders Decomposition approach for solving discretely constrained MPECs with application to the power sector. A similar method was implemented in addition to a heuristic approach by de la Torre et al. (2007) where a three-level problem was solved for bidding decisions in the power sector. Baumrucker (2009) presented pipeline operational cost minimization problem, formulated as an MPEC structured for nitrogen and hydrogen gas pipelines. The work also indicated the differences with natural gas pipelines. The major difference of these networks was identified to be the multiple branching, while for natural gas the pipeline does not consider such technical issues. There are many more models dedicated to MPEC formulations for the power sector, but are not presented here (e.g., Su 2005; Yao et al. 2008; Gabriel and Leuthold 2010),

In this chapter we develop a model for natural gas network capacity expansions as a two-level leader-follower problem known as a Stackelberg game (von Stackelberg 2011), in which the lower-level is an equilibrium (complementarity) problem, which when combined with the upper-level is known as a mathematical program with equilibrium constraints (MPEC). Previously Stackelberg games have been applied to gas markets by De Wolf and Smeers (1997) where the authors discussed the European gas market to illustrate the effect of using such an approach, although it was dedicated to decision-making for production levels only. The current work considers the effect of network expansion in addition to production levels for a multi-period time horizon.

MPECs are more general than bi-level optimization programs, but with different objectives at each stage (Scholtes 2008). MPECs are important problems and play a significant role in engineering and economic analyses, but in general are hard problems to solve (Luo et al. 2008). Some of the solution techniques include Vertex Enumeration, Penalty method, Benders decomposition method for discretely-constrained problems (Gabriel et al. 2010; Fricke 2003; Pang and Fukushima 1999).

One of the distinguishing exogenous factors is representing dependence on suppliers. Different than most other approaches, we model this dependence via a key coefficient which represents an upper bound on the percentage of entire supply from each supplier for a given market. In the current worldwide market where decisions go beyond just cost effectiveness, this term plays a significant role in identifying the most preferable solution. In addition, we consider costs from greenhouse gas emissions due to capacity expansions and from the transportation and use of gas.

The rest of this chapter is organized as follows. Section 3.2 presents the two-level formulation including an overview of the problem addressed in the chapter; Section 3.3 provides numerical results for a case study involving Russia and China; in Section 3.4 results and conclusions are given followed by Appendix 3-A and 3-B.

3.2 Formulation

The problem discussed in this chapter deals with decision-making for strategic investments in natural gas network capacity expansion and for annual gas production levels by the leader firm to maximize its profits. Followers are modeled using as a Nash-Cournot game, which later gets combined through disjunctive modeling with the upper-level problem. In the lower-level problem, followers compete with each other while taking into account the amount of production by the leader firm as a fixed value. The followers also indirectly take into account the network capacity expansions by the leader since the level of production by the leader changes based on the decisions made for expansions. The leader decides how much to expand the network capacity for a certain market while anticipating the behavior from the followers and adjusting its decisions accordingly.

Players at both levels consider costs associated with carbon dioxide equivalent (CO_2e) pollution stemming from natural gas operations. In particular, the leader considers carbon costs that would result from the expansion of capacities in addition to those associated with supply and use of the natural gas. In contrast the followers problem consider only the amount of carbon being generated from the supply and use of gas, since in the formulation they do not make decisions for a supply network expansions. The leader also faces fixed charges when it decides to expand a capacity in a considered time period, while followers do not have such expenditures.

The constraints of the model include technical capacity limitations that may reduce the amount of gas being extracted from gas supply node (region), and consumer preferences for the delivered gas. The model also takes into account the time value of money through a discounting factor. In the leader's problem, three modes of gas network expansion and production are considered: traditional pipelines, LNG delivered through vessels, and LNG through cryogenic pipes. In contrast, the followers' problems consider only the first two modes, since there are no cryogenic pipelines in place that might be considered as existing capacity for followers. Cryogenic pipelines are a novel technology pipe that allows transportation of LNG over relatively long distances. A specially designed wall of cryogenic pipes allows extremely low temperature LNG to be transported. Cryogenic pipe-in-pipe technology in comparison to traditional pipes is advantageous as it may transport 600 times more natural gas due to low temperature compression (down to -160 C^o). Due to temperature differences with the surrounding environment traditional pipelines are not capable of transporting the LNG and therefore the traditional mode for LNG transportation has been vessels. The latest technological achievements have made it possible to transport LNG over relatively long distances using cryogenic pipes. The novel technology by Technip promises to transport it over longer distances and a pilot five-mile project is in its procurement stage (Technip 2011). ITP (2011) has similar projections and uses such pipelines for transporting heavy and waxy oil or other cryogenic liquids. Even though it seems a reasonable form of transport mode for LNG supply the length of a single link and the cost still make it an expansive option for broader integration into the natural gas supply network.

In the next section we provide the details of the formulation.

3.2.1 Notation for the Model

This section presents the sets and short description of notation used in the model formulation with capital letters (generally) referring to the leader's problem unless when defining sets. The bulk of the notation can be found in the Appendix 3-A.

Indices:

f	follower firms
i	origin node
j	destination
t	five-year time increment

Sets:

F	set of all followers
N	set of all nodes
T	set of all time periods included in the model

Subscripts indicate origin and destination nodes followed by the time period. In the followers' problems, subscripts also include the index for the firm. Superscripts indicate the mode of natural gas such as P for pipelines, LNG for liquefied natural gas and PCRY for cryogenic pipelines. The superscript notation is followed by "exp" for expansion and "supp" for supplies. For example the term $INTR_{ijt}^{P\,exp}$ means intercept ($INTR$) for pipeline (P) expansion (exp) from origin (i) to destination (j) at time period (t) in the inverse demand function used to formulate the objective function as a profit maximization for the leader. Similarly, $SLP_{ijt}^{P\,exp}$ stands for the slope of the same item. Also, it should be noted that in the case study the network capacities are expressed in trillion cubic feet per year (Tcf/y)[3]. Production levels are also expressed in Tcf/y for consistency.

The next section presents a mathematical formulation for the leader's problem.

3.2.2 The Leader's Problem

The leader is modeled as maximizing its own profits based on consideration of the followers' market behavior. Its decision variables are capacity expansions in conventional pipelines, LNG plant and vessels, cryogenic pipes, and the amount of natural gas being supplied through those capacities. The conventional pipeline capacity expansion level is the difference between capacity at time t and the previous time interval: $\left(\Delta_{ijt}^{P} Q_{ijt} - \Delta_{ij(t-5)}^{P} Q_{ij(t-5)}\right)$, where Δ_{ijt}^{P} is an exogenous factor in $[1, \infty)$ representing the difference between supply level and the maximum capacity. Q_{ijt} is the supply level at time t.[4] Similar capacity expansions are: LNG with term $\left(\Delta_{ijt}^{LNG} LNG_{ijt} - \Delta_{ij(t-5)}^{LNG} LNG_{ij(t-5)}\right)$, and term for cryogenic pipes

[3] 1 cubic foot is equal to 0.02831 cubic meters.

[4] An alternative approach is to have separate capacity variables, but for computational efficiency reasons the approach above was selected.

$\left(\Delta_{ijt}^{PCRY} PLNG_{ijt} - \Delta_{ij(t-5)}^{PCRY} PLNG_{ij(t-5)}\right)$. For liquefied natural gas supply levels are represented by $LNG_{ijt}, PLNG_{ijt}$. Since the model is developed for capacity expansion decisions, all supply levels are presented in total annual values which may not exceed the total network capacity for each mode. The objective function for the leader's profit maximization problem is given in (3-1). Profit is the difference of revenues and costs. Revenues are from expansion of network by three sources: for conventional gas by pipelines, for LNG through vessels and through cryogenic pipes. All three revenue terms are of the same form namely:

$$\left(INTR_{ijt}^{(*)exp} \; - SLP_{ijt}^{(*)exp}(\cdot)\right)\left(\Delta_{ijt}^{(*)} Z_{ijt} - \Delta_{ij(t-5)}^{(*)} Z_{ij(t-5)}\right)$$

Revenues generated from supplies will have similar structure to those from expansion:

$$\left(INTR_{ijt}^{(*)supp} \; - SLP_{ijt}^{(*)supp}(\cdot)\right) Z_{ijt}.$$

where Z_{ijt} represents the quantity in conventional, LNG or cryogenic pipelines, $Z_{ijt} \epsilon \left\{Q_{ijt}, LNG_{ijt}, PLNG_{ijt}\right\}$ and super and subscripts for the inverse demand function are suppressed for simplicity $(*) \epsilon \left\{P_{ijt}, LNG_{ijt}, PCRY_{ijt}\right\}$.

There are five cost terms: expansion costs, supply costs,[5] carbon costs from expansion associated with pipeline expansion and gas supply, and capital investments. Respectively, for the pipelines the cost terms are: $\left(C_{ijt}^{P\,exp}\left(\Delta_{ijt}^{P} Q_{ijt} - \Delta_{ij(t-5)}^{P} Q_{ij(t-5)}\right)\right)$ between time *t* and *t-5*, $\left(C_{ijt}^{P\,supp} Q_{ijt}\right)$ the cost for supply, $\left(CARBC_{ijt}^{P\,exp}\left(\Delta_{ijt}^{P} Q_{ijt} - \Delta_{ij(t-5)}^{P} Q_{ij(t-5)}\right)\right)$ the cost of carbon resulting from expansion for the time interval between *t* and *t-5*,

[5] The Leader can either produce its own gas or procure it from others; hence gas supply term is the general term used. Also, the supply cost includes the levelized cost from any previous installations.

$\left(CARBC_{ijt}^{P\,supp}Q_{ijt}\right)$ the carbon cost from the supplied gas, $\left(K_{ijt}^{P\,exp}\cdot X_{ijt}^{P\,exp}\right)$ for fixed charges if expansion is selected.

In a similar approach the cost terms are included for LNG plant and vessels and LNG cryogenic pipelines.

All cost terms are of the same form namely for expansion:

$\left(C_{ijt}^{(*)\,exp}\left(\Delta_{ijt}^{(*)}Z_{ijt}-\Delta_{ij(t-5)}^{(*)}Z_{ij(t-5)}\right)\right)$.

For supply the general term is: $\left(C_{ijt}^{(*)\,supp}Z_{ijt}\right)$.

Carbon cost terms that are also related to different modes of natural gas network expansion are expressed as: $\left(CARBC_{ijt}^{(*)\,exp}\left(\Delta_{ijt}^{(*)}Z_{ijt}-\Delta_{ij(t-5)}^{(*)}Z_{ij(t-5)}\right)\right)$

For gas supply and final use related carbon terms in formulation are of the form: $\left(CARBC_{ijt}^{(*)\,supp}Z_{ijt}\right)$, while terms for fixed charges are expressed as: $\left(K_{ijt}^{(*)\,exp}\cdot X_{ijt}^{(*)\,exp}\right)$.

In this formulation, five-year time increments are used which are indicated via the notation *t* and *t-5*. This is an assumption based mostly on an idea that on average the investment and construction process take about five years until the new link between origin-destination (OD) nodes materialize. In (3-1), the revenues are generated through capacity expansion and the gas transported through those capacities. For the case study in this chapter, the profits from expansion are set to be non-positive, since it is assumed that the expansion is done by the same company and there is no external funding. The results in the case study indicate that the expansion is made only enough to produce zero profits from expansion. However from a tax perspective it may be advantageous to show the expansion as an expense.

For instance the firms may be characterized as in Figure 3-2. The diagram on the left indicates that the firm does not have external funding while the figure on the right accounts for an external source for network expansion projects. These two options are the reason for the given structure of the objective function to allow for having profits maximized also from expansion construction activities.

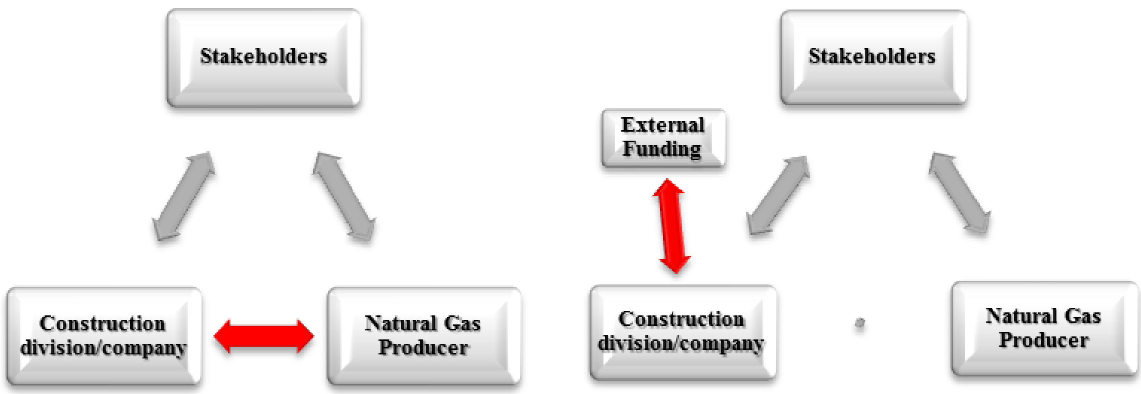

Figure 3-2: Firm's Possible Structural Forms Considered in Model Formulation

Considering the discussion above about the possible profit maximization options for a leader firm the general form the objective function of the leader firm will be:

$$
\begin{aligned}
\max_{Z_{ijt}} \sum_{(*)\in\{P_{ijt},LNG_{ijt},PCRY_{ijt}\}} \sum_i \sum_j \sum_t \Bigg(\sum_{Z_{ijt}-Z_{ij(t-5)}} \Big(& INTR_{ijt}^{(*)exp} \\
& - SLP_{ijt}^{(*)exp}(\cdot)\Big)\left(\Delta_{ijt}^{(*)} Z_{ijt} - \Delta_{ij(t-5)}^{(*)} Z_{ij(t-5)}\right) \\
& + \sum_{Z_{ijt}} \left(INTR_{ijt}^{(*)supp} - SLP_{ijt}^{(*)supp}(\cdot)\right) Z_{ijt} \\
& - \sum_{Z_{ijt}-Z_{ij(t-5)}} C_{ijt}^{(*)\,exp}\left(\Delta_{ijt}^{(*)} Z_{ijt} - \Delta_{ij(t-5)}^{(*)} Z_{ij(t-5)}\right) - \sum_{Z_{ijt}} C_{ijt}^{(*)\,supp} Z_{ijt} \\
& - \sum_{Z_{ijt}-Z_{ij(t-5)}} CARBC_{ijt}^{(*)\,exp}\left(\Delta_{ijt}^{(*)} Z_{ijt} - \Delta_{ij(t-5)}^{(*)} Z_{ij(t-5)}\right) \\
& - \sum_{Z_{ijt}} CARBC_{ijt}^{(*)\,supp} Z_{ijt} - \sum_{Z_{ijt}} K_{ijt}^{(*)\,exp} \cdot X_{ijt}^{(*)exp} \Bigg) \rho_{ijt} \qquad (3-1)
\end{aligned}
$$

The extensive form of the objective function is given in the Appendix 3-A as (A.1).

For designing supply networks with detailed engineering considerations the nonlinear model might be better for accuracy. For instance the flow–pressure relationship or the impact of atmospheric pressure on pipelines is not linear and nonlinearity is appropriate for development of such models for natural gas systems. However, these issues are less common and probably less appropriate for higher-level decision-making models that are used to answer policy questions such as extent of market power by certain players, effects of capacity on prices, regional and seasonal price differentials and others (Gabriel et al. 2005b). In many other situations the linearity assumption is supported by the fact that in the range of the solution the demand curve is almost linear and the model does not suffer due to this assumption (von Hirschhausen et al. 2005; Schirillo 2006). This assumption is an analogy to the demand curve of nuclear power, which has a high cost for installation and a constant production level per unit capacity. In this case the cost of installation is moderately high while the capacity is designed in a way that would mostly be served with its full capacity so any addition of an extra unit will add up the cost linearly.

The leader's problem has the following constraints, which are formulated based on technological and natural conditions (the node capacity) of production/supply and security of supplies expressed as preferences of a consumer for delivery from suppliers:

General form for equations (3-2) - (3-4):

$$0 \leq \left(Z_{ijt} - Z_{ij(t-5)}\right) \leq TCAP_{ijt}^{(*)\,exp} \cdot X_{ijt}^{(*)\,exp}, \quad \forall i,j,t$$

In extensive form:

$$0 \leq \left(Q_{ijt} - Q_{ij(t-5)}\right) \leq TCAP_{ijt}^{P\,exp} \cdot X_{ijt}^{P\,exp}, \quad \forall i,j,t \qquad (3-2)$$

$$0 \leq \left(LNG_{ijt} - LNG_{ij(t-5)}\right) \leq TCAP_{ijt}^{LNG\ exp} \cdot X_{ijt}^{LNG\ exp}, \quad \forall i,j,t \qquad (3-3)$$

$$0 \leq \left(PLNG_{ijt} - PLNG_{ij(t-5)}\right) \leq TCAP_{ijt}^{PCRY\ exp} \cdot X_{ijt}^{PCRY\ exp}, \quad \forall i,j,t \qquad (3-4)$$

$$\sum_i \sum_j \left(\sum_f \delta_{fijt}^{p} q_{fijt} + \Delta_{ijt}^{P} Q_{ijt} + \sum_f \delta_{fijt}^{lng} lng_{fijt} + \Delta_{ijt}^{LNG} LNG_{ijt} + \Delta_{ijt}^{PCRY} PLNG_{ijt} \right) \leq H_{it}, \quad \forall f,i,j,t \qquad (3-5)$$

General form for equations (3-6) - (3-10):

$$Z_{ijt} \leq D_{ijt}^{(*)\ supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right), \forall f,i,j,$$

Particular form:

$$Q_{ijt} \leq D_{ijt}^{P\ supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right), \quad \forall f,i,j,t \qquad (3-6)$$

$$LNG_{ijt} \leq D_{ijt}^{LNG\ supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right), \quad \forall f,i,j,t \qquad (3-7)$$

$$PLNG_{ijt} \leq D_{ijt}^{PCRY\ supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right), \quad \forall f,i,j,t \qquad (3-8)$$

$$q_{fijt} \leq d_{ijt}^{p\ supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right), \quad \forall f,i,j,t \qquad (3-9)$$

$$lng_{fijt} \leq d_{ijt}^{lng\ supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right), \quad \forall f, i, j, t \qquad (3-10)$$

$$Q_{ijt} = 0, \qquad \forall i, j, t \text{ when } i = j \text{ and when defined by user (i.e. political obstacle)} \qquad (3-11)$$

$$LNG_{ijt} = 0, \qquad \forall i, j, t \text{ when } i = j \text{ and when defined by user} \qquad (3-12)$$

$$PLNG_{ijt} = 0, \qquad \forall i, j, t \text{ when } i = j \text{ and when defined by user} \qquad (3-13)$$

$$X_{ijt}^{P\ exp}, X_{ijt}^{LNG\ exp}, X_{ijt}^{PCRY\ exp} \in \{0,1\}, \qquad \forall i, j, t \qquad (3-14)$$

$$Q_{ijt}, LNG_{ijt}, PLNG_{ijt} \geq 0, \qquad \forall i, j, t \qquad (3-15)$$

$$CONS_{jt} - \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right) = 0, \quad \forall f, i, j, t \qquad (3-16)$$

In the leader's problem the capacity expansion is subject to technical limitations for a given time interval between origin and destination nodes. Such limitation is enforced through constraints (3-2 to 3-4). In particular constraint (3-2) limits pipeline capacity expansion in a given time interval, and constraint (3-3) for LNG plant and vessel capacity expansions. For cryogenic pipeline expansion such limitation is enforced by constraint (3-4). In addition to technical constraints, the capacity of expansion can be limited because of the natural gas availability from the ground due to natural resource extraction rate regulations, which is expressed through constraint (3-5). In this constraint players from the lower-level problem are also included since the capacity of a particular location can be used by multiple players and hence the total capacity of expansions and accordingly flow capacities cannot exceed the maximum capacity possible to extract from a particular location. The formulation of this constraint with inclusion of the time factor in the indices together with cost terms in the objective functions allows analysis of the market subject to geological and economic perspectives of technological achievements and their impact on resource availability.

Consumers may prefer to have more capacities from one supplier and less from another supplier for political or other reasons. Having information about consumers' preferences the leader can make more favorable decisions for its investments. Constraints (3-6)-(3-10) are designed to use the consumers' preferences in the decision-making process. These constraints are formulated for different modes of natural gas supplies (i.e. conventional gas, LNG and LNG through cryogenic pipelines) including both upper and lower-level players, and provide more flexibility both for supply preferences, security and accuracy. Constraints (3-6)-(3-10) consider supplier dependency for example something that might be useful for supply diversity. The term on right-hand side of these constraints (e.g., $D_{ijt}^{P\,supp}$) represents the maximum percent of supply from a given supplier for a given mode of gas. Constraints (3-11 to 3-13) are useful to "turn off" capacity options consistent with geographic or political considerations. Constraints (3-14) are binary variables enforcing capital investment costs in to the function if the installation is selected. Constraints (3-15) are for non-negativity of variables. The additional constraint (3-16) is a calibration constraint initially used to find appropriate values for the inverse demand function parameters. Once these parameters have been determined this constraint is removed, as it was done in the case study.

3.2.3 Followers' Problems

The followers are modeled as maximizing their profits by maximizing their production levels while taking the leader's supply quantities as fixed. Followers are included in this problem with fixed capacities, which means they do not solve the problem for capacity expansion. The idea of fixed capacity should not be mixed with the supply level, which may be a fraction of the existing capacity. Since cryogenic pipe-in-pipe technique for LNG transportation over long distances is a novel technology it is assumed that the follower firms do not invest in these novel technologies. The objective function for the followers' problem is given in (3-17). The formulation of this function follows the same structure from leader's problem with the difference of not including network expansion-related terms:

$$\max_{q_{fijt}, lng_{fijt}} \sum_i \sum_j \sum_t \left(\left(intr_{ijt}^{p\,supp} - slp_{ijt}^{p\,supp} \left(\sum_f q_{fijt} + Q_{ijt} \right) \right) q_{fijt} + \left(intr_{ijt}^{lng\,supp} - slp_{ijt}^{lng\,supp} \left(\sum_f lng_{fijt} + LNG_{ijt} \right) \right) lng_{fijt} - \left(\sum_f \left(\left(c_{ijt}^{p\,supp} q_{fijt} + c_{ijt}^{lng\,supp} lng_{fijt} \right) + \left(carbc_{ijt}^{p\,supp} q_{fijt} + carbc_{ijt}^{lng\,supp} lng_{fijt} \right) \right) \right) \rho_{ijt} \right) \qquad (3-17)$$

The followers have only upper bound due to technical capacity limitations on their production levels. Those are presented below:

$$0 \le q_{fijt} \le tcap_{ijt}^{p\,supp}, \quad \forall f, i, j, t \qquad (\alpha_{fijt}) \qquad (3-18)$$

$$0 \leq lng_{fijt} \leq tcap_{ijt}^{lng\ supp}, \quad \forall f,i,j,t \qquad (\beta_{fijt}) \qquad (3-19)$$

As described above, the followers maximize their profits shown in the objective function. Costs included in (3-17) are for production and for related carbon dioxide equivalent emissions. Constraints (3-18) and (3-19) enforce capacity limitations, which are related to the upper levels of existing capacities in terms of pipelines and LNG plants and vessels (LNG Plants 2006).

In the following section KKT conditions for the followers' problem are presented, which later are transformed into a disjunctive program.

3.2.4 KKT conditions for followers' problem

The lower-level problem with Nash-Cournot competition needs to be solved as an equilibrium problem. This problem is solved as a complementarity problem by using the KKT conditions. A generic complementarity problem is defined as finding a vector ($z \in R^n$) which satisfies the following conditions (Cottle et al. 2009):

$$\begin{aligned} &z \geq 0 \\ &q + Mz \geq 0 \\ &z^T \cdot (q + Mz) = 0 \end{aligned}$$

where vector $q \in R^n$ and M is a matrix $\in R^{n \times n}$.

The following KKT conditions are derived for the followers' problem:

$$0 \leq \left(-intr_{ijt}^{p\ supp} + slp_{ijt}^{p\ supp} \cdot q_{fijt} + slp_{ijt}^{p\ supp} \sum_{f} q_{fijt} + slp_{ijt}^{p\ supp} \cdot Q_{ijt} + c_{ijt}^{p\ supp} + carbc_{ijt}^{p\ supp} \right) \rho_{ijt} + \alpha_{fijt} \perp q_{fijt} \geq 0, \quad \forall f,i,j,t \qquad (3-20)$$

$$0 \leq \left(-intr_{ijt}^{lng\ supp} + slp_{ijt}^{lng\ supp} \cdot lng_{fijt} + slp_{ijt}^{lng\ supp} \sum_{f} lng_{fijt} + slp_{ijt}^{lng\ supp} \cdot LNG_{ijt} + c_{ijt}^{lng\ supp} + carbc_{ijt}^{lng\ supp} \right) \rho_{ijt} + \beta_{fijt}$$

$$\perp lng_{fijt} \geq 0, \ \forall f, i, j, t \qquad (3-21)$$

$$0 \leq -q_{fijt} + tcap_{ijt}^{p\ supp} \perp \alpha_{fijt} \geq 0 \qquad \forall f, i, j, t \qquad (3-22)$$

$$0 \leq -lng_{fijt} + tcap_{ijt}^{lng\ supp} \perp \beta_{fijt} \geq 0 \qquad \forall f, i, j, t \qquad (3-23)$$

3.2.5 Disjunctive form of followers' problem

A disjunctive constraint form was used to formulate the followers' problem (Sherali and Shetty 1980; Fortuny-Amat and McCarl 1981; Hobbs 2001; Winston 2009; Gabriel and Leuthold 2010).

The generic structure to convert complementarity conditions to disjunctive constraints is provided below by using notation used in Section 3.2.4 for deriving KKT conditions. The complementary conditions are generally in the form:

$$\mu_i \cdot g_i(x', y) = 0$$

where $\mu_i$is a primal or dual variable and g_i is associated function. With the disjunctive programming technique this complementarity condition is converted as follows:

$$\mu_i \leq M \cdot r_i$$

$$g_i(x', y) \leq M(1 - r_i)$$

where r_i is a binary variable for replacing complementarity by disjunctive constraint and *M* is a large enough constant. Once the disjunctive constraints are used they can be combined into the upper-level problem. The combined upper- and lower-level problems are presented in Appendix 3-A.

The key to making the disjunctive constraints approach work is to correctly select the constant M. Too large a value of M may produce computational difficulties, too small a value may overly constrain the feasible region. Based on Gabriel and Leuthold (2010), in this chapter we have used 16.536 selected as the maximum from values of intercepts, slopes of inverse demand function and capacity limitations.

3.3 Case Study

The case study is presented to illustrate the functionality of the model. Instead of hypothetical case study analysis considered a proposed pipeline for natural gas from Russia to China called "Altai" (see Figure 3-3). The objective is to decide how much conventional pipeline, LNG plant and vessel or cryogenic pipeline capacity to install from Russia to China. Certain assumptions were made along the way of scenario development, which are discussed in more detail in the following sections.

Considering the fact that Russia is a major energy supplier to other continents and expressed its willingness to satisfy all of China's natural gas demand in the future, Russia's entry into this market may become an important issue and have an impact on other suppliers' capacities.

Figure 3-3 illustrates existing and planned pipelines in and to China.

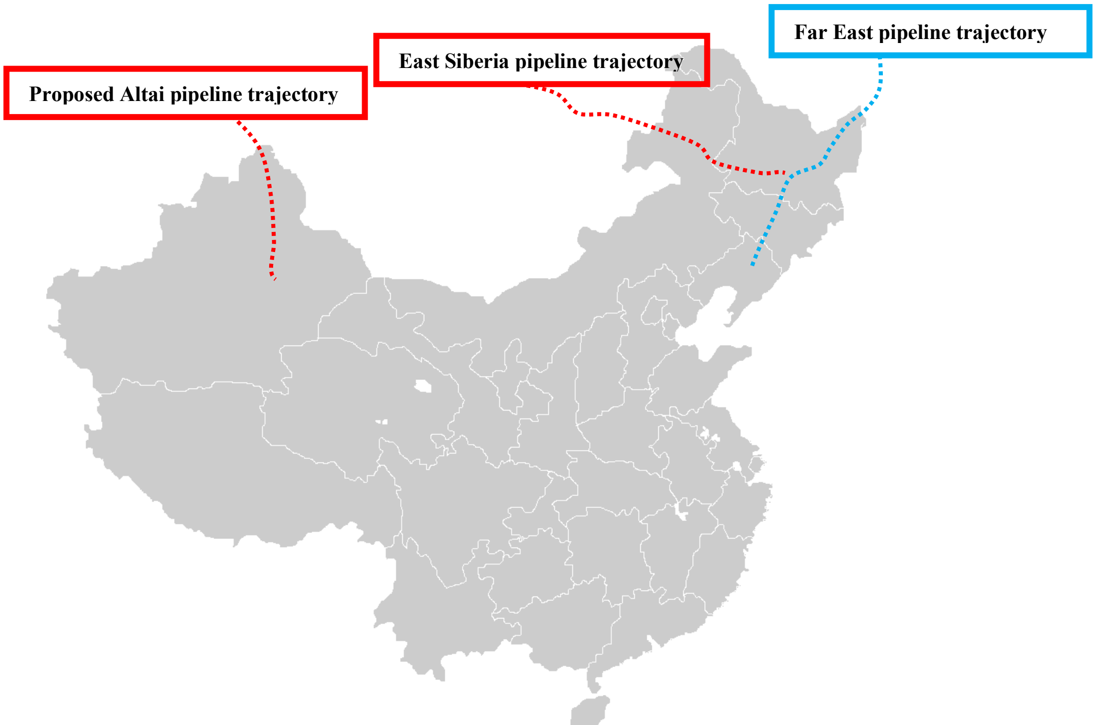

Figure 3-3: Planned natural gas pipelines in China

From Figure 3-3 three pipeline projects from Russia (Altai, East Siberia, and Far East) can be observed for approximate routing purposes (Yamaguchi 2003).

Currently, Russia is not a major supplier in the Chinese natural gas market, but it desires to be so given the growing demand (see Figure 3-4). Therefore, in our formulation the upper-level player for the case study represents Russia. Other market players considered in the model are Turkmenistan and Uzbekistan, which currently are even more major players in the Chinese market, but for the purpose of analysis when Russia desires to become a leader those players are considered as followers. Given this set of players we analyze the level of capacity that needs to be installed by the leader while maximizing its profits and seeing the impact of those decisions on the followers' production levels. The results of the analysis indicate why current market conditions are not favorable for investments and also discuss what should those parameters be in order to make it more attractive for the leader to invest on a given project.

The Altai project was approved by Order N 372 on 16th May 2006, but because of a lack of agreement on natural gas prices between Russia and China, the construction of the pipeline has not yet started (Lebedeva-Hooft 2007). On September 27, 2010 other major terms were approved and signed by Gazprom and CNPC (China National Petroleum Corporation), but again those terms were not enough to start the construction of the pipeline. Figure 3-4 depicts the likely route for the Altai pipeline.

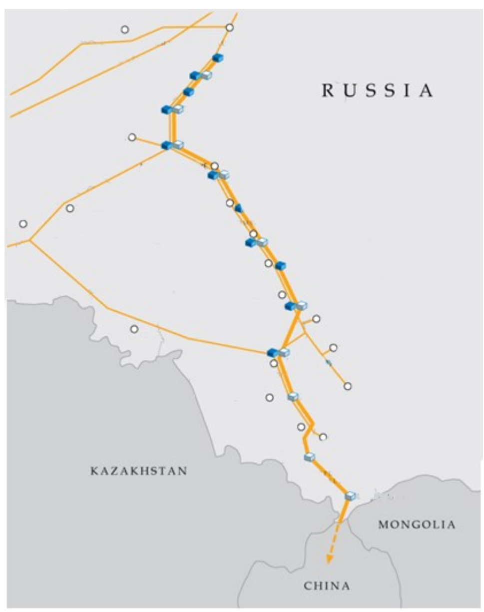

Figure 3-4: Potential route for Altai gas project trajectory

Source: (Gazprom, 2011)

China plans to expand its natural gas imports because of growing energy demand and insufficient local production (Figure 3-5).

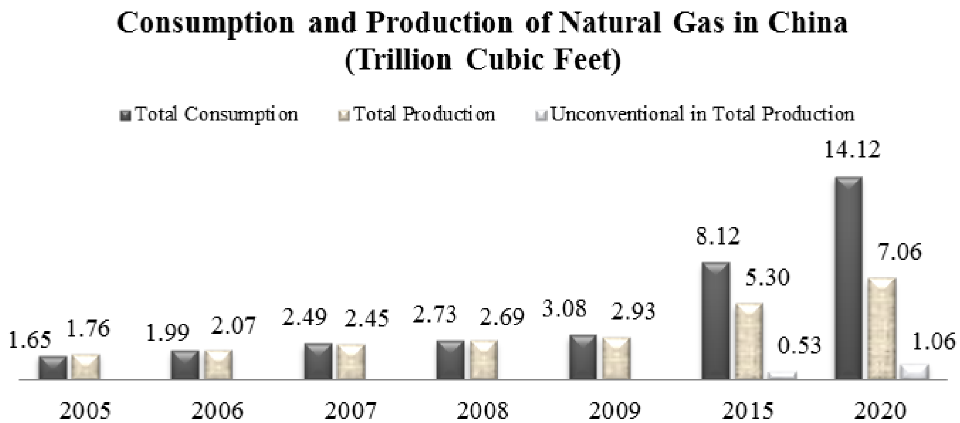

Figure 3-5: Consumption and Production of Natural Gas in China (2015 and 2020 are forecasts)

Source: (EIA 2011c; LNG 2010)

From Figure 3-5 it can be seen that in 2015 already a 34.7% (5.3Tcf/8.12 Tcf) of total projected consumption needs to be satisfied by additional imports and in 2020 imports would be almost 50% of 14.12 Tcf of total consumption.

The Altai Project would connect Russia's Kovykta gas field to Xinjiang (northwest of China). The capacity of the proposed pipeline would be from 1 to 1.4 Tcf/y which should come online by 2015. Another proposed pipeline with Russia, called the Eastern-Siberia pipeline, would connect Russia's east and Sakhalin Island to northeastern China. Plans for the eastern route also call for a pipeline capacity of 1.06 to 1.41 Tcf/y. Russia and China continue to have ongoing negotiations on price and pipeline financing measures. The third proposed pipeline (Far East) project is 0.42 Tcf/y capacity pipeline from two of Myanmar's offshore blocks to China. In March 2009 CNPC signed a contract with Myanmar to finance the construction of a 1,123-mile pipeline (EIA 2010b; CNPC 2010).

As mentioned earlier, to illustrate the use of the model, two follower suppliers were included in the lower-level problem (Turkmenistan and Uzbekistan) and Russia is modeled as the upper-level leader. The factor specifying the dependence on suppliers is included in the model formulation. An example of dependence is the differences between announced supply capacities of 2.825Tcf (80 BCM) from the Russian side and China's later announcement of 2.401 Tcf (68 BCM), which may indicate China's preference for being less dependent on Russian gas supplies (Kommersant 2006). The ratio between these two values for supply can be used as a proxy for supply dependence or a security of supply factor which in this particular case is almost 85% (2.401 Tcf/2.825 Tcf) of the total supplies proposed by the leader. This information can be interpreted as a dependency factor/security of supplies or political preference as a representation of a consumer side "market power".

Scenarios presented below consider two values of the dependency factor for the upper-level problem. Figure 3-6 illustrates the schematic structure of the case study where the followers have installed capacities and the leader decides how much capacity to install and to supply for a given market (China).

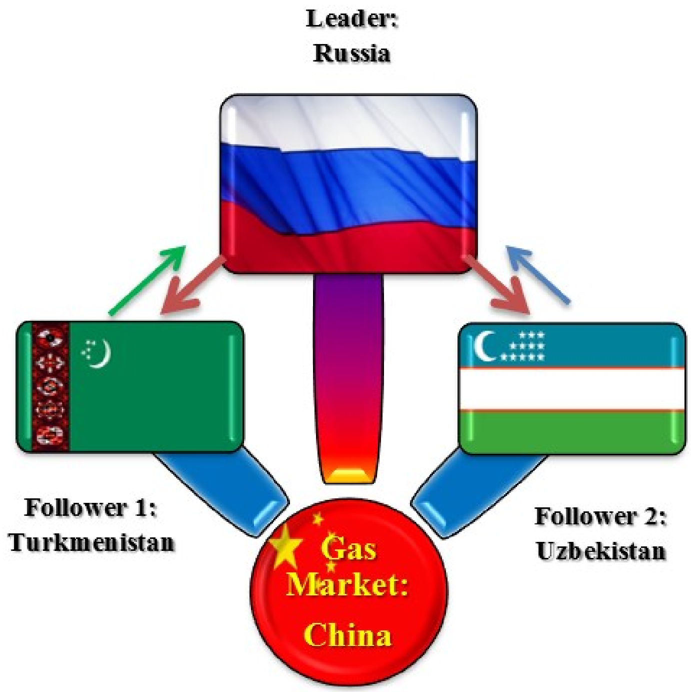

Figure 3-6: Schematic representation of supply from leader and followers

The cost of capacity expansions for pipelines is based on per inch of the diameter per mile data presented below. For LNG plants and vessels cost it is converted to a dollar per volume of natural gas per year, since usually LNG is measured in million metric tonnes per annum (MMTPA), which is equivalent to 140 million cubic feet per day. Installation costs for cryogenic pipelines is assumed to be 10% lower than that of vessels per unit of natural gas, but it is still higher than the cost of conventional pipes by a factor of 2.66. The 10 percent figure is an assumption needed due to lack of data but justified to some extent by the fact that manufacturers clearly indicate the cost advantages over LNG vessels (ITP 2011). Lastly, the transportation costs through cryogenic pipes is assumed to be higher than that of LNG vessel-based transportation, since the pressure should be

[6] If installation costs for cryogenic pipeline are 10% less than the LNG vessels then compared to conventional pipelines it costs 2.6 times less.

maintained over the length of the links by pump stations which require extensive maintenance and resource related investments.

Conventional pipeline expansion costs were previously studied and are broken down into material cost (approximately 26% of total), labor cost (approximately 40-50% of total), right of way (approximately 22% of total), miscellaneous (approximately 7% of total) (Parker 2004)

The pipeline construction cost equation is given as:

$$Construction\ Cost\ (dia, length) = [674(dia)^2 + 11{,}754(dia) + 234{,}085](length) + 405{,}000$$

where (dia) is the diameter of the pipeline in inches,
(length) is the length of the pipeline in miles, and
Cost is in dollars.

For a 56-inch diameter and 1,700-mile long pipeline (Altai) the cost according to the above equation is $5.11 billion. If we use this equation with a given set of data to calculate the cost of the Altai project and compare it with the announced cost, there is a difference of about $8.89 billion ($14 Billion-$5.11 Billion).

Based on the data from INGAA (2009) the cost of a 56-inch diameter and 1700-mile long pipeline is about $5.81 billion. When the cost of 11 compression stations is added to the cost of pipeline construction, which is assumed to have four units in each station by 3,590 horsepower each, the cost gets to about $6.1 billion, which is still lower than the proposed $14.0 billion (IFPA 2007; Gazprom 2011; ICF 2009). According to the U.S. Bureau of Labor Statistics the labor costs are less in China than in the U.S. (data for Russia are not available and assumed to be the average of China and U.S. values). Hence the Chinese labor component being about 50% of the pipeline construction costs the total cost was supposed to be even lower than in the U.S. (USBLS 2010).

Although the above analyses resulted in lower costs ($5.11 billion or $6.1 billion) than the actual total costs of $14 billion, the latter was used in the case study to match the announced cost level. However, the value of the above analysis is to show that the announced costs are probably too high. If the $14 billion figure is used and then converted to a cost per inch diameter per mile, the resulting value is $147,000 which is comparable to but still a bit higher than the Nabucco pipeline project, which has similar technical characteristics as the Altai project.

The cost of a typical LNG plant and necessary number of vessels to service such a plant are assumed to be $1.5 billion/1 MMTPA plus $120 million for each vessel (50 vessels for and approximated distance of 1,250 miles[7]) and $1 billion for receiving terminal 1 bcf/day. Thus, the typical total cost for an LNG plant for the Case Study would be about $45.4 billion.[8]

Considering technological improvements and the fact that the cost of vessels has decreased over time and the capacity has increased per vessel the estimated cost is decreased by 20% resulting in about $36.3 billion as opposed to the $45.4 billion figure.

To summarize, the costs per Tcf/y capacity the pipeline installation for Altai will be about $12.727 billion, but LNG plant and vessels would be about $36.3 billion and cryogenic pipelines for LNG about $33.03 billion, for further details about cost estimations see the Appendix 3-B.

We assume that Russian production cost is $80 per kcm. This is based on data provided by Tarr and Thomson (2003) for long-run marginal costs of natural gas at $35

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[7] 1 mile is equal to 1.6 kilometers.
[8] See the Appendix 3-B for details.

to $40 per kcm and we doubled it to account for replacing old infrastructure investments as well as losses and money inflation.

Costs associated with environmental issues are also considered in the decision-making process. The carbon footprint of pipeline construction is presented below and the carbon-related costs from capacity expansion are assumed to be $15/tonne of CO_2e (INGAA 2009). Table 3-1 presents emissions from various stages of pipeline manufacture and installation.

Table 3-1. CO_2e emissions from pipeline construction

Diameter (inch)	CO_2e emissions (tonne/km pipe)					
	Steel Production and Pipe Rolling	Transport (1000km)	Equipment fuel usage	Coating and Welding	Overhead	**Total**
16	133.7	9.9	49.2	6.9	40.7	**240.4**
20	206.4	16.0	53.4	8.6	40.7	**325.1**
24	258.6	22.3	84.0	10.4	40.7	**416.0**
36	543.0	48.8	119.7	15.8	40.7	**768.0**
48	973.7	85.6	138.6	21.5	40.7	**1,260.1**

Source: (NACAP, 2010)

Since we use pipeline capacities in our model that correspond to a proposed 56-inch pipe the corresponding CO_2e emissions are extrapolated based on the data provided in Table 3-1 and resulting in 3421.7 tonne/mile[9] while considering increasing average percentage pattern for emissions over varying diameters of pipes (from 20% to 25%). Considering the length of the proposed pipeline and its capacity the amount of emissions for this pipeline per Tcf[10] would be (1,700*3,421.7)/1.4= 4,154,921.43 tonnes/Tcf.

[9] 3421.7 tonne/mile=Kilometer to Mile factor 1.6 *Average percentage increase of emissions by diameter 20%*(Diameter of 56")*((Emission from 48"/Diameter of 48")+((Diameter of 56"-Diameter of 48")*((Emission from 48"/Diameter of 48")-(Emission from 36"/Diameter of 36"))/(Diameter of 48"-Diameter of 36"))); 1 inch is equal to 25.4 millimeters.

[10] Since the proposed pipeline capacity is 1.4Tcf.

The amount of emissions associated with the energy content of natural gas is equal to 117 pounds[11] of CO_2e per million BTU, or 0.12 pounds per cubic foot of gas (EPA 2010). The cost factor considering these emissions is also included in the objective function in both the upper and the lower-level problems. The amount of CO_2e emissions per Tcf of natural gas is thus $0.12*10^{12}/2{,}204.62=54{,}431{,}150$ tonnes.

More details of the input data are presented in Table 3-2 and Table 3-3 in the case study section.

3.3.1 Cases and Scenarios

The case study consists of two cases. The first case analyzes the effect of capacity expansion if prices stay the same as those in China as reported in (FGE 2009). The second case analyzes scenarios where the leader increases the price in China by making it equal to European prices, while the followers keep the same price as in the first case as reported in (Bloomberg 2011).[12] In the case study it is assumed that there is only one firm at each supply location (although for the followers' problem it can be any number). Each case has the following scenarios with corresponding major characteristics:

1) The dependence factor is 1 for both the upper and lower-level problem players. The leader and followers supply with their given prices calibrated to publicly available values as of 2010. The leader has no capacity limitations since it wants to determine the optimal capacity it needs to install. It is assumed that followers have enough supply to satisfy the difference between the leader's supply and the demand.

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[11] 1 pound is equal to 0.4535 kilograms.

[12] This increase is achieved through calibrating the parameters of the demand curve.

2) The dependence factor is 1 for both the upper and lower-level problem players. The leader and followers supply with their given prices available publicly. The leader has no capacity limitations since it wants to determine the optimal capacity it needs to install. The followers have supply limitations of 1.1 Tcf/y for pipelines according to existing capacities and 1.226 Tcf/y for LNG.
3) The dependence factor is 1/1.17 (0.85 as specified above as willingness for total supplies) for the upper and 1 for lower-level problem players. The leader and the followers supply with their given prices available publicly. It is assumed that the followers have enough supply to satisfy the difference between the leader's supply and the demand.
4) The dependence factor is 1/1.17 (0.85 as specified above as willingness for total supplies) for upper and 1 for lower-level problem players. The leader and the followers supply with their current prices available publicly. The followers have supply limitations of 1.1 Tcf/y for pipelines according to existing capacities and 1.226 Tcf/y for LNG.

The cases and scenarios are summarized in Table 3-2.

Table 3-2. Summary of Case and Scenario assumptions

Case 1/Case 2	Prices	Capacity Tcf/y Leader/Follower NG/Follower LNG	Dependence % Leader/Follower NG/Follower LNG
Scenario 1	Chinese/European	No limit / No limit/ No limit	1 /1 /1
Scenario 2	Chinese/European	No limit on Leader /1.1 /1.226	1 /1 /1
Scenario 3	Chinese/European	No limit/ No limit/ No limit	0.85 /1 /1
Scenario 4	Chinese/European	No limit on Leader /1.1 /1.226	0.85 /1 /1

The cases consider that the next unit of capacity can be installed with a lower cost. In particular for pipelines, on average, the right of way may be responsible for 22%

of the total cost. The same approach was used for LNG plants as well as for LNG cryogenic pipes. This cost structure is taken care of by binary variables that impose capital investment fixed costs.

The model was calibrated to current natural gas prices in China and then the effect of changes such as dependence factor and price from the leader were analyzed. The slope and the intercept of the inverse demand function for natural gas were selected based on historical data. However, since the data for China were available only for certain regions, the slope and intercepts were compared and approximated to those from the Russian natural gas inverse demand curve. Calibration was also used for fine tuning the inverse demand parameters for capacity expansion. A reverse approach is used for identifying more precise values for the Chinese natural gas inverse demand curve. This process is based on price approximation of natural gas price in China and recording the corresponding inverse demand function parameters.

Table 3-3 presents the Leader's data for Case 1 and Scenario 1. The data for additional cases and scenarios are described afterwards. Note that the demand curve for 2025 is the same as the demand curve for 2020 due to data unavailability. The leader's data for the inverse demand function intercepts and corresponding slopes are assumed to have about 20% cost reduction for each additional unit of expansion. Capital investments are assumed to be around 10% of total expansion costs. Capacity limitations are selected to be greater than the expecting demand. Costs for capacity expansion, related carbon emissions and production are also presented in Table 3-3. Costs are assumed to have an increase of 10 to 15% within each 5 year intervals, due to inflation.

Table 3-3. Leader's data used for Case 1-Scenario 1

Leader's data are in Tcf/y and $ billions/Tcf			
Data by Years	**2015**	**2020**	**2025**
$INTR_{ijt}^{P\ exp}$,	$13.990	$15.390	$16.930
$SLP_{ijt}^{P\ exp}$	***<u>Lower bound 2.700</u>***	***<u>3.078</u>***	***<u>Upper bound 3.400</u>***
$INTR_{ijt}^{LNG\ exp}$	$40.730	$44.810	$49.290
$SLP_{ijt}^{LNG\ exp}$	***<u>Lower bound 8.100</u>***	***<u>8.962</u>***	***<u>Upper bound 9.900</u>***
$INTR_{ijt}^{PCRY\ exp}$	$36.700	$40.370	$44.400
$SLP_{ijt}^{PCRY\ exp}$	***<u>Lower bound 7.3</u>***	***<u>8.073</u>***	***<u>Upper bound 9.0</u>***
$INTR_{ijt}^{P\ supp}$	$5.310	$5.840	$6.420
$INTR_{ijt}^{LNG\ supp}$	$6.250	$6.880	$7.570
$INTR_{ijt}^{PCRY\ supp}$	$6.380	$7.020	$7.720
$SLP_{ijt}^{P\ supp}$, $SLP_{ijt}^{LNG\ supp}$, $SLP_{ijt}^{PCRY\ supp}$	0.0001629	0.0001629	0.0001629
$K_{ijt}^{P\ exp}$	$1.270	$1.460	$1.680
$K_{ijt}^{LNG\ exp}$	$1.480	$1.700	$1.960
$K_{ijt}^{PCRY\ exp}$	$2.750	$3.170	$3.640
$TCAP_{ijt}^{P\ exp}$, $TCAP_{ijt}^{LNG\ exp}$, $TCAP_{ijt}^{PCRY\ exp}$	10.000	10.000	10.000
H_{it}	20.000	20.000	20.000
$CONS_{it}$	2.830	7.060	7.060
$D_{ijt}^{P\ supp}$, $D_{ijt}^{LNG\ supp}$, $D_{ijt}^{PCRY\ supp}$	1.000	1.000	1.000
$C_{ijt}^{P\ exp}$	$12.720	$14.63	$16.82
$C_{ijt}^{LNG\ exp}$	$37.030	$42.59	$48.97
$C_{ijt}^{PCRY\ exp}$	$33.360	$38.36	$44.12
$CARBC_{ijt}^{P\ exp}$, $CARBC_{ijt}^{LNG\ exp}$, $CARBC_{ijt}^{PCRY\ exp}$	$0.816	$1.089	$1.361
$CARBC_{ijt}^{P\ supp}$, $CARBC_{ijt}^{LNG\ supp}$, $CARBC_{ijt}^{PCRY\ supp}$	$0.062	$0.083	$0.104
$C_{ijt}^{P\ supp}$	$3.390	$ 3.900	$4.480
$C_{ijt}^{LNG\ supp}$	$4.070	$4.680	$5.380
$C_{ijt}^{PCRY\ supp}$	$4.150	$4.770	$5.490

For LNG plant expansions the intercept of the inverse demand curve is considered to be the same for years 2015, 2020 and 2025, because of not realistic technological advancement in relatively short timeframe from 2015 to 2025.

For LNG cryogenic pipes the intercept of the inverse demand function increases over time, since it is a new option for LNG transportation over long distances and is assumed to have a more promising future for LNG transportation.

Emissions costs are assumed to get much higher over years and the marginal increase is assumed to be $5/tonne for each five-year interval (Capoor 2007).

The data information for Case 2 is not presented in tabular form since the only difference is in the leader's selling price set to be equal to European prices, which allow having more profit per unit of supplied natural gas. Table 3-4 presents similar input data for the followers.

Table 3-4. Followers' data used for Case 1-Scenario 1

Data are in Tcf/y and $ billions/Tcf				
Data by Years		**2015**	**2020**	**2025**
$intr_{ijt}^{p\ supp}$	Turkmenistan	$4.240	$4.880	$5.610
	Uzbekistan	$4.920	$5.660	$6.510
$intr_{ijt}^{lng\ supp}$	Turkmenistan	$5.090	$5.850	$6.730
	Uzbekistan	$5.900	$6.790	$7.810
$slp_{ijt}^{lng\ supp}$ same for Turkmenistan and Uzbekistan		0.0001629	0.0001629	0.0001629
$tcap_{ijt}^{p\ supp}$, $tcap_{ijt}^{lng\ supp}$ same for Turkmenistan and Uzbekistan		10.000	10.000	10.000
$d_{ijt}^{p\ supp}$, $d_{ijt}^{lng\ supp}$ same for Turkmenistan and Uzbekistan		1.000	1.000	1.000
$carbc_{ijt}^{p\ supp}$, $carbc_{ijt}^{lng\ supp}$ same for Turkmenistan and Uzbekistan		$0.816	$1.089	$1.361
$c_{ijt}^{lng\ supp}$	Turkmenistan	$2.120	$2.440	$2.800
	Uzbekistan	$2.460	$2.830	$3.250
$c_{ijt}^{p\ supp}$	Turkmenistan	$2.540	$2.930	$3.360
	Uzbekistan	$2.950	$3.400	$3.900

In Table 3-4 the data include intercepts and slopes for inverse demand functions followed by capacity limitations, which in two cases in Scenarios 1 and 3 are assumed to be enough to satisfy the gap between leader's supply and the demand. In Scenarios 2 and 4 those are assumed to have lower caps on production as discussed in major characteristics of scenarios. Costs for production are based on publicly available data discussed in previous sections.

The next section presents results and conclusions that discuss the usefulness of the model based on the output of case studies.

3.4 Results and Conclusions

This section provides an analysis of results. It is found that for the leader it would not be profitable to install publicly announced 1.4 Tcf/y capacity by 2015. Tables 3-5 and 3-6 present the output of the runs for Case 1 and Case 2 accordingly.

Results for Case 1:

Table 3-5. Results for Case 1

Leader and Followers	Scenario 1 and 3			Scenario 2			Scenario 4		
Data by Year	**2015**	**2020**	**2025**	**2015**	**2020**	**2025**	**2015**	**2020**	**2025**
Q_{ijt} *(Tcf/y)*	0.743	1.835	2.847	1.204	3.832	6.203	1.094	3.723	5.834
LNG_{ijt} *(Tcf/y)*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$PLNG_{ijt}$ *(Tcf/y)*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
q_{fijt} from Turkmenistan *(Tcf/y)*	0.000	0.005	0.135	0.526	1.100	0.729	0.524	1.099	0.000
lng_{fijt} from Turkmenistan *(Tcf/y)*	0.721	3.801	4.078	0.000	1.028	0.000	0.112	0.000	0.175
q_{fijt} from Uzbekistan *(Tcf/y)*	0.014	0.247	0.000	1.100	1.100	0.128	1.100	1.100	1.051
lng_{fijt} from Uzbekistan *(Tcf/y)*	1.352	1.172	0.000	0.000	0.000	0.000	0.000	1.138	0.000
Total *(Tcf/y)*	**2.830**	**7.060**	**7.060**	**2.830**	**7.060**	**7.060**	**2.830**	**7.060**	**7.060**

Table 3-5 indicates that under Scenarios 1 and 3 the leader should have only 0.743 Tcf/y installed by 2015 and then add more capacities for years 2020 and 2025. These gradual capacity additions will result in $4.574 billion of profit over the specified time period. It should be noticed also that the profit is discounted over time by 12% for every five-year interval (USBLS 2009).

Results for Case 1 Scenario 3, which other than the dependence factor of 85% uses the same parameters calibrated for Scenario 1, are the same as in Scenario 1, since in the first scenario the amount of supply from the Leader did not exceed 85% of the total demand.

It can be concluded for these scenarios that a capacity of 1.4 Tcf/y that the leader has announced to have installed by 2015 may not be the most favorable to maximize its profits in the short-run.

At the same time it can be seen from the data in Table 3-5 that by 2020 the leader needs to have more capacity in place than it has announced publicly for optimal investments. However, this higher capacity (1.835 Tcf/y versus 1.4 Tcf/y) may actually be realized if negotiations take extra years.

LNG supplies both through vessels or cryogenic pipelines under current prices seem to be not profitable and the model did not suggest any capacity installation for all years considered. This suggestion also matches with existing discussions for natural gas supply to China from Russia where these options were not discussed as a form of gas supply.

What happens if prices stay as those were in 2010 used in case study and the followers can supply only up to the existing capacities they have?

In this case the problem becomes infeasible or the leader makes a negative profit (if this is allowed by the model) to supply the demand. This may become a question of negotiations where decision makers can use the model and see what would be the tradeoff for negotiations. Obviously, for the leader the best option would be if China covers the pipeline installation expenses, but then raises the question of ownership and operational rights of the pipeline.

Using the calibration capability of the model the decision-maker can find the demand function parameters that would make the supplier profitable. These cases are depicted by Scenario 2 and 4.

Initially the lower and upper bounds for slope of the demand function were used based on the real life market data (Table 3-3). By removing lower bounds for slope for pipeline capacity installation inverse demand function and keeping all other input data the same as in Scenario 1 and calibrating the model it is found that the slope would need to be 0.954 in year 2015, 0.947 by 2020 and in 2025 it should be 1.303 compared to 2.7, 2.821 and 2.837 respectively to make the Leader interested in supplying the demand without taking the negative profits. Numbers for Scenario 2 are obviously lower than the market data, but provide good information to the leader on what they need to concentrate during negotiations to become profitable. If demand function conditions met then the Leader can receive $15.997 billion in profits.

Next, Scenario 4 analyzes the same conditions as Scenario 2 with an additional restriction of not exceeding the total supply from the leader by 85% of total demand, as it was described for Scenario 2. Results for Scenario 4 are also presented in Table 3-5.

From a comparison of the cases in Table 3-5 it is noticed that for the followers there is a significant change in total natural gas market share for certain time periods, while for the leader the restriction of 85% changed the production in 2025 decreasing it from 6.203 Tcf to 5.834 Tcf, in 2020 from 3.832 Tcf to 3.723 Tcf and in 2015 from 1.204 Tcf to 1.094 Tcf. These numbers indicate that even with the 85% limitation the leader may stay profitable and receive $15.642 billion in profits if it can affect the market conditions as discussed in Scenario 2.

These analyses indicate that there is some additional power to the leader, since it can anticipate its impact on followers' production volumes and use it as a political instrument. From Table 3-5 it can also be noticed that when the assumption for demand in 2025 stays the same as in 2020 the leader adds more capacity for 2025, which indicates a gradual takeover of the market due to a profitable environment.

Results for Case 2:

Under Case 2, the leader's inverse demand function parameters evaluated at the reported solution are comparable to real life European market prices as in 2010 (assumed to be \$11.328 billion/Tcf) for natural gas. But at the same solution the followers' inverse price function yields lower supply prices at roughly the level of the Chinese market. Similar to Case 1 Scenario 1 here in Case 2 also the LNG option is excluded because of its high installation costs.

Table 3-6. Results for Case 2 Scenarios

Leader and Followers	Scenario 1 and 3			Scenario 2			Scenario 4		
Data by Year	**2015**	**2020**	**2025**	**2015**	**2020**	**2025**	**2015**	**2020**	**2025**
Q_{ijt} *(Tcf/y)*	0.788	2.202	3.530	2.830	7.060	7.060	2.352	5.983	5.983
LNG_{ijt} *(Tcf/y)*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$PLNG_{ijt}$ *(Tcf/y)*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
q_{fijt} from Turkmenistan *(Tcf/y)*	0.005	0.028	0.024	0.000	0.000	0.000	0.400	0.550	1.077
lng_{fijt} from Turkmenistan *(Tcf/y)*	1.048	2.508	0.000	0.000	0.000	0.000	0.078	0.527	0.000
q_{fijt} from Uzbekistan *(Tcf/y)*	0.000	0.074	0.000	0.000	0.000	0.000	0.000	0.000	0.000
lng_{fijt} from Uzbekistan *(Tcf/y)*	0.989	2.248	3.506	0.000	0.000	0.000	0.000	0.000	0.000
Total *(Tcf/y)*	**2.830**	**7.060**	**7.060**	**2.830**	**7.060**	**7.060**	**2.830**	**7.060**	**7.060**

Here in Scenario 2 the followers have capacity limitations similar to Case 1 (Scenario 2). For Scenario 2 since the leader inverse demand function parameters are calibrated as real life European market prices as in 2010, the leader supplies all the demand. This result coincides with the announcement by Russia expressing its willingness to satisfy all of China's natural gas demand in the future. Indeed, if negotiations result in higher prices for natural gas in China then it would be extremely profitable for the leader to make all necessary investments and still generate $111.588 billion profit over the considered time horizon.

The results for Scenarios 1 and 3 are the same since the only difference between them, the 85% dependence constraint, is not binding. In contrast when the 85% dependence factor is included in Scenario 4 we see the followers picking up some market share. All the results are presented in Table 3-6.

Analyses for favorable parameters

In addition to these scenarios more analyses were conducted to understand parameters that would make the LNG option more favorable for the leader. This was done by removing lower bounds for the slope of inverse demand curves in all supply modes. It was found that with current prices, no parameter can make an LNG supply favorable for the leader. With high prices as in Case 2 it is found that if the leader can make the consumer pay higher prices for each additional unit capacity installation then it may supply LNG. In particular if the slope for the LNG plant and vessel expansion were 0.404 in 2020 and 0.829 for LNG pipeline in 2015 then the leader would install LNG plants for 4.313Tcf by 2020 and LNG pipeline of 2.747 Tcf by 2015 and generate profits. The difference of supply 0.083 Tcf would be covered by Turkmenistan in 2015. Although profits are attractive, it would not be easy to have that much influence on the market that would allow changing the slope of the inverse demand curves so much below the lower bounds indicated in Table 3-3.

Conclusions

Both cases with their scenarios analyzed in this research provide an important intuition for decision-making. The model can be used by any player in the market and also by consumers during contractual negotiations. It is important to highlight that many cases need to be investigated in order to have a clear understanding for negotiations and political decisions; hence the developed model is important for investors, policy makers and other decision-makers in natural gas industry. The model can be used for carbon policy analyses and analyze the impact of carbon costs under different policies, on natural gas supply network expansion and production levels. Due to self-calibration capability the model allows to determine favorable parameters that may help to get the desired profit values, to be used by decision-makers for contractual agreements or political orientation.

Appendix 3-A

NOTATION

Table 3-A. Notation

Parameters	Leader			Follower	
	Pipeline	**LNG Plant and Vessel**	**Cryogenic Pipeline for LNG**	**Pipeline**	**LNG Plant and Vessel**
Intercept of the linear demand functions for capacity expansion between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$INTR_{ijt}^{P\ exp}$	$INTR_{ijt}^{LNG\ exp}$	$INTR_{ijt}^{PCRY\ exp}$	N/A	N/A
Slope of the linear demand functions for capacity expansion between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$SLP_{ijt}^{P\ exp}$	$SLP_{ijt}^{LNG\ exp}$	$SLP_{ijt}^{PCRY\ exp}$	N/A	N/A
Intercept of the linear demand functions for natural gas supplied between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$INTR_{ijt}^{P\ supp}$	$INTR_{ijt}^{LNG\ supp}$	$INTR_{ijt}^{PCRY\ supp}$	$intr_{ijt}^{p\ supp}$	$intr_{ijt}^{lng\ supp}$

Slope of the linear demand functions for natural gas supplied between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$SLP_{ijt}^{P\ supp}$	$SLP_{ijt}^{LNG\ supp}$	$SLP_{ijt}^{PCRY\ supp}$	$slp_{ijt}^{p\ supp}$	$slp_{ijt}^{lng\ supp}$
Fixed cost term if capacity expansion is selected between nodes i ∈ N and j ∈ N at time t ∈ T and i ≠ j	$K_{ijt}^{P\ exp}$	$K_{ijt}^{LNG\ exp}$	$K_{ijt}^{PCRY\ exp}$	N/A	N/A
Constant for disjunctive program: KKT (I) and (II) for followers $f \in F$ between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	N/A	N/A	N/A	Kq_{fijt},	$Klng_{fijt}$
Constant for disjunctive program: KKT (III) and (IV) for followers $f \in F$ between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	N/A	N/A	N/A	$\overline{Kq_{fijt}}$	$\overline{Klng_{fijt}}$
Expanded pipeline operational capacities, between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$TCAP_{ijt}^{P\ exp}$	$TCAP_{ijt}^{LNG\ exp}$	$TCAP_{ijt}^{PCRY\ exp}$	N/A	N/A
Existing pipeline operational capacities for followers $f \in F$, between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	N/A	N/A	N/A	$tcap_{ijt}^{p\ supp}$	$tcap_{ijt}^{lng\ supp}$
Wellhead or play capacity at node $i \in N$ over time $t \in T$	H_{it}	H_{it}	H_{it}	H_{it}	H_{it}
Consumption at node $j \in N$ over time $t \in T$	$CONS_{jt}$	$CONS_{jt}$	$CONS_{jt}$	$CONS_{jt}$	$CONS_{jt}$
Dependence/security factor ranging from 0 to 1 for volumetric supplies between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$D_{ijt}^{P\ supp}$	$D_{ijt}^{LNG\ supp}$	$D_{ijt}^{PCRY\ supp}$	$d_{ijt}^{p\ supp}$	$d_{ijt}^{lng\ supp}$
Discounting factor,	ρ_{ijt}	ρ_{ijt}	ρ_{ijt}	ρ_{ijt}	ρ_{ijt}

which may vary between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$					
Factor identifying the desired gap between capacity and production level between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	Δ_{ijt}^{P}	Δ_{ijt}^{LNG}	Δ_{ijt}^{PCRY}	δ_{fijt}^{p}	δ_{fijt}^{lng}
Costs of capacity expansion as a function of distance and diameter between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$C_{ijt}^{P\ exp}$	$C_{ijt}^{LNG\ exp}$	$C_{ijt}^{PCRY\ exp}$	*N/A*	*N/A*
Costs of supplied natural gas between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$C_{ijt}^{P\ supp}$	$C_{ijt}^{LNG\ supp}$	$C_{ijt}^{PCRY\ supp}$	$c_{ijt}^{p\ supp}$	$c_{ijt}^{lng\ supp}$
Carbon costs of capacity expansion as a function of distance and diameter between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$CARBC_{ijt}^{P\ exp}$	$CARBC_{ijt}^{LNG\ exp}$	$CARBC_{ijt}^{PCRY\ exp}$	*N/A*	*N/A*
Carbon costs of volumetric use of natural gas delivered between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$CARBC_{ijt}^{P\ supp}$	$CARBC_{ijt}^{LNG\ supp}$	$CARBC_{ijt}^{PCRY\ supp}$	$carbc_{ijt}^{p\ supp}$	$carbc_{ijt}^{lng\ supp}$

Variables	**Leader**			**Follower**	
	Pipeline	**LNG Plant and Vessel**	**Cryogenic Pipeline for LNG**	**Pipeline**	**LNG Plant and Vessel**
Production level in Tcf/Y between nodes i ∈ N and j ∈ N at time t ∈ T and i ≠ j	Q_{ijt}	LNG_{ijt}	$PLNG_{ijt}$	q_{fijt}	lng_{fijt}
Binary variable for fixed costs if expansion is selected between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$	$X_{ijt}^{P\ exp}$	$X_{ijt}^{LNG\ exp}$	$X_{ijt}^{PCRY\ exp}$	*N/A*	*N/A*
Shadow price of technical capacity constraint for followers' $f \in F$ problem between	*N/A*	*N/A*	*N/A*	α_{fijt}	β_{fijt}

nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$					
Variables used to replace complementarity conditions by disjunctive constraints in followers' $f \in F$ problem (for KKT (I) and (II)) between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$.	*N/A*	*N/A*	*N/A*	rq_{fijt}	$rlng_{fijt}$
Binary variables used to replace complementarity conditions by disjunctive constraints in followers' $f \in F$ problem (for KKT (III) and (IV)) between nodes $i \in N$ and $j \in N$ at time $t \in T$ and $i \neq j$.	*N/A*	*N/A*	*N/A*	$\overline{rq_{fijt}}$,	$\overline{rlng_{fijt}}$

Extended form of the Leader's objective function (A.1) in combined formulation of upper- and lower-level problems (A.1) to (A.25):

$$
\max_{Q_{ijt},LNG_{ijt},PLNG_{ijt},q_{fijt},lng_{fijt},rq_{fijt},rlng_{fijt},\overline{rq_{fijt}},\overline{rlng_{fijt}}} \sum_i \sum_j \sum_t \Bigg(\Bigg(\Bigg(INTR_{ijt}^{P\,exp} - SLP_{ijt}^{P\,exp} \Bigg(\sum_f \delta_{fijt}^{p}\, q_{fijt}
+ \left(\Delta_{ijt}^{P} Q_{ijt} - \Delta_{ij(t-5)}^{P} Q_{ij(t-5)}\right) \Bigg) \Bigg) \left(\Delta_{ijt}^{P} Q_{ijt} - \Delta_{ij(t-5)}^{P} Q_{ij(t-5)}\right)
+ \left(INTR_{ijt}^{P\,supp} - SLP_{ijt}^{P\,supp} \left(\sum_f q_{fijt} + Q_{ijt} \right) \right) Q_{ijt}
+ \Bigg(INTR_{ijt}^{LNG\,exp} - SLP_{ijt}^{LNG\,exp} \Bigg(\sum_f \delta_{fijt}^{lng} lng_{fijt}
+ \left(\Delta_{ijt}^{LNG} LNG_{ijt} - \Delta_{ij(t-5)}^{LNG} LNG_{ij(t-5)}\right) \Bigg) \Bigg) \left(\Delta_{ijt}^{LNG} LNG_{ijt} - \Delta_{ij(t-5)}^{LNG} LNG_{ij(t-5)}\right)
+ \left(INTR_{ijt}^{LNG\,supp} - SLP_{ijt}^{LNG\,supp} \left(\sum_f lng_{fijt} + LNG_{ijt} \right) \right) LNG_{ijt}
+ \left(INTR_{ijt}^{PCRY\,exp} - SLP_{ijt}^{PCRY\,exp} \left(\Delta_{ijt}^{PCRY} PLNG_{ijt} - \Delta_{ij(t-5)}^{PCRY} PLNG_{ij(t-5)}\right) \right) \left(\Delta_{ijt}^{PCRY} PLNG_{ijt} - \Delta_{ij(t-5)}^{PCRY} PLNG_{ij(t-5)}\right) + \left(INTR_{ijt}^{PCRY\,supp} - SLP_{ijt}^{PCRY\,supp} \left(PLNG_{ijt}\right) \right) PLNG_{ijt}
- \Big(C_{ijt}^{P\,exp} \left(\Delta_{ijt}^{P} Q_{ijt} - \Delta_{ij(t-5)}^{P} Q_{ij(t-5)}\right) + C_{ijt}^{LNG\,exp} \left(\Delta_{ijt}^{LNG} LNG_{ijt} - \Delta_{ij(t-5)}^{LNG} LNG_{ij(t-5)}\right)
+ C_{ijt}^{PCRY\,exp} \left(\Delta_{ijt}^{PCRY} PLNG_{ijt} - \Delta_{ij(t-5)}^{PCRY} PLNG_{ij(t-5)}\right) \Big)
- \left(C_{ijt}^{P\,supp} Q_{ijt} + C_{ijt}^{LNG\,supp} LNG_{ijt} + C_{ijt}^{PCRY\,supp} PLNG_{ijt} \right)
- \Big(CARBC_{ijt}^{P\,exp} \left(\Delta_{ijt}^{P} Q_{ijt} - \Delta_{ij(t-5)}^{P} Q_{ij(t-5)}\right)
+ CARBC_{ijt}^{LNG\,exp} \left(\Delta_{ijt}^{LNG} LNG_{ijt} - \Delta_{ij(t-5)}^{LNG} LNG_{ij(t-5)}\right)
+ CARBC_{ijt}^{PCRY\,exp} \left(\Delta_{ijt}^{PCRY} PLNG_{ijt} - \Delta_{ij(t-5)}^{PCRY} PLNG_{ij(t-5)}\right) \Big)
- \left(CARBC_{ijt}^{P\,supp} Q_{ijt} + CARBC_{ijt}^{LNG\,supp} LNG_{ijt} + CARBC_{ijt}^{PCRY\,supp} PLNG_{ijt} \right)
- \left(K_{ijt}^{P\,exp} \cdot X_{ijt}^{P\,exp} + K_{ijt}^{LNG\,exp} \cdot X_{ijt}^{LNG\,exp} + K_{ijt}^{PCRY\,exp} \cdot X_{ijt}^{PCRY\,exp} \right) \Bigg) \rho_{ijt} \qquad (A.1)
$$

$$0 \leq \left(Q_{ijt} - Q_{ij(t-5)}\right) \leq TCAP_{ijt}^{P\,exp} \cdot X_{ijt}^{P\,exp}, \qquad \forall i,j,t \qquad (A.2)$$

$$0 \leq \left(LNG_{ijt} - LNG_{ij(t-5)}\right) \leq TCAP_{ijt}^{LNG\,exp} \cdot X_{ijt}^{LNG\,exp}, \qquad \forall i,j,t \qquad (A.3)$$

$$0 \leq \left(PLNG_{ijt} - PLNG_{ij(t-5)}\right) \leq TCAP_{ijt}^{PCRY\,exp} \cdot X_{ijt}^{PCRY\,exp}, \qquad \forall i,j,t \qquad (A.4)$$

$$\sum_i \sum_j \left(\sum_f \delta_{fijt}^{p} q_{fijt} + \Delta_{ijt}^{P} Q_{ijt} + \sum_f \delta_{fijt}^{lng} lng_{fijt} + \Delta_{ijt}^{LNG} LNG_{ijt} + \Delta_{ijt}^{PCRY} PLNG_{ijt}\right) \leq H_{it}, \qquad \forall f,i,j,t \qquad (A.5)$$

$$CONS_{jt} - \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt}\right) = 0, \quad \forall f,i,j,t \qquad (A.6)$$

$$Q_{ijt} \leq D_{ijt}^{P\,supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt}\right), \quad \forall f,i,j,t \qquad (A.7)$$

$$LNG_{ijt} \leq D_{ijt}^{LNG\,supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt}\right), \quad \forall f,i,j,t \qquad (A.8)$$

$$PLNG_{ijt} \leq D_{ijt}^{PCRY\,supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt}\right), \quad \forall f,i,j,t \qquad (A.9)$$

$$q_{fijt} \leq d_{ijt}^{p\,supp} \sum_i \sum_j \left(\sum_f q_{fijt} + Q_{ijt} + \sum_f lng_{fijt} + LNG_{ijt} + PLNG_{ijt}\right), \quad \forall f,i,j,t \qquad (A.10)$$

$$lng_{fijt} \leq d_{ijt}^{lng\ supp} \sum_{i} \sum_{j} \left(\sum_{f} q_{fijt} + Q_{ijt} + \sum_{f} lng_{fijt} + LNG_{ijt} + PLNG_{ijt} \right), \quad \forall f, i, j, t \qquad (A.11)$$

$$Q_{ijt} = 0, \qquad \forall i, j, t \ when\ i = j\ and\ when\ defined\ by\ user\ (i.e. political\ obstacle) \qquad (A.12)$$

$$LNG_{ijt} = 0, \qquad \forall i, j, t \ when\ i = j\ and\ when\ defined\ by\ user \qquad (A.13)$$

$$PLNG_{ijt} = 0, \qquad \forall i, j, t \ when\ i = j\ and\ when\ defined\ by\ user \qquad (A.14)$$

$$X_{ijt}^{P\ exp}, \cdot X_{ijt}^{LNG\ exp}, \cdot X_{ijt}^{PCRY\ exp} \in \{0,1\}, \qquad \forall i, j, t \qquad (A.15)$$

$$Q_{ijt}, LNG_{ijt},\ PLNG_{ijt} \geq 0, \qquad \forall i, j, t \qquad (A.16)$$

$$0 \leq \left(-intr_{ijt}^{p\ supp} + slp_{ijt}^{p\ supp} \cdot q_{fijt} + slp_{ijt}^{p\ supp} \sum_{f} q_{fijt} + slp_{ijt}^{p\ supp} \cdot Q_{ijt} + c_{ijt}^{p\ supp} + carbc_{ijt}^{p\ supp} \right) \rho_{ijt} + \alpha_{fijt} \leq Kq_{fijt} \cdot rq_{fijt}, \qquad \forall f, i, j, t \qquad (A.17)$$

$$0 \leq q_{fijt} \leq Kq_{fijt}\left(1 - rq_{fijt}\right), \qquad \forall f, i, j, t \qquad (A.18)$$

$$0 \leq \left(-intr_{ijt}^{lng\ supp} + slp_{ijt}^{lng\ supp} \cdot lng_{fijt} + slp_{ijt}^{lng\ supp} \sum_{f} lng_{fijt} + slp_{ijt}^{lng\ supp} \cdot LNG_{ijt} + c_{ijt}^{lng\ supp} + carbc_{ijt}^{lng\ supp} \right) \rho_{ijt} + \beta_{fijt} \leq Klng_{fijt} \cdot rlng_{fijt}, \qquad \forall f, i, j, t \qquad (A.19)$$

$$0 \leq lng_{fijt} \leq Klng_{fijt}\left(1 - rlng_{fijt}\right), \qquad \forall f, i, j, t \qquad (A.20)$$

$$0 \leq -q_{fijt} + tcap_{ijt}^{p\ supp} \leq \overline{Kq_{f\imath\jmath t}} \cdot \overline{rq_{f\imath\jmath t}}, \qquad \forall f, i, j, t \qquad (A.21)$$

$$0 \leq \alpha_{fijt} \leq \overline{Kq_{f\imath\jmath t}}\left(1 - \overline{rq_{f\imath\jmath t}},\right) \qquad \forall f, i, j, t \qquad (A.22)$$

$$0 \leq -lng_{fijt} + tcap_{ijt}^{lng\ supp} \leq \overline{Klng_{fijt}} \cdot \overline{rlng_{fijt}}, \quad \forall f, i, j, t \qquad (A.23)$$

$$0 \leq \beta_{fijt} \leq \overline{Klng_{fijt}}\left(1 - \overline{rlng_{fijt}}\right), \quad \forall f, i, j, t \qquad (A.24)$$

$$rq_{fijt}, rlng_{fijt}, \overline{rq_{fijt}}, \overline{rlng_{fijt}} \in \{0, 1\} \quad \forall f, i, j, t \qquad (A.25)$$

Followers' Problem Disjunctive Form:

$$0 \leq \left(-intr_{ijt}^{p\ supp} + slp_{ijt}^{p\ supp} \cdot q_{fijt} + slp_{ijt}^{p\ supp} \sum_{f} q_{fijt} + slp_{ijt}^{p\ supp} \cdot Q_{ijt} + c_{ijt}^{p\ supp} + carbc_{ijt}^{p\ supp}\right)\rho_{ijt} + \alpha_{fijt} \leq Kq_{fijt} \cdot rq_{fijt}, \quad \forall f, i, j, t \qquad (A.26)$$

$$0 \leq q_{fijt} \leq Kq_{fijt}\left(1 - rq_{fijt}\right), \quad \forall f, i, j, t \qquad (A.27)$$

$$0 \leq \left(-intr_{ijt}^{lng\ supp} + slp_{ijt}^{lng\ supp} \cdot lng_{fijt} + slp_{ijt}^{lng\ supp} \sum_{f} lng_{fijt} + slp_{ijt}^{lng\ supp} \cdot LNG_{ijt} + c_{ijt}^{lng\ supp} + carbc_{ijt}^{lng\ supp}\right)\rho_{ijt} + \beta_{fijt} \leq Klng_{fijt} \cdot rlng_{fijt}, \quad \forall f, i, j, t \qquad (A.28)$$

$$0 \leq lng_{fijt} \leq Klng_{fijt}\left(1 - rlng_{fijt}\right), \quad \forall f, i, j, t \qquad (A.29)$$

$$0 \leq -q_{fijt} + tcap_{ijt}^{p\ supp} \leq \overline{Kq_{fijt}} \cdot \overline{rq_{fijt}}, \quad \forall f, i, j, t \qquad (A.30)$$

$$0 \leq \alpha_{fijt} \leq \overline{Kq_{fijt}}\left(1 - \overline{rq_{fijt}},\right) \quad \forall f, i, j, t \qquad (A.31)$$

$$0 \leq -lng_{fijt} + tcap_{ijt}^{lng\ supp} \leq \overline{Klng_{fijt}} \cdot \overline{rlng_{fijt}}, \quad \forall f, i, j, t \qquad (A.32)$$

$$0 \leq \beta_{fijt} \leq \overline{Klng_{fijt}}\left(1 - \overline{rlng_{fijt}}\right), \quad \forall f, i, j, t \qquad (A.33)$$

$$rq_{fijt}, rlng_{fijt}, \overline{rq_{fijt}}, \overline{rlng_{fijt}} \in \{0, 1\} \quad \forall f, i, j, t \qquad (A.34)$$

Appendix 3-B

As an expression the cost associated with LNG plant is calculated as the following (Najibi et al. 2009; LNG Plants 2006; EIA 2010d):

- LNG plant costs $1.5 billion per one million metric tonne per annum capacity (MMTPA) and 1MMTPA is equivalent to 140 million cubic feet per day. Also, for the same capacity similar to proposed pipeline, the plant needs to have 24 MMTPA.
- Vessels to transport the LNG from origin to destination cost about $120 million each.
- Number of vessels necessary to serve the plant with a capacity that is equivalent to suggested pipeline capacity is 50 with approximate distances of 1,250 miles for shipping.
- Receiving terminals cost $1 billion per 1 billion cubic feet per day. Therefore for the given capacity per year the daily capacity of the terminal is being determined by dividing the annual capacity of production to number of days in the year, while assuming year round operation of a plant.

Given these values the formula can be derived for cost calculations using the following notation:

CapF – capacity factor,

UCost – LNG plant unit cost per MMTPA,

ConvF – conversion factor from MMTPA to cubic feet,

NVes – number of necessary vessels,

VCost – vessel cost,

TCost –receiving terminal costs for a given capacity,

CapT – terminal capacity for annual capacity of the plant,

YDays – operational number of days per year.

Values used for above terms are:

CapF = 24 MMTPA

UCost = $1.5 billion

ConvF = 140 million

NVes = 50 Vessels

VCost = $120 million

TCost = $1 billion per bcf/d

YDays = 365 Days

CapT = 24*140 million*365 = 1.226Tcf/y

Cost of LNG through vessel supplies= UCost* CapF+ VCost* NVes+ TCost* CapF* ConvF/ YDays = $1.5 billion*24 MMTPA+$120 million*50 Vessels+$1.0 billion*CapT/365 Days = $45.4 billion

CHAPTER 4: EFFECTS OF VEHICLE TECHNOLOGIES, TRAFFIC VOLUME CHANGES, INCIDENTS AND WORK ZONES ON GREENHOUSE GAS EMISSIONS PRODUCTION

Abstract

This chapter seeks to quantify the effects of newer, more efficient vehicle technologies, traffic volume changes, incidents and work zones on emissions production from on-road traffic. These effects are studied using microscopic traffic simulation and developed emissions estimation tools that together can capture emissions effects from the operating parameters of vehicles (e.g., second-by-second velocities and accelerations, power demand). An emissions estimation tool is proposed that estimates all air pollutants (except air toxics), namely CO_2, CO, CH_4, THC, NO_x, SO_x, PM_{10} and $PM_{2.5}$, from on-road traffic. A case study involving Montgomery County, Maryland's I-270-MD-355 corridor, including connecting arterials, was conducted. Findings from the case study indicate that vehicle composition greatly affects the amount of emissions, and significant potential for reaching emissions reduction goals exists through improvements in vehicle mix efficiencies within the traffic composition. It was also noted that work zones and traffic incidents reduce the amount of emissions produced over a time increment due to reduced average speeds, while per vehicle emissions rise over the span of the simulation network and simulation period. Non-linear multi-regression emissions estimation models were also developed to support GHG emissions analyses for other comparable roadways. Implications for policy-makers are discussed.

4.1 Introduction and Motivation

Greenhouse gases (GHGs) are responsible for maintaining the earth's temperature; however, excessive presence of these gases can be harmful. In recent years, national and international support for GHG reduction has grown by proposing and enforcing certain requirements aimed at reducing the activities that cause climate change. Thus, many restrictions have been imposed to minimize GHG emissions (Intergovernental Panel on Climate Change (IPCC) 2007). The transportation sector accounts for 28% of total U.S. GHG emissions. 84% of these emissions are due to on-road vehicle use (DOT 2011; EPA 2012a).

The generation of emissions from on-road vehicles is directly affected by vehicle technology, roadway geometry, and traffic congestion, among other factors. The U.S. Department of Transportation (DOT) attributes a cost of approximately $200 billion annually to traffic congestion (DOT 2011; GAO 2012). Congestion directly impacts traffic speed, stops and starts, and frequent acceleration and deceleration actions, thereby affecting the amount of fuel burned. An optimal speed of approximately 32 miles per hour (mph) (or 50 kilometers per hour) has been found to produce the minimum rate of emissions (Barth and Boriboonsomsin 2008; Rao et al. 2010; Unal et al. 2003). Stops and starts not only negatively affect overall speed, but increase the number of acceleration stages and, thus, emissions generation. Barth and Boriboonsomsin (2008) studied the effects of a variety of traffic stabilizing approaches, including congestion mitigation strategies (e.g., ramp metering, incident management), speed management techniques (e.g., enforcement, active accelerator pedal (Hjalmdahl and Varhelyi 2004) used to constrain vehicular speed to below allowable speed limits), and shock wave suppression techniques (e.g., variable speed limits, Intelligent Speed Adaptation) that eliminate the acceleration/deceleration events due to stop-and-go traffic. The study concluded that a 20% reduction in emissions could be achieved through such approaches.

Traffic congestion has had a continuing upward trend over past decades. This is in part due to an increase in vehicle ownership and use. However, a significant portion of this increase can be attributed to so-called non-recurring events, such as construction projects and traffic incidents. In fact, the DOT attributes approximately half of the costs of congestion to construction operations and traffic incidents (DOT 2011). In a study from 1999, it was found that work zones and incidents were responsible for 24.3% and 45% of traffic delays, respectively (Rao et al. 2010). Therefore, a number of policies and programs have aimed to mitigate the effects of work zones on traffic congestion. Additionally, traffic incident management (TIM) programs are widely implemented with the goal of reducing response time to incidents, thus, reducing incident duration and ensuing traffic delays and congestion. Many strategies that apply for incident management, such as implementing signage or traffic redirection, have application in work zone management as well (FHWA 2010). However, the impact of these strategies may differ between applications (Ruehr 2010) primarily due to differences in duration and length of affected area. For example, while roadway maintenance is scheduled in advance, incidents arise stochastically; thus, plans for their management may differ.

A host of programs and policies, often relying on incentives and disincentives, are being considered across the U.S. with the aim of supporting efforts that directly reduce emissions from on-road vehicle traffic (Ou et al. 2010; Wise et al. 2010). These include those that aim to reduce traffic congestion, such as programs that aim to increase transit ridership, reduce roadway use during peak hours (e.g., congestion pricing), eliminate bottlenecks and improve traffic flow along arterials through changes in traffic control strategies and improve traffic signal coordination. Often, these programs and policies (DOE 2012) aim to increase rates of penetration of improved vehicle technology on the roadways by promoting ownership of more efficient vehicle technologies, such as electric plug-in vehicles. The effectiveness of a particular vehicle technology in reducing emissions from vehicle use is also impacted by the type of fuel used (Westerholm and Egeback 1994). Other policies, like those that impose taxes on fuel purchases or charge for roadway use, have been designed to reduce vehicle miles traveled (VMT) (e.g., Beevers and Carslaw 2005). Moreover, programs that incentivize construction plans with goals to reduce emissions have been applied in a variety of locations (Ahn et al. 2010). Additional efforts have been expended to assess the effectiveness of these programs (e.g., Anas 2009); however, it must be noted that the potential impact on emissions reduction is often difficult to ascertain both before its implementation and after.

A number of tools have been developed for general estimation of emissions from on-road vehicles. Barth and Boriboonsomsin (2008) developed a regression emissions estimation model for emissions from freeways considering average speeds. Microscopic emissions estimation models, including MOVES (EPA 2010), CMEM (CMEM 2011), MEASURE (Bachman 1997), VT-MICRO (Rakha et al. 2003), have been proposed in the literature. These models provide vehicle-specific emissions estimates. While some models can be used independently, others (such as CMEM, VT-Micro,) function in parallel with traffic simulation models as plug-ins receiving modal vehicular parameters (e.g., vehicular speed, engine mode) as inputs for emissions estimation.

In addition to these general tools, a number of works have proposed models with more specific application. Unal et al. (2003) proposed a model for estimating emissions produced by on-road traffic that employs emission factors (EFs) associated with each stage of the driving cycle, including idling, acceleration, deceleration and cruising. They applied their approach to study the cost of emissions reduction through vehicle technology adoption and found that the cost of a trip would increase by 10% for every 1% reduction in CO_2 emitted. In their work, Unal et al. also considered the impact of congestion management strategies on congestion, but comment that changes in congestion cannot necessarily be equilibrated to changes in emissions. Further, two tools have been developed specifically for the analysis of work zone effects on emissions production: Enhanced QUEWZ-98 with "Emission Workbook" (Benz and Fenno 2011) and WZCAT (Lee et al. 2008). These tools base their estimates on average emissions rates and consider limited vehicle classes, e.g., light- and heavy-duty vehicles. Based on a study in Beijing, Anas (2009) reported that improvements in vehicle technology can significantly reduce fuel consumption and CO_2 emissions; although, details of the analysis were not provided.

Ahn et al. (2002) developed nonlinear regression models to predict the amount of CO_2 emissions as a function of second-by-second vehicle speed and acceleration. In an effort to address impracticalities of these models, Afotey (2008) proposed alternative models for highway and arterial CO_2 emissions estimation that similarly incorporate vehicle speed and acceleration, but using data derived through real-world experiments. Afotey presented linear multiple regression models with emissions as the dependent variable and vehicle speed, acceleration, deceleration and power demand as the independent variables for both highways and arterials. Obtaining input data related to power demand is impractical. Additionally, the models were found to have R-squared values of 0.26 and 0.61, respectively. Afotey suggested that inclusion of other important factors, including road grade, weather conditions, air conditioning usage, tire pressure, road surface conditions and total vehicle weight, could result in a model with better fit; however, no such models were provided. In general, models that employ a linear formulation have been found to provide insufficient prediction capability. A model with greater prediction capability and obtainable input data is desired. This chapter seeks to fill this need.

In this chapter, the effects of changes in vehicle volume and composition, as well as the impact of temporary roadway capacity reductions due to construction activities or traffic incidents on GHG emissions resulting from on-road traffic, are studied. The effects of these changes and reductions along arterials and freeways are investigated and compared by analyzing results from systematically designed simulation runs using a microscopic traffic simulation model of a corridor in Maryland. Results in terms of the carbon dioxide equivalent of calculated emissions, including CO_2, CO, CH_4, THC, NO_x, SO_x, PM_{10}, and $PM_{2.5}$, are obtained through application of ORSEEM (On-Road Simulation Emission Estimation Model) described in the next section. From this study, general insights were derived and statistically verified nonlinear multi-regression emission estimation models were developed to support analyses for other comparable roadways. Insights into potential gains that can be achieved from specific emissions reduction strategies associated with these occurrences can inform policy and program development.

The authors know of no other work that studies the effectiveness in terms of emissions reduction of policies or other programs aimed at changing vehicle technology adoption or work zone/incident management implementations.

4.2 On-Road Simulation Emissions Estimation Model (ORSEEM)

ORSEEM, developed for this study and designed to be portable from project to project, is a microscopic emissions estimation tool that estimates the production of air pollutants as a function of modal vehicular parameters (e.g., velocity, acceleration, stops, starts, and idling), vehicle composition categories (e.g., passenger cars, trucks, semis, and buses) and class (age and tier level), and accounts for the increased prevalence of alternative vehicles on our roadways. ORSEEM also includes commercially available alternative fuels, like biodiesel blends, ethanol blends and reformulated gasoline. It estimates all criteria air pollutants (except air toxics), namely CO_2, CO, CH_4, THC, NO_x, SO_x, PM_{10} and $PM_{2.5}$. ORSEEM employs empirical formulae suggested by Barth et al. (2002), but an updated EFs database to account for new technologies and alternative fuels. Adjustment factors are applied to account for greater efficiencies of hybrid passenger vehicles, including both cars and light-duty trucks. Further, the impact on emissions of added power requirements due to roadway grade changes is included in ORSEEM. This is important because a 1% increase in roadway grade can result in more than 9% increase in fuel consumption and carbon emission rates (Park and Rakha 2006). Moreover, an increase in emissions on the order of 42 to 80% was found for some emission types resulting from increased grade-weight combinations (Fernández and Long 1995).

ORSEEM input information includes: vehicle characteristics (such as vehicle type, fuel type, weight, vehicle age group, vehicle make year, vehicle engine size), vehicle speed, acceleration, study time span, and position in the network (i.e. link number). Users may obtain these vehicle records by either utilizing a traffic simulation model, such as VISSIM, PARAMICS, or CORSIM, or through field investigation. The module, however, was developed based on output options available through the microscopic traffic simulation modeling platform VISSIM (version 5.40) from PTV, Inc. This platform was chosen due to its wide use, flexibility, detailed output, and tested ability to replicate traffic conditions.

Building on EFs employed within MOVES, and equations and concepts used in the development of CMEM, ORSEEM uses a power-based approach to estimate emissions wherein vehicle characteristics and modal parameters, namely vehicle mass, velocity and acceleration were used to calculate vehicle specific power (VSP) demand. VSP and related instantaneous velocity were used to determine the EFs for CH_4, PM_{10}, CO_2 and SO_x pollutants and subsequently the related emissions results.

ORSEEM was developed and coded as a spreadsheet tool in Microsoft Excel Visual Basic for Application (VBA). It uses lookup tables for emission rates obtained from EPA's MOVES (EPA 2012b) along with additional updated database extensions to account for newer vehicular technologies. The ORSEEM database was classified by base fuel type (i.e. gasoline or diesel) and includes seven categories of on-road vehicles based on their gross vehicle weight rating (GVWR), namely: light-duty vehicles (LDV), light-duty trucks (LDTs), two classes of light heavy-duty vehicles (LHDs), medium heavy-duty vehicle (MHDs), heavy heavy-duty vehicles (HHDs) and buses. Each vehicle category was classified by model year extending from 1995 to 2020, and then by vehicle age class and 22 operating modes. Vehicle age classes, or the difference in the current year and the vehicle model year, were categorized as 0-3, 4-5, 6-7, 7-9, 10-14, 15-19 and 20 years and older.

It is known that vehicle emissions are a product of several operating modes, such as start exhaust, running exhaust, idle exhaust, evaporation permeation, fuel vapor venting, brake, brake wear and tire wear. Running and idle exhaust emissions are determined using ORSEEM as these operating modes are displayed most on highways and arterial roadways. It is also assumed that since instantaneous emission estimates are determined within ORSEEM, those emissions that result from the process of evaporating fuel in the vehicle's fuel injection system, especially between fuel pump cycles and during conditions resulting in negative power demand, are inherently captured within the results produced by ORSEEM, either within the running exhaust emission results (when power demand is positive), or within vehicular process emissions, i.e. THC, CO, PM, CH_4 emissions (when power demand is negative). Moreover, there are many variables that contribute to engine power, such as engine speed, air-to-fuel ratio, fuel use and catalyst pass fraction, but vehicle emissions are most influenced by engine power and fuel use. Thus, these variables were included in the emissions estimation process of ORSEEM. See (Miller-Hooks et al. 2012) for additional details.

Naturally occurring atmospheric gases, such as water vapor, CO_2, N_2O, CH_4, ozone (O_3), and anthropogenic-produced gases, such as halocarbons, nitric oxide (NO), CO, aerosols, and fluorinated gases, are collectively classified as GHGs. Other air pollutants, such as SO_x, ROGs and particulate matter (PM), also indirectly affect greenhouse effect (EPA 2010). GHGs are measured qualitatively through global warming potentials (GWPs), a measure of the amount of radioactive force absorbed by one unit mass of a GHG to that of one unit mass of reference gas over a specified time period (IPCC 2007). That is, GWP measures how much heat the corresponding GHG traps in the atmosphere in comparison to carbon dioxide. The existence of such gases creates a greenhouse effect, a natural phenomenon that is induced when atmospheric gases trap the ultraviolet rays from the sun within the earth's atmosphere, that is essential in maintaining the earth's temperature and climatic conditions. ORSEEM calculates the total emissions in carbon dioxide equivalents by using appropriate 100 year GWPs. In general GWPs are calculated for 20, 100 or 500 years, but the most commonly used rate is for 100 year increment (Gillenwater 2010).

Estimates from numerical experiments involving ORSEEM fell within reasonable accuracy as per the 2011 CAFÉ standards (LDV: 27.3 mpg and 326 g CO_2/mi; LDT: 24.1 and 369 g CO_2/mi). However, it must be noted that on average ORSEEM's emissions production estimates were 40% lower than the national values, and fuel consumption estimates were 29% lower for LDVs. For LDTs, the values were 80% and 5% lower for emissions and fuel consumption, respectively. Such conservative estimates were likely produced, because ORSEEM uses a microscopic approach (i.e. summation of instantaneous estimates) and updated EF data for emissions and fuel consumption estimation as compared with EF data used to produce the national values. Moreover, it must be noted that the national values were derived from average fuel consumption estimates using a macroscopic approach, based on EFs and vehicle technologies related to older data sets (EPA 2000). Thus, it was expected that the results would be lower as compared to the national values derived from average fuel consumption.

ORSEEM explicitly considers important variables relevant to assessing transportation policies and management programs and is, therefore, comprehensive in its estimation of on-road modal emissions. It provides an essential tool for considering the environmental effects of proposed policies, congestion and incident management programs, maintenance operations, changes in driver behavior or vehicle composition, and alternative roadway designs or new approaches to operations (e.g., High Occupancy Vehicle (HOV) to High Occupancy Toll (HOT) lane conversion). In the next section, ORSEEM is applied in the quantification of savings in emissions due to roadway enhancements, as well as of negative impacts from lane closures due to maintenance activities and incidents.

4.3 Case Study

The impacts from older vehicular technologies, work zones, and traffic incidents on emissions quantities are investigated through simulation on a case study involving a corridor located primarily in Rockville, Maryland. Simulation runs replicated an hour within the morning peak period (6:00 a.m. – 9:00 a.m.). VISSIM (version 5.40) was used and ORSEEM was applied. From each simulation run, information pertaining to vehicular movements on a second-by-second basis was recorded. This information was employed by ORSEEM post-simulation to provide estimates of on-road emissions from simulated roadway use. For each combination of different factors considered in the simulation design, three simulation runs were made, each with a different seed value. Average results over these runs are reported. Parameters, such as driving behavior for arterials and highways, were set identically across all simulation runs. One run of the VISSIM model replicated traffic movements for 5,400 seconds, the first 1,800 seconds of which was the warm-up period.

The study area is depicted in Figure 4-1, both on a roadway map (1a and b) and in the chosen simulation modeling framework (see Figure 4-1c and 4-1d). The corridor spans a 7 mile stretch of I-270 (a freeway) and MD-355 (an arterial), major north-south roadways connecting the Washington Beltway (I-495) with the newly constructed Intercounty Connector (ICC), and connecting arterials. It is bounded by Montrose Road in the south end. The network depicting this corridor includes not only freeway, but arterials with signalized intersections. Just south of this location are the Nuclear Regulatory Commission's headquarters and the National Naval Medical Center in Bethesda. Moreover, the corridor is a focus of smart growth initiatives and home to several companies, medical facilities and government agencies (e.g., the Food and Drug Administration (FDA). These facilities are additional commuter traffic generators for this area.

The study roadway segment consists of six interchanges connecting I-270 with local roads. The interchanges involve eight on-ramps from local roads to Collector / Distributor (CD) lanes, five off-ramps from the CD lanes to the local roads, four slip ramps from CD lanes to General Purpose (GP) lanes, and two slip ramps from GP lanes to CD lanes. Access to/from the 1,000 foot section of the existing HOV lane that is closest to the Spur was restricted. For simplicity, continuous access was assumed. Traffic demand data was provided by the Maryland State Highway Administration (SHA) based on 2006 survey data. MD-355 runs parallel to the I-270 freeway and consists of multiple interchanges with local roads. North and southbound lanes were included in each model. A total of 162 (91 freeway and 71 arterial) lane miles were modeled as depicted in Figure 4-1c and d.

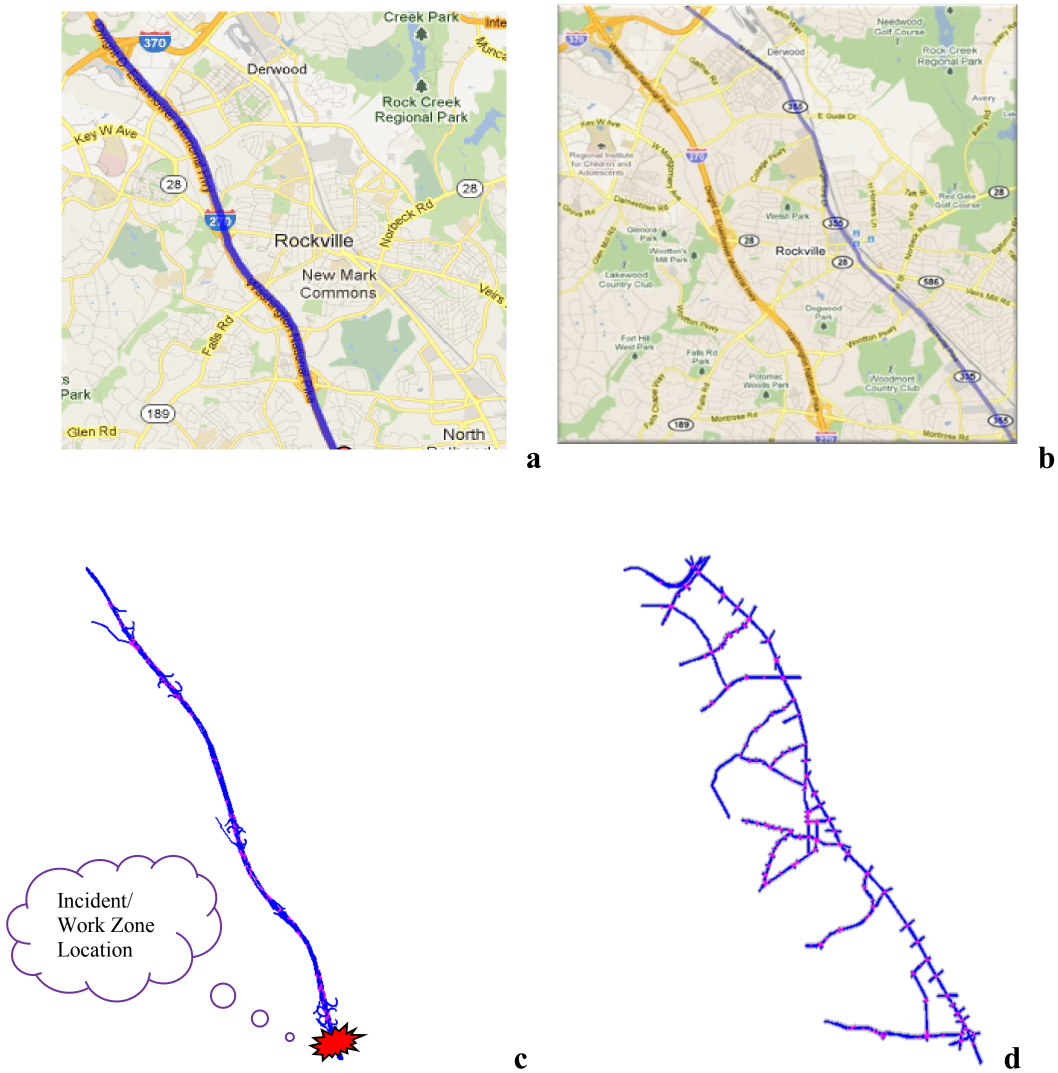

Figure 4-1: Freeway I-270 and arterial road MD-355 (6.5 and 7 mile stretches)

The simulation environment requires significant data input. Traffic demand data for this network of roadways was provided by SHA based on 2011 data and was assumed to enter the network over the simulated period. For the freeway portion of the corridor, the northbound and southbound 2006 vehicle composition data (Table 4-1) from Chou et al. (2010) was employed. Truck and bus percentages were between 6 and 11% for freeway segments and approximately 2% for arterials. Arterial data were extracted from 2010 Synchro input files supplied by SHA. For the arterial simulation runs, actual traffic signal timing plans specific to the analyzed area were obtained from SHA. Information for vehicle-specific characteristics, such as traffic composition, type, model, make and engine specifications, were obtained from the Maryland Department of the Environment (MDE). Heavy-duty trucks, including buses, were included with an average share of 7.46% for northbound and 6.87% for southbound directions typical to the considered area (Chou et al. 2010). Parameters used in the simulation runs were calibrated based on travel times obtained from field measurements. A description of the calibration effort associated with I-270 can be found in (Miller-Hooks et al. 2011).

The VISSIM simulation software offers a COM (Component Object Model) (PTV 2009) interface that permits flexibility in controlling various parameters of the simulation environment. The COM interface was used to create batch runs and lane blockage events developed to imitate lane closures due to work zones and incidents. The approach used to model the lane blockage events of work zones and incidents within the VISSIM platform is based on procedures developed in a prior work (Chou et al. 2010). While VISSIM permits direct modeling of such events through the introduction of a parking space with duration of application, the timing of such events is random. This alternative methodology involves the use of the “Add vehicle” function that exists within VISSIM’s COM interface. The function places a vehicle with zero speed at a specific location and time, and also removes the vehicle at a desired time. A reduced speed area is applied in the lane adjacent to the incident one-quarter mile upstream of the incident location. The work zone is assumed to be 2,500 feet in length with a set speed of 30 mph and reduced speed area along the length of the work zone. A speed limit reduction between 5 and 10 mph from the original speed limit is applied based on recommendations in (Chin et al. 2002; SHA 2009).

The VISSIM simulation platform allows the setting of a variety of parameters that govern driving behavior and vehicular interactions. Their specific settings affect travel time, delay, speed, acceleration and other estimates produced in each run. The appropriate value of each parameter depends on the particular characteristics of the roadway being modeled and aggressiveness of drivers in the area of study. This study involves a network of both arterial and freeway links; thus, parameter settings must be chosen to suit the particular link characteristics. Simulation of arterial roads involves modeling of frequent stop-and-go driving conditions due not only to congestion but traffic control devices. Moreover, maximum speed limitations along with frequent need for lane changing and turning affect driving behavior. Parameter values obtained in a prior calibration study using observed segment travel times conducted for a VISSIM model of I-270 (Miller-Hooks et al. 2011) are used herein for the freeway portion of the developed corridor model. Their values are given as follows. CC1: 0.9 second (default); CC2: 12 feet; CC4&5: ±1.4 mph; SDRF: 0.4; WTBD: 9999 seconds; and LBD: 800 (GP lanes), 800 (off-ramp/slip ramp), 400 (on-ramp), 600 (CD lane), and 1,000 meters (spur). In addition, the Wiedmann 99 model for car following is employed.

For portions of the network involving arterial links, the Wiedmann 74 model was employed in which safety distance calculations included within the model capture nonlinear relationships that exist on arterials. Additionally, "look back" distances are smaller for arterials than freeways, and thus are set to 65.6-98.42 feet (20-30 meters) for arterials as compared with 656.16 feet (200 meters the VISSIM default) for freeways. For the arterial portion of the network, the minimum “look ahead” distance is set to a default value of zero meters, allowing for adequate space for driving decisions. The average standstill distance is set to the default value of 6.56 feet. The additive and multiplicative portions of the safety distance factor are 2 and 3 feet, respectively. The desired speed for the main artery (MD-355) was set to be between 45 and 50 mph. For approaching local roads, based on data received from SHA, the desired speed was set to 22.5 mph. Traffic control, including stop signs and signals, were set up in all intersections of the arterial network as per actual operations.

4.4 Vehicle Composition and Volume Change Impacts

To assess the effects of changes in vehicle composition and total volume on emissions for the case study location, each experiment involved the setting of vehicular composition in terms of manufacture year, engine capacity, fuel type (conventional fuel vs. diesel), and total volume. These factors directly influence emissions and can be affected through incentives and policies. Each specific setting of composition and volume is referred to as a scenario. Data required to support the experiments, scenario development, results of simulation runs and development of a regression model for emissions estimation are described next.

4.4.1 Simulation Data

Data associated with vehicle composition were obtained for Montgomery County, Maryland for years 2005 and 2010 from the MDE. This data was provided in the form of a list of registered vehicles and their vehicle identification numbers (VINs). Each VIN was reviewed using AutoCheck, a commercial entity that provides detailed information on any vehicle with a registered VIN. As obtaining information on every registered vehicle in the county would require years of effort, a stratified sampling technique was used to choose a representative sample from which the vehicle composition was determined. The sampling method considered the following categories: 0-3; 4-5; 6-7; 8-9; 10-14; 15-19; 20+ years old, corresponding to manufacturing years: 2010-2007; 2006-2005; 2004-2003; 2002-2001; 2000-1996; 1995-1991; 1990-1800. Based on guidelines given in (Survey Systems 2012), a total sample size of 500 vehicles was chosen. The number of randomly selected vehicles in each age category, i.e. the split of the 500 samples over vehicle age, is shown in Table 4-1 for both study years. Note that 2010 is used as the benchmark year; thus, there are zero vehicles "less than 5 years old" for 2005 vehicles.

Table 4-1. Number of VINs to be selected for each age group for 2005 and 2010 data

Age	**Year interval**	**Quantity**		**Share in Total**		**Number of selected VINs by group**	
		2005	2010	2005	2010	2005	2010
0-3	2010-2007	0	183,201	0.00%	25.14%	0	126
4-5	2006-2005	51,036	109,747	7.37%	15.05%	37	75
6-7	2004-2003	126,356	112,065	18.25%	15.37%	91	77
8-9	2002-2001	121,185	96,955	17.51%	13.30%	88	67
10-14	2000-1996	226,557	150,422	32.73%	20.64%	164	103
15-19	1995-1991	109,529	49,097	15.82%	6.74%	79	34
20+	1990-	57,519	27,354	8.31%	3.75%	42	19
Total		**692,182**	**728,841**	**100%**	**100%**	**501***	**501***

*extra vehicle due to rounding error

Information on engine capacity, style, make, body shape, and year of manufacture were collected for all samples. Ideally, 172 combinations would be used to characterize the variety of vehicles registered in Montgomery County, as there are 172 combinations of engine style and make in the set of registered vehicles. These characteristics affect the fuel burn rate. However, such a large number of categories would be prohibitive for the VISSIM modeler. It is more typical to work with ten or fewer categories. Thus, an engine capacity-based categorization approach was adopted. Specifically, engine capacities were divided into eight categories ranging from 1 to 8.99 liters. Figure 4-2 and 4-3 depict the distribution of engine capacity categories for the 501 samples in each year. The number of different engine capacities falling within each category is also noted.

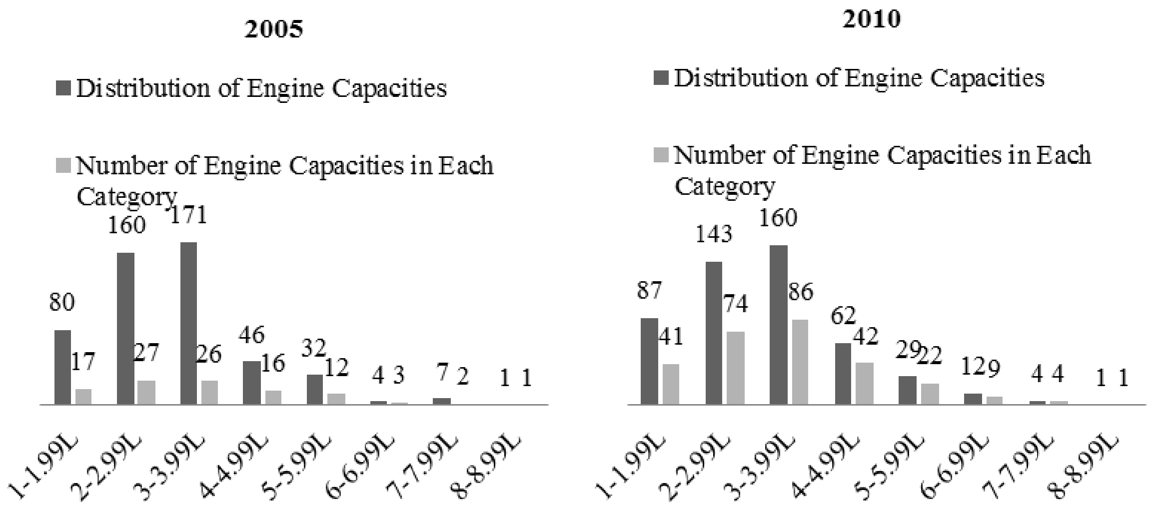

Figure 4-2: Distribution of engine capacities and number of engines by category

4.4.2 Experimental Design

The impact on on-road emissions from changes in vehicle composition in terms of engine capacity and increases in traffic volume in proportion to increases in vehicle ownership was studied through extensive simulation testing on the case study over a set of scenarios. Specification of each scenario entails the setting of two model elements: the distribution of vehicles by engine capacity (composition) and total number of vehicles entering the network in the simulation period (traffic volume). The effects of changes to these elements were explored by comparing results across scenarios. The first set involves increases in total volume from base year 2005 to levels observed in 2010 and higher. A 5.3% increase in total vehicle ownership arose between 2005 and 2010. Base year data were computed from the actual Montgomery County vehicle registration data described in the previous section. Increases of between 0 and 20% in 5% increments were made. For any given percentage change, the increase is applied uniformly over the eight engine categories. Five design scenarios were considered for both freeway and arterial studies: (a) 2005 base data, (b) 2005 base data with 5% increase in traffic volume, (c) 2005 base data with 10% increase in volume, (d) 2005 base data with 20% increase in volume, and (e) 2010 base data.

Within these experiments, input data, such as speed and acceleration at small time steps for each vehicle given vehicle characteristics, were produced through VISSIM. Ideally, modal parameters, like speed, will be input on a second-by-second basis, for each simulated vehicle, over the entirety of the network and simulation period. For this study, a typical data set produced was between 2 and 4 gigabytes in size. Even opening a file with such a large amount of data can be problematic. Thus, it was necessary to take steps to reduce the size of the output data set. In this effort, a methodology to collect modal parameters for link groups within the simulation network was developed. For the purpose of recording and reporting this data, the study area was divided into sections, consisting of groups of model links. The arterial network was divided into 12 link groups and the freeway network into 7 link groups. VISSIM runs were made separately for each link group, because VISSIM does not have the capability to generate separate output files for the individual groups in a single run. Thus, a total of 285 simulation runs were made.

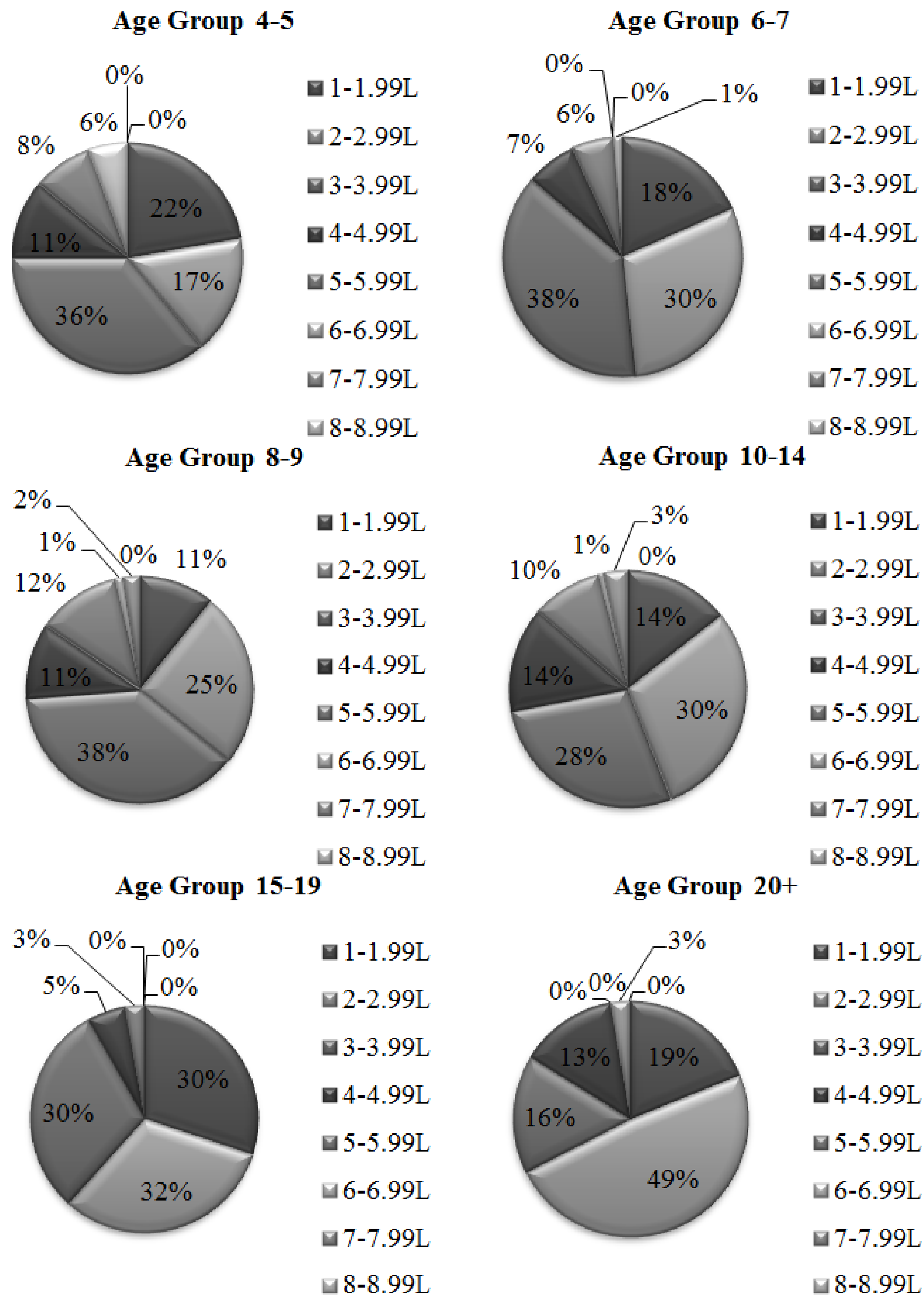

Figure 4-3: Engine capacity distributions by age groups in 2005

In the runs, modal parameters were collected at 5-second increments (recording every 5th data point). Each smaller data set associated with a link group was fed to ORSEEM, which produced emissions estimates. Preliminary runs to compare accuracy of emissions estimates that are computed from such a sampling method by time step indicated a 0.4% loss in accuracy due to the use of 5-second increments. Once emissions estimates for the chosen time steps were obtained, total emissions were derived by scaling emission values by time step increment (i.e. multiplying the result by 5).

After the simulation runs were conducted, a mapping of engine capacities to age group and tier level was required to produce emissions estimates from the simulation output. ORSEEM needs 12 categories of data for evaluation, namely: link number (based on micro-simulation model notation), time step (a number greater than zero, increment in which emissions estimates are calculated), vehicle type (LDV, LDT, LHD<=14K, LHD<=19.5K, MHD, HHD, urban bus), make year (<1995 to 2010), age group (0 - 3, 4 - 5, 6 - 7, 8 - 9, 10 - 14, 15 - 19, 20 – 99 years), fuel type (gasoline, RFG, CNG, E10, E85, diesel, LSD, ULSD, B5, B20, B50), weight of vehicle, engine size (LDV(2.2 L), LDV hybrid (2.5 L), LDT (3.9 L), LDT hybrid (6 L), LHD<=14K (5.95 L), LHD<=19.5K & MHD (6.7 L), HHD (12.84 L), urban bus and urban bus hybrid (8.2 L)), speed (0-70 mph), desired acceleration, hybrid information (percentage of total), and gradient.

To complete this mapping, developed distributions of engine capacity by age group for both 2005 and 2010 data sets were used. These distributions were determined based on the sampled set of the vehicles described in Table 4-1. To illustrate, consider Figure 4-3 and an output file with data for 100,000 vehicles. 7.37% of the total vehicle population in 2005 fell within the 4-5 year age group (see Table 4-1). For the same age group and base year, the share of 2-2.99 L engine vehicles was calculated to be 17%. Thus, 17% of 7.37% vehicles would fall in age group 4-5 and of the 100,000 vehicles, 1,253 vehicles have a 2-2.99L engine and are 4-5 years in age.

Each VISSIM run on the freeway and arterial portions of the corridor required approximately 5 and 7 minutes, respectively, on a Dell C750 personal computer with a 3.10 gigahertz core i5-2000 processor, and 3.88 usable gigabytes of RAM, running a 64 bit Windows 7 operating system. ORSEEM required nearly 27 hours to process the output from VISSIM on the same machine for a single scenario with one seed (i.e. 12 runs for the arterial portion of the network and 7 runs for the freeway portion together). Additional time was required for pre-processing some of the VISSIM output to create the correspondence with categories needed in ORSEEM.

4.4.3 Results

Table 4-2. ORSEEM results for a freeway I-270 segment and arterial MD-355

Scenario	Total CO_2e emissions in grams		CO_2e per vehicle per mile in grams		CO_2e per VMT in grams	
	Freeway	Arterial	Freeway	Arterial	Freeway	Arterial
Base 2005 + 0%	54,724,819	17,786,342	1971	900	625	721
Base 2005 + 5%	60,218,544	18,440,419	2090	911	662	734
Base 2005 + 10%	62,326,869	19,229,943	2131	919	674	737
Base 2005 + 20%	66,836,794	20,333,908	2133	951	679	774
Base 2010 + 0%	51,076,119	15,402,411	1765	752	556	612

For each scenario (comprised of link groups), total emissions given in terms of carbon dioxide equivalents, CO_2e, taken over only the GHGs computed by ORSEEM were recorded as presented in Table 4-2. Results in Table 4-2 indicate that emissions increase better than linearly with increasing volume on the arterials and worse than linearly on the freeways. For example, a 5% increase in volume on the arterials resulted in a 3.67% increase in total emissions; whereas, the same increase resulted in a 10.03% increase in total emissions for freeways. As volume increases, the incremental change in emissions along both arterials and freeways diminished. A comparison between the 2005+5% scenario (with total volume of 20,246) and 2010 base case (with total volume of 20,489) was made to assess the impact of traffic composition change, while holding traffic volume essentially constant. The results indicate an emissions reduction of over 15% can be expected for both arterials (16.47%) and freeways (15.18%) as a consequence of this change.

These results do not account for throughput. As volume increased, speeds decreased resulting in greater emissions. An increase in emissions is expected under such conditions, because at the extreme ends of vehicular operating speeds, greater emissions are generated (Barth and Boriboonsomsin 2009), thereby increasing emissions rates per mile. To investigate the effects of volume and composition change, a comparison was made on both per vehicle and VMT bases. On a per vehicle basis, emissions were greater on the freeway than along the arterials. For both roadway classes, emissions per mile increased better than linearly with increasing volume. When comparing emissions by VMT, greater emissions were generated on the arterials as compared with the freeway. In general, this measure increased better than linearly with increasing traffic volume for both roadway classes. Generally, all measures improved with the more efficient 2010 vehicle composition. Similar to findings for total emissions, in a comparison of 2005+5% with 2010 base case, emissions per VMT decreased by approximately 16% for both roadway types. Thus, the magnitude of emissions reduction due to vehicle technology improvements was quantified, providing numerical estimates to support policy decisions associated with incentivizing the use or development of new vehicle technologies.

4.4.4 Multi-Regression Model Development for Traffic Volume and Composition Change

Two multi-regression models of emissions in CO_2e designed to capture the effects of traffic volume change on emissions were developed from the detailed output of the simulation runs involving millions of data points (for 1.66 million and 1.09 million data points for freeways and arterials, respectively) for the studied roadways. Each data point provided information on emissions associated with the movement of all vehicles in 5 second time increments. A model was developed for arterials and another for freeways. The developed estimation models are intended to enable quick calculations for on-road traffic emissions. Such calculations can be used to estimate the effects of traffic volume, changes in vehicular composition (in terms of weight and engine capacity), average speed, acceleration, and roadway grade on emissions. These factors are known to be the main drivers of emission rates (Scienceonline 2012).

Calibration of the regression model was completed using SAS, a state-of-the-art statistical software package. The statistical importance of terms used in ORSEEM was investigated. The data used in model development for the freeway and arterial network consisted of the vehicular make year (MY), engine capacity/size (ES), speed of the vehicle at a given time instance (V), acceleration at the same time instance (A), roadway grade (G), and calculated value of emissions (E) for a particular vehicle at a given time instance. Nonnumeric inputs, like fuel type, were included in the analysis as categorical data. A surrogate, binary variable (H) was used to indicate whether or not each vehicle is a hybrid vehicle. The dependent variable in each multi-regression model is CO_2e emissions in units of grams per second. The following multi-regression models were produced.

Freeway Multi-regression Function

$$E_{freeway} = 3168.32 - 1.63MY + 53.67ES - 1.74V + 15.34A - 23.78H + 5.43G - 251.58ES^2 + 0.16V^2 + 2.03A^2 + 0.34G^2 - 3.49ES^3 - 0.003V^3 - 0.035A^3 + 0.0005G^3 + 0.42ES^4 + 0.00002V^4 - 0.012A^4 - 0.0001G^4 - 0.0003A^5$$

Arterial Multi-regression Function

$$E_{arterial} = 1016.48 - 0.8MY + 578.18ES + 2.27V + 6.95A - 16.23H + 1.58G - 199.58ES^2 - 0.34V^2 + 0.44A^2 - 0.17G^2 + 28.78ES^3 + 0.02V^3 - 0.04G^3 - 1.43ES^4 - 0.0005V^4 + 0.002A^4 + 0.01G^4 + 0.000004V^5 + 0.0001A^5$$

Application of these regression models requires input related to: MY, ES, V, A, H, and G. Plugging this information into the appropriate (arterial or freeway) model provides an estimate of emissions in CO_2e generated by the vehicle at the given time instance. To evaluate the amount of emissions for a time interval, values for each time instance can be summed.

A polynomial function with a power of five was found to provide a good fit for the data for both arterial and freeway emissions. The dataset on which each multi-regression model was fitted is exceptionally large and thus concern associated with the use of a high power polynomial function and data over-fitting can be neglected (Agresti 2009). Simulation time point, vehicle weight and various independent variables taken to a power were found to be insignificant. These terms were removed from the models. The effect of vehicle weight was captured through the vehicle engine size variable, which can be justified statistically (Agresti 2009).

A power of five was chosen for the models based on a process that began with a linear model, and power terms were increased to the point where no significant improvement in R-squared value could be detected. R-square values are not used in the assessment of polynomial models since their values can artificially be improved by increasing the power of the function. The change in R-square is a helpful measure as a stopping criterion for increase in degree of a function only. The mean square error resulting from the 5^{th} degree function is 1784.5 for freeways and 1072.2 for arterials. These values are acceptable, because they represent a ratio of mean squares and corresponding error degree of freedom resulting in satisfactory F value. Based on these values, the null hypothesis that all coefficients in the model are equal to zero was rejected. The results of tests, such as the F-test, show that the models provide a good fit to the data and the final chosen independent variables of the models are statistically significant. Additionally, residual plots support the choice of a polynomial form for the multi-regression model. The models were validated on an independent data set involving 500 data points from three additional, similarly generated VISSIM runs. The difference in aggregate amount of emissions was approximately 5% for both models. Finally, a data partitioning approach was considered as an alternative; however, due to the shape of the plotted dataset, there was no partition that could provide a better fit than the chosen polynomial forms. Based on results of model validation and goodness-of-fit tests, the chosen explanatory variables were found to be suitable, variables were noted to be independent as per the Durbin-Watson test of autocorrelation, and goodness-of-fit of the models was validated through a series of tests: Akaike Information Criterion, Mallow's C_p, Bayesian Information Criterion, and Schwarz's Bayesian information criterion.

Earlier works by Ahn et al. (2002) and Yerramalla (2007) developed linear and polynomial regression functions to estimate emissions generated from on-road vehicles. The model developed by Ahn is based on instantaneous fuel consumption while considering vehicle operational speed and acceleration. Acceleration is taken to be a polynomial function with power of 3. Yerramella used cruise speed to derive linear and later polynomial functions with powers of 2 and 3. Neither work captured the second-by-second impact of vehicle operation on emissions estimates. The fuel consumption based model of Ahn employed the traffic simulation platform INTEGRATION and its embedded emissions estimation tool, which uses average modal parameters. Models proposed by Yerramalla estimate CO, HC, and NOx emissions using data from MOBILE 6.2 and field measurements. Polynomial regression models with higher order were used in other works for similar analyses using independent variables of average fuel consumption and speed, again considering only one emission type from CO, HC and NOx (e.g., EPA 2005; Guensler et al. 1993; Stefanopoulou et al. 2008).

4.5 Impact of Traffic Incidents and Work Zones

4.5.1 The Experimental Data and Design for Traffic Incident and Work Zones

Simulation runs were conducted to assess the impact of work zones resulting in single-lane closures and shorter duration incidents similarly blocking one lane. In all runs, the traffic volume and vehicle composition were based on 2010 values. Each experimental run is defined by incident and work zone duration: 15, 30, 45 or 60 minutes. Work zones may last as long as days or weeks if not months, the effects of only as long as a one hour closure in morning rush hour were studied here.

Because an incident of significant duration can impact traffic flow many miles upstream of the event, it was necessary to set the incident location at a point near the downstream end of the model. Thus, the incident location was set to arise 500 feet south of the off-ramp to Montrose East for the Southbound portion of the model (see Figure 4-1c). The work zone was located at the end of the Southbound lanes of the modeled roadway.

This design involved eight scenarios and, thus, 168 simulation runs for incidents and work zones combined while considering seven link groups for analyzing the effect of incidents and work zones on the entire freeway network. Once the simulation runs were conducted, a mapping of engine capacities to age group and tier level was completed. This mapping associates the engine capacities from the sample with age groups from the larger, original data set. The generated data files were fed to ORSEEM for emissions calculation. Similar run times were required as in the vehicle volume and composition runs of Section 4-4.

4.5.2 Results

Total emissions estimates, again in terms of CO_2e equivalents, from the simulation runs associated with incidents of varying duration and work zones over the study area are provided in Table 4-3.

Emissions estimates associated with the blocking of a lane due to an incident or work zone were found in general to decrease with lane closure duration. This is counterintuitive, but can be explained. First, given original speed levels for this congested network, an increase in average speed due to the incident can reduce overall emissions. In these runs, average speeds of 34 and 35 mph were noted for the 60 minute incident and work zone freeway scenarios respectively. In contrast, where no lane closure exists (zero minute scenarios), the average speed was 25 mph. The optimal speed range for minimizing emissions generation is approximately 32 mph (Barth and Boriboonsomsin

2008; Rao et al. 2010; Unal et al. 2003). This nearly 10 mph increase in average speed arises from the increase in speed of vehicles just downstream of the rubbernecking area. Vehicles back up behind this area. Once passing the incident or workzone location, they can quickly attain desired speed levels. Second, while the average speed increased, the total throughput in the simulated hour decreased. Thus, one can expect total emissions for the time period to drop. Likewise, emissions decreased per VMT. Emissions rates per vehicle, however, generally increased with increasing incident or work zone duration, indicating that the total emissions that would be produced to serve the same number of vehicles as served under the no-lane blockage scenario will increase. A decrease in this rate was noted, however, where average speeds near 30 mph were attained, which is, again, consistent with theory from the literature (Barth and Boriboonsomsin 2009).

Table 4-3. ORSEEM results for a freeway I-270 segment for incidents and work zones

Item	Unit measure	Case		Scenario				
				0 min	15 min	30 min	45 min	60 min
Total CO_2e emissions	grams	Incident		51,076,119	49,004,221	46,486,317	49,343,474	47,140,041
		Work Zone		51,076,119	49,331,136	47,343,453	48,836,028	48,764,005
CO_2e per vehicle	grams	Incident		1765	1770	1679	1783	1703
		Work Zone		1765	1780	1708	1762	1759
CO_2e by VMT	grams	Incident		556	545	517	549	524
		Work Zone		556	549	526	543	542
Total delay	hours	Incident		680.771	690.036	711.655	719.994	723.47
		Work Zone		680.771	681.32	682.955	683.599	684.579
Throughput	vehicles	Incident	In the network	3,193	2,642	2,642	2,642	2,718
			Left the Network	25,699	25,040	25,040	25,040	24,964
		Work Zone	In the network	3,193	2,642	2,642	2,642	2,698
			Left the Network	25,699	25,078	25,078	25,078	25,022
Total traveled distance in miles (VMT)		Incident		91,835.69	89,938.36	89,938.35	89,938.31	89,898.08
		Work Zone		91,835.69	89,938.22	89,938.07	89,937.91	89,931.01

A noticeable increase in emissions production from work zone events in comparison to incidents of comparable duration can be seen. This difference is largely due to the longer length of the lane blockage in the work zone event. Even larger differences would be expected if stricter speed reductions near work zones were required and modeled. Note, too, that greater throughput is noted for the work zone as compared to incident events. Emissions, however, did not increase proportionately.

These findings support potentially novel incentive options. In designing this study, it was assumed that work zones in general, including construction of buildings and other structures along the side of roadways that reduce capacity of adjacent traffic lanes, would lead to increased congestion and, therefore, increased emissions. Thus, policies could be designed that would assign costs associated with emissions abatement to construction project owners. However, under circumstances where average speeds approach optimal speed values for limiting emissions from on-road vehicular use, benefits of the work zone or incident may be derived. This would infer that incentives, rather than disincentives, might be offered to these firms if ideal speeds could be maintained as a consequence of the construction. It is standard to install reduced speed zones just prior to constructions zones. Speed reductions on the order of 5 to 10 miles per hour from the design speed are commonly suggested as noted earlier (Chin et al. 2002; Ruehr 2010, SHA 2009). This 5 to 10 miles per hour decrease in speed from the design speed rule may need to be revisited. Additionally, ORSEEM and developed regression models can provide the tools needed for evaluating the benefits of shifting work-day hours on emissions production and the potential return on investment from providing incentives to companies that support such work-day changes.

4.5.3 Multi-Regression Model Development for Traffic Incidents and Work Zones

The two regression models developed for estimating per time increment carbon dioxide equivalent emissions resulting from incident and work zone events are presented next. The relationship between dependent variable and explanatory variables for both models were found to be nonlinear, and a fifth degree polynomial regression was implemented for both based on a similar incremental experimental approach as used in the development of the models in section 4.4.4. The regression models for both incidents and work zones were developed for freeways only. In model validation on an independent data set generated through additional VISSIM runs and goodness-of-fit tests, the chosen explanatory variables were found to be suitable, variables were noted to be independent as per the Durbin-Watson test of autocorrelation, and goodness-of-fit of the models was validated through a series of tests: Akaike Information Criterion, Mallow's C_p, Bayesian Information Criterion, and Schwarz's Bayesian information criterion. The final models are presented next in which BT refers to the duration of the lane blockage.

Traffic Incident Emissions Estimation Model for Freeways

$$
\begin{aligned}
E_{freeway\_traffic\_incident} &= 3224.76 - 2.13MY + 1012.01ES - 2.71V + 17.87A - 39.49H \\
&+ 6.77G + 0.43BT - 335.58ES^2 + 0.26V^2 + 2.29A^2 + 0.52G^2 \\
&- 0.01BT^2 + 45.4ES^3 - 0.007V^3 - 0.076A^3 - 0.01G^3 + 0.0001BT^3 \\
&+ 2.11ES^4 + 0.00009V^4 - 0.016A^4 - 0.0003G^4 - 0.0004A^5 \\
&+ 0.000006G^5
\end{aligned}
$$

Work Zone Emissions Estimation Model

$$
\begin{aligned}
E_{freeway\_work\_zone} &= 3123.26 - 2.07MY + 1006.02ES - 2.99V + 17.69A - 38.41H \\
&+ 6.65G - 0.24BT - 334.04ES^2 + 0.28V^2 + 2.28A^2 + 0.45G^2 \\
&+ 0.006BT^2 + 45.27ES^3 - 0.009V^3 - 0.07A^3 - 0.009G^3 \\
&- 0.00005BT^3 - 2.11ES^4 - 0.0001V^4 - 0.015A^4 - 0.0003G^4 \\
&+ 0.000001V^5 - 0.0004A^5 + 0.000005G^5
\end{aligned}
$$

These models were constructed on 3,835,825 and 4,804,895 data points for incident and work zone models, respectively. In validating the results on separate data, emissions estimates fell within 5-7% of ORSEEM-generated estimates. In comparison to related studies (e.g., Afotey 2008; Ahn et al. 2002; EPA 2005; Guensler et al. 1993; Stefanopoulou et al. 2008; Yerramalla 2007) in which regression models were developed for fuel consumption or a specific emission type, this combined modeling approach produced significantly improved estimation capability with practical utility, i.e. using easily obtainable input data.

4.8 Conclusions

This chapter studies the effects on emissions due to traffic volume increases and composition changes for both arterials and freeways. Additionally, the impact of traffic incidents and work zones along freeways were analyzed. Estimates were made from numerical experiments on a case study involving a 7-mile stretch, with a total of 162 lane miles of a major Maryland corridor in close proximity to Washington, D.C. The potential utility of the models proposed herein in policy and incentive development to achieve emissions reduction goals related to on-road traffic are discussed, new potential policy directions are suggested, and findings from the numerical experiments are provided. Specifically, the results of the analysis indicate that vehicle composition greatly affects the amount of emissions, and significant potential for reaching emissions reduction goals exists through improvements in vehicle mix efficiencies within the traffic composition. Due to lower throughput as a consequence of an incident or work zone that reduces roadway capacity, emissions during the simulation period decreased. However, emissions rates per vehicle passing through the study segment during the incident or work zone time period were found to generally rise. Thus, total emissions will generally increase when serving the same total number of vehicles. It was noted, however, that the lane blockage due to a work zone or incident could lead to an increase in average speed over the segment due to free flow conditions that result downstream of the event. When the average speed over the segment approached 30 mph, overall improvements in emissions output, even when accounting for all throughput to be served, were noted. This has interesting and non-intuitive regulatory repercussions. Additional runs would be required to study these events with a larger number of lanes blocked or shoulder-only blockages. Moreover, simulation runs for both incident and work zone cases were for a single location along the study segment stretch. Runs with varying locations for both cases may provide additional insights.

Nonlinear multi-regression emissions estimation models were derived for vehicle volume, work zone and incident scenarios. The models were validated on a second set of data and were found to meet goodness-of-fit requirements. In all four models, improvement in model fit due to inclusion of an intercept and statistical conflict associated with removing intercepts from the models, were significant enough to warrant their inclusion despite the anomaly for the zero vehicle case.

There are a number of limitations of this study, and hence the use of the developed regression models. For example, traffic volume increases of only up to 20% from the 2005 base year were considered. An increase of only 5.3% occurred between 2005 and 2010. This, however, might be constraining in future years when traffic volumes may increase beyond the 20%, it is not likely to be a limiting factor for near-term future analyses. Even though the models were developed based on millions of data points, only one change in vehicle composition was tested. Systematic study of vehicular technology changes is required to draw more general conclusions. Findings given herein were developed from numerical experiments. Field tests would be needed to validate the findings and estimates generated through VISSIM and ORSEEM. Comprehensive field tests as would be required would be very difficult and expensive to conduct, however.

This study employed a single corridor in a congested urban area. Actual, rather than general, signal timing plans and estimated turning percentages were employed. General findings obtained from the numerical experiments may apply only to locations with similar roadway geometry (including grade), traffic operations and vehicular mixes, and emissions estimates derived from the regression models should be applied accordingly.

Despite these limitations, this chapter makes a significant contribution to the literature. In addition to providing insights from results of numerical experiments based on a detailed, calibrated model of a real corridor involving both freeway and arterials in the Washington, D.C. region, it provides multiple regression equations that can be employed on comparable roadways to estimate the emissions effects of a variety of inputs, thus, obviating the need for expensive and extensive computer runs. Model run results and regression equations were derived from second-by-second modal information from a range of vehicle technologies, thus, supplying more representative estimates and capturing emissions resulting from roadway geometry characteristics and driver behavior. Another advantage of the results and proposed models is that they were obtained using ORSEEM, which uses more accurate, updated EFs as compared with other available emissions tools used in prior related studies. ORSEEM also includes a wide range of

GHG emissions, and thus the findings and tools provided here incorporate multiple emission types. This allows detailed analyses associated with a vehicle composition that includes newer vehicular technologies. Power demand is explicitly considered in the creation of the regression models, yet the regression models do not require its direct input from the user. This provides a practical means for its consideration. Moreover, developed regression models are implementable, requiring input that is available in practice. Finally, few works have provided quantification tools for computing the implications of work zones, incidents and a shift in vehicle technology on total roadway emissions as is addressed herein.

CHAPTER 5: ANALYZING CARBON PRICING EFFECTS ON GLOBAL NATURAL GAS MARKETS: SUPPLIERS' AND CONSUMERS' PERSPECTIVE

Abstract

The carbon policy impact on the natural gas industry has not been analyzed in detail. Thus, given the importance of this industry and climate change goals this chapter provides an analysis which will hopefully guide decision-makers for sustainable future for the industry. In particular this chapter examines what fraction of carbon taxes should be applied to various parts of the natural gas supply chain. Some findings include: the larger the fraction applied to the supply side can be either detrimental or beneficial to consumer surplus; the effects of this fraction can vary by type of carbon policy.

5.1 Introduction

Global climate change is already a proven fact that has devastating consequences. Naturally occurring greenhouse gas emissions commonly expressed in terms of CO_2e (carbon dioxide equivalents) are filtered by nature itself. Unfortunately, emission levels increase over time due to human activities and the excess amount of emissions contribute to global warming (IPCC 2001; Stern 2007; EPA 2012; NASA 2012). Climate change would not become an issue if the excess amount of emissions were successfully filtered by the surrounding environment. The impact of climate change is already obvious-rising sea levels, hurricanes and tornados, droughts or heavy rainfalls (NASA 2012). Therefore any measures and steps aimed at reducing the rate of climate change are of interest to many researchers and environmental agencies across the world. Natural gas is comparably a less emitting and low-cost fossil fuel making it a preferable alternative energy source or a bridging fuel between conventional fuels and renewable energy sources. It is expanding its market share due to its abundant reserves, technological achievements and environmental considerations thereby minimizing adverse impacts on the climate.

Understanding the importance of reducing emissions and the impacts of climate change, many decision-makers and researchers joined efforts to develop short- and long-term policies that would hold emitting industries responsible and accountable for their emissions (EPA 2007). These industries represent mainly large energy producers and consumers. Traditionally, a significant portion of energy demand has been satisfied mainly through the combustion of natural resources, such as coal, oil, and natural gas. Since natural gas is the most environmentally friendly fossil fuel and is more abundant than oil or coal, it is considered to be the bridging fuel between future efficient renewable energy sources and traditional fossil fuels. The consumption of natural gas is growing worldwide (Figure 5-1). It has increased from 15% in 1965 to 24% in 2010, or equivalently from 23 trillion cubic feet (Tcf) to 104 Tcf (MIT, 2010). The expansion of the natural gas market is determined not only by direct preferences of major consumers, such as electricity producers or cement and steel manufacturers, but also by gradual and steady technological changes.

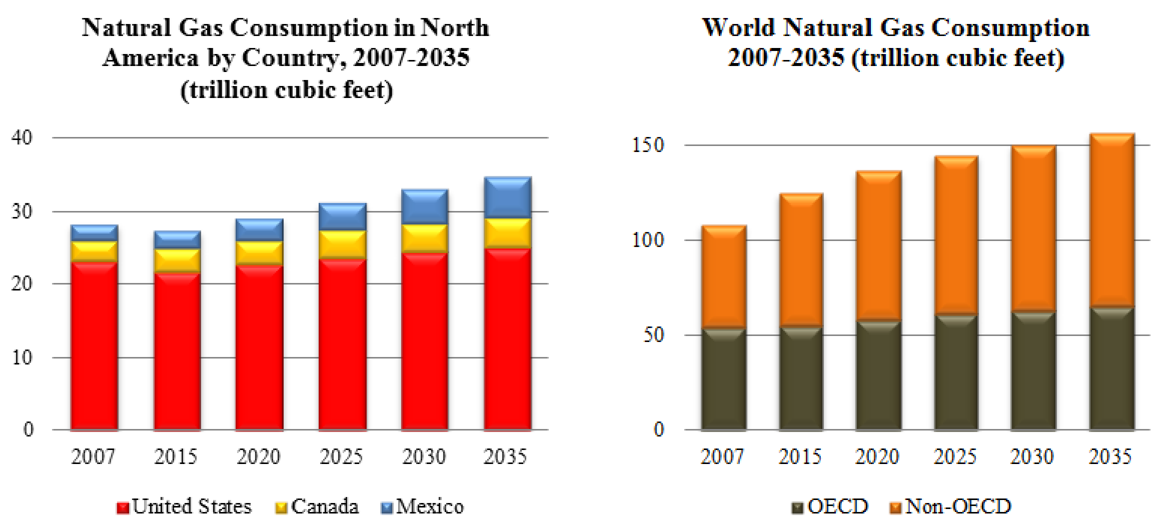

Figure 5-1: North American (left) and Total World (right) Natural Gas Consumption.

Source: (EIA 2010a)

Natural gas has the potential to be a widely traded energy source for consumers that have high energy demand but suffer from insufficient and expensive supplies. Forecasts indicate further growth in natural gas demand in North American, Eurasian and Middle Eastern energy markets (Figure 5-1) (AGA 2008; EIA 2010a; MIT 2010).

Since natural gas is expanding its share in global energy markets, it becomes important to regulate emissions from this industry. Even though natural gas is cleaner than other fossil fuels, its extraction and combustion still generate greenhouse gases contributing to global warming. The decision-making process aimed at building a cleaner environment is a challenging task and sometimes it becomes necessary to address problems of not only technical, but also of economic and political feasibility.

To regulate the amount of emissions in specific industries, a number of policies and bills have been proposed in the U.S. and around the world. For instance, the proposed Waxman-Markey Climate Bill (H.R. 2454 2009), represented the trade part of the carbon cap-and-trade mechanism by imposing a cap on 85% of polluting industries, including electricity producers, oil refineries, natural gas suppliers, and energy-intensive industries (iron, steel, cement, paper manufacturers, etc.). Given such approach for industries, it is important to determine the most appropriate policies for implementing carbon taxation, cap and trade programs along with carbon permits and allowances. Developing and determining the efficiency of policy mechanisms is complicated when considering both the supply and the demand sides of the market.

A number of studies addressed the issue of finding an optimal greenhouse gas tax used in carbon taxation policies. For instance, Baumol (1972) states that it is hard to measure the impact of any externality, and, hence, there is a need for further analysis to understand the impact of carbon policies, particularly for the natural gas sector. In this chapter, we discuss game theoretic approaches for the natural gas industry that can be indirectly applied for such analyses and help in assessing the impact of greenhouse gas taxes.

There are various methods used to determine the amount of a greenhouse gas tax, and the social cost (considered as an inclusive cost of adverse impacts of carbon emission on the society) of the carbon is one of them. The social cost of carbon per unit to be paid is calculated based on the damage caused by carbon emissions. The issue of carbon policies and price determination was studied previously by others. Yonal et al. (2007a) suggested that the cost of allowances (which can be transformed and used as a cost of carbon in cap and trade system) for carbon should be equal to the social cost of carbon. They also found that the social cost of carbon (the cost of the damage caused by carbon emissions) is uncertain and there is no single approach that may satisfy all industries (Yonal et al. 2007b). To determine the impact of the social damage from carbon emissions, the Intergovernmental Panel on Climate Change (IPCC) conducted a large-scale analysis (IPCC 2001b) assessing the impact of carbon emissions on global temperature change and world gross domestic product, and then compared the outcome with the results of Stern (2007). Findings of these two analyses consistently suggest that carbon-caused damage estimates, as a percent of global (Gross Domestic Product (GDP), are correlated with increases in global mean temperature. Scheffran and Pickl (2000) developed a game theoretic model for determining the cost of GHG emissions by country. In this study they used options of joint implementation to achieve the desired reduction levels. In an earlier work, Scheffran (1998) applied game theoretic modeling technique to analyze conditions for cooperation, stability and cost minimization in the energy sector and climate change problem.

Climate-change research in relation to natural gas markets has also been previously analyzed. For instance Gabriel at al. (2000) explored the carbon stabilization programs in Canada to export natural gas to the U.S. They found that the impacts of stabilization programs vary by region even if such programs are applied to the same industry. Modeling approaches were used for analyzing North American carbon emission policies by Kanudia and Loulou (1998 a,b,c), where they analyzed energy planning by considering 150 energy sources through a stochastic approach, and also found advantages for using probabilistic modeling techniques over deterministic optimization modeling. It should be noted though that more realistic and industry-specific market structure representation is also important for accurate and conclusive results. Similar approaches along with the results can be found in Loulou et al. (1996), Loulou and Kanudia (1997, 1998) and in Chung et al. (1997).

Brown et al. (2010) analyzed the impact of the natural gas market/industry on carbon policy and found that natural gas has a big potential for being a preferred fuel under cap-and-trade or tax policies, although it would be more efficient if nuclear power and renewable power were kept limited, so the energy demand would be supplied by fossil fuels. Stern et al. (2006) also indicated the importance of using natural gas as an alternative to highly emitting fossil fuels to avoid long-term climate change impacts. At the same time the authors stated that the significant amount of emissions generated from natural gas industry, just from flaring related activities, represents about 30% of total global emissions. Even though all emission reduction techniques can be translated to per unit equivalent cost, the taxation of emissions was found to be an effective measure for emissions mitigation, providing greater price predictability (Stern et al. 2006; IAE 2006).

Certain countries pioneered the way to adopt carbon mitigation mechanisms to meet the target emission reductions. A good example is the UK applying the Climate Change Levy, which was a revenue-neutral mechanism encouraging emissions reduction across different sectors, including the industrial sectors. Norway is another example that introduced a carbon tax system in the early 1990s. The carbon tax mechanism in Norway covers much of its heavy industry as well as the transport sector. There are also other Scandinavian countries that implemented carbon taxation schemes. Norway left certain areas exempt from taxation, even though it was one of the early adopters of this system that covered nearly 60 percent of the energy-related CO_2 emissions. This includes the natural gas and electricity sectors in addition to the cement industry, foreign shipping, and fisheries. Emissions taxation in Norway showed a significant increase in government revenue and according to Bruvoll and Larsen (2002) the revenue from taxation was 0.7% of the entire GDP in 1993, which reached to 1.7% in 2001. The corresponding CO_2 emissions reduction resulted from this action was 2.3% as of 1999. Observations indicated improvement in technology innovation in Norway (Stern et al. 2006).

When the tax is applied directly to the amount of emissions from a facility/plant, the producer has an incentive in technology improvements if the general structure of the applied tax system can be differentiated from other application schemes (Pigou 1920). However, the implementation of a tax mechanism for the natural gas industry faced some difficulties due to a lack of information on competitiveness with foreign producers. Also, despite the fact that different fuels emit at different rates, the suggested tax structure was uniform over the variety of fuels. Even though Norway, Finland, Sweden, and Denmark implemented carbon taxes in the early 1990s, they could not balance their approaches in coordinating tax policies internationally (Ekins and Barker 2001).

The research in this chapter was funded by the Norwegian Research Council and seeks to fulfill the existing gaps in research and development of emissions taxation policy implementation for the natural gas industry. In contrast to existing approaches, this research considers the impact of various carbon policies from both the suppliers' and consumers' perspective. We also compare our main results with a no-carbon policy scenario to show the impact of the suggested policies. The analyses were conducted through extension and improvement of the existing World Gas Model (WGM) (Gabriel et al. 2012) to account for environmental aspects in the natural gas market.

This chapter examines internalization of carbon dioxide emissions costs from the supply and demand sides of the market in order to provide a model for the development of a robust policy for the natural gas industry. The World Gas Model (WGM) developed at the University of Maryland is suitably modified in order to perform this analysis. Particularly, the objective functions of players in WGM have been extended to account for carbon emissions related costs in the supply chain. Additionally a novel approach is applied to allow a proportional application of carbon costs both on the suppliers and consumers side of the market. It was found that depending on the place of carbon cost allocation on natural gas supply chain the loss of total surplus can be lessened. Therefore much better carbon policies can be developed for natural gas industry. It is also observed that to lower the adverse impact of carbon policy adoption on total surplus the policy should not be applied uniformly in different regions. To provide better results in terms of lowered loss of surplus the carbon costs need to be assigned to consumers or be shared between consumers and suppliers. In most scenarios it was noticed that when carbon cost is entirely applied only on suppliers the average wholesale prices increase significantly. This same adverse effect is also noticed on the corresponding decreasing production volumes. It is observed that depending on the time of carbon policy adoption total surplus can be higher if the tax is entirely collected from consumers. With varying years of carbon policy adoption in different regions can make shared tax policy between suppliers and consumers more preferable and lessen the adverse impact on total surplus.

5.2 The World Gas Model

The WGM is a long-term, game-theoretic model of global gas markets with representation of Nash-Cournot market power based on the North American version of the model (Gabriel et al. 2005a,b) eventually extended to a global version (Gabriel et al. 2012). For the United States, the forecasts presented in the Annual Energy Outlook (April 2009 ARRA version) were used. For Europe, the PRIMES model (European Commission 2008) was used which provided consumption and production projections for the EU27. For the rest of the world, the World Energy Outlook (WEO) (IEA 2008) was used. The WGM was then extensively calibrated to match these multiple sources for all countries/aggregated countries and years considered. WGM is capable of analyzing U.S. shale gas availability in addition to conventional natural gas sources (Gabriel et al. 2012).

5.3 Practical Techniques to Reduce the Amount of Fuel-Based Emissions in the Environment

Many emission reduction techniques had been suggested and implemented both in the U.S. and around the world. As such the cap-and-trade programs have been extensively considered. Emissions cap program supporters suggest restrictions on the amount of released emissions, while those inclined to carbon trade also support carbon credit trades. Some prefer to have a flat tax rate on the amount of emissions, while others prefer dynamic application of the tax. For an easier application of such policies as well as for better capturing total emissions, a carbon dioxide equivalent is commonly used to measure the amount of generated emissions. This approach allows carbon taxation, allowances and caps to be applied to polluting sectors more easily. One of the important aspects of optimal carbon policy development is the avoidance of distortions in the market behavior. No matter where carbon policy is used, it is necessary to decide on the carbon price and its impact on the industry, since any policy eventually can be transformed into its equivalent money value and vice-versa. As such, carbon pricing either as a tax or as a price per unit emission is considered an efficient measure for environmental regulation enforcement. Even though carbon pricing is found to be an effective method for some industries, for others, including the natural gas sector, it still had not been thoroughly analyzed. The impact of carbon pricing or taxation might have severe results for some market players while for others there would still be an opportunity to operate and generate profits. Such impact usually depends on many factors including the size of the company, market power, demand levels and resource availability to name a few.

In other terms, the taxation for environmental pollution is known as a negative externality or external costs. The negative impact of such taxation is the overall increased price for the consumer that may lessen the suppliers' profits either by the tax partially being deducted from the profit margin of suppliers or by reducing the demand for goods by changing the consumer preference for a given product (Pigou 1920). This effect is true for any industry. If designed improperly, the environmental tax or more generally "negative externalities" may result in a market failure or relocation of businesses to places where such policies do not apply, which in its turn may lead to job losses. This form of tax is defined as Pigouvian tax in honor of the English economist Pigou, who first analyzed taxation of negative externalities. The impact of emissions taxation as a

Pigouvian tax is discussed in many areas of modern economics and illustrates that if the tax is applied to the amount of emissions generated by a facility/plant then there is an incentive for the producer to cut back on the supply quantities. The graphical representation of the impact of taxation on quantity and price is given in Figure 5-2. Depending on the tax policy or the suppliers' preference the tax may or may not be transferred directly to the consumer in its entirety. For instance the producer may pay a larger portion of the tax if its pre-taxation profits allow for such a move. By taking a large share of the tax without increasing the price, the supplier may keep its market share and still be better off compared to transferring a large portion of the tax to the consumer and limiting its market demand via a higher price. This depends on the elasticity of demand and supply curves. Also, the taxation results to deadweight loss due to shifted supply and demand curves (see Figure 5-2). The deadweight loss is the inefficiency resulting from a tax or monopolistic pricing. The diagram in Figure 5-2 shows the deadweight loss as a triangle caused by a tax. By creating a difference between the before-tax price (P_{bt}) received by producers and the after-tax price (P_{at}) paid by consumers, the triangle of the deadweight loss is formed (the triangle formed from the after tax supply curve, the before tax demand curve and the vertical line corresponding to reduced quantity Q_{at}) when a vertical line corresponding to Q_{at} is drawn from the after tax equilibrium (the intersection point of before tax and the supply curve after tax). From this intersection point when the horizontal line is drawn the new equilibrium price can be found. The government secures the area labeled government revenue. The width of the rectangle for the government revenue is determined by the intersection of the Q_{at} vertical line and the before tax supply curve. This revenue comes at the expense of the consumer surplus and producer surplus that would have existed in the pre-taxation equilibrium. The triangle of the deadweight loss goes to no one. If the tax is applied to a supplier as a percentage of emissions per unit of produced good then there would be an incentive for the supplier to improve technologies.

The effect of a tax incidence explains that depending on the elasticity of demand and/or supply either the consumer or the producer may bear the significant share of tax. It is thought though that in the long run, it is the consumer that is always affected due to taxation mechanisms. In general, when a tax is applied, some portion of the tax is deducted from the consumer surplus (the upper portion of the government revenue rectangle, divided by the before tax equilibrium price horizontal line) and the other portion by the producer surplus (the lower portion of the same rectangle) based on no tax option (P_{bt}). After the tax proportion is deducted by the government, the remaining triangles on the top and on the bottom left sides represent the new surpluses for the consumer and producer (Figure 5-2). Depending on the supply elasticity, the major portion of costs of negative externalities may be transferred from the supplier to the consumer. The opposite is also true, i.e. a larger portion of the tax can be applied to the producer and then be deducted from the producers' revenues (including the producers' surplus area in Figure 5-2). Such an approach is explained by a need to develop a carbon policy that targets multiple goals (Metcalf 2011), including emissions reduction and also satisfaction of market conditions when suppliers are interested in continuous investments, rather than exiting the market.

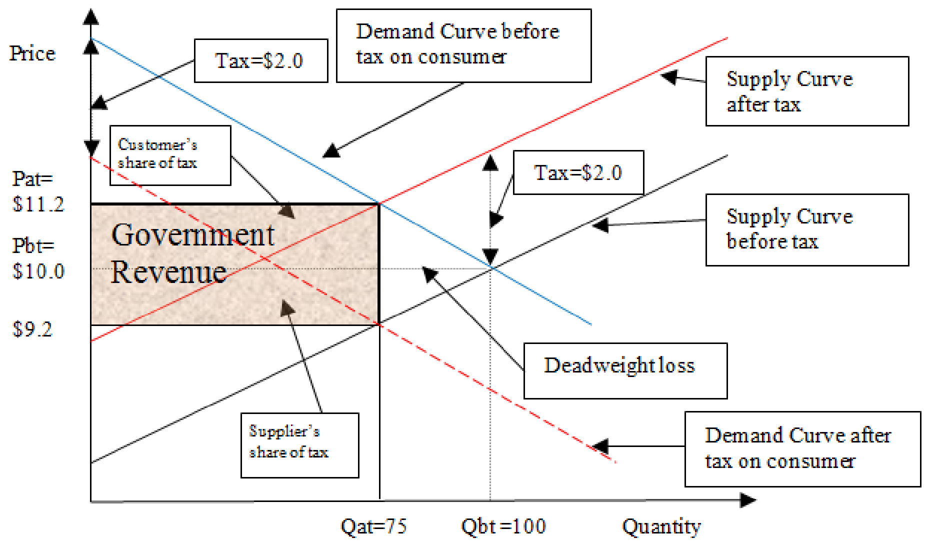

Figure 5-2: Graphical representation of tax application - the impact on demand and price (case of perfect competition)

In the perfect competition the overall tax burden (the area of a rectangle for government revenue) will not be affected by a location change of tax application in the supply chain. The tax paid for a certain quantity of products would be the same if there is no change in the demand (i.e. consumers' may have a non-linear preference for the good depending subject to price change) and supply curve elasticities of the product. If we consider the case where the tax is shifting the demand curve downwards by the amount of tax then we still form the same intersections of lines indicating that the government revenue stays the same. The following numerical example will make this concept clear. Let's assume the before tax demand for gadgets is 100 units (Q_{bt}) and the before tax price is $10.00 ($P_{bt}$). Let's also assume that a $2.00 tax is imposed on gadgets thereby shifting the supply curve to a new after tax price $11.20 ($P_{at}$) and corresponding after tax quantity 75 (Q_{at}). The government revenue will be $150.00. Now if we consider the case where the demand curve is shifted downwards by a $2.00 tax, we notice that same quantity Q_{at}

equals 75 units. This means that the size of the government revenue stays the same and is again equal to $150.00.

This reasoning holds in case of perfect competition, considering a simplified market structure and assumptions for a single firm and a consumer. If we consider a non-parallel shift of the demand or supply curves, and, hence, changes in elasticity, the assumption of the overall tax burden not being affected by a change in the tax payers might no longer hold. It would also be interesting to analyze the resulting changes in welfare, but this is out of the scope of the chapter. The WGM is formulated as a Nash-Cournot market model, and therefore we analyze the effects of taxation on an oligopolistic market.

5.4 Tax Impact on Price under Non-Perfect Competition

Imposition of a tax on a non-perfectly competitive market may have even larger impacts than the actual amount of the tax. A good example is an oligopolistic market, the case of a few suppliers for a homogeneous product. A Nash-Cournot equilibrium model is a simple representation of such market. Nash-Cournot games are based on the original work of Cournot (1838), where the firms compete on quantities. For simplicity, assume two equally positioned firms competing over the quantity of supply in the market. Each firm makes its output decision by assuming that the opponent firm's behavior is fixed. Finding a Nash-Cournot equilibrium is a production level where neither firm desires to deviate from what they are doing. The production levels are built through reaction functions of firms, indicating how one firm reacts on supply quantity changes of the other firm. In Nash-Cournot games, firms may exercise market power by adjusting the quantities of supply (Han and Liu 2011). In a Nash-Cournot model, when the rival firm has already sold a certain quantity, the other firm acts as monopolist (Figure 5-3) for the remaining demand and sets its marginal revenue equal to its marginal cost. The response of a firm to its rival firms is observed through reaction functions. All rival firms in the market will react by the same approach and will get to the equilibrium point for price and quantity from the monopolistic perspective. The equilibrium is reached when firms have no after-the-fact regret for their decisions. Such approach leads to higher prices compared to perfectly competitive markets and less than the price of a monopolistic market.

To maximize profits the monopolist always produces in an elastic region of a demand curve, which is when marginal cost is positive, that is when the elasticity $\varepsilon \epsilon (-\infty;-1]$. Therefore it is able to decrease the quantity and increase the price, and, consequently, increase its profits. This is illustrated in Figure 5-3, which presents the reaction of a firm in a Nash-Cournot game to its rival firm's decision, where the rival firm covers 50 units of the market demand and the demand curve shifts back (left) by 50 units. In this case, the monopolistic approach produces 20 units and the marginal revenue of reduced demand is set equal to marginal costs of $10. In the monopolistic approach, the slope of the marginal revenue curve is twice as large as the slope of the residual demand.

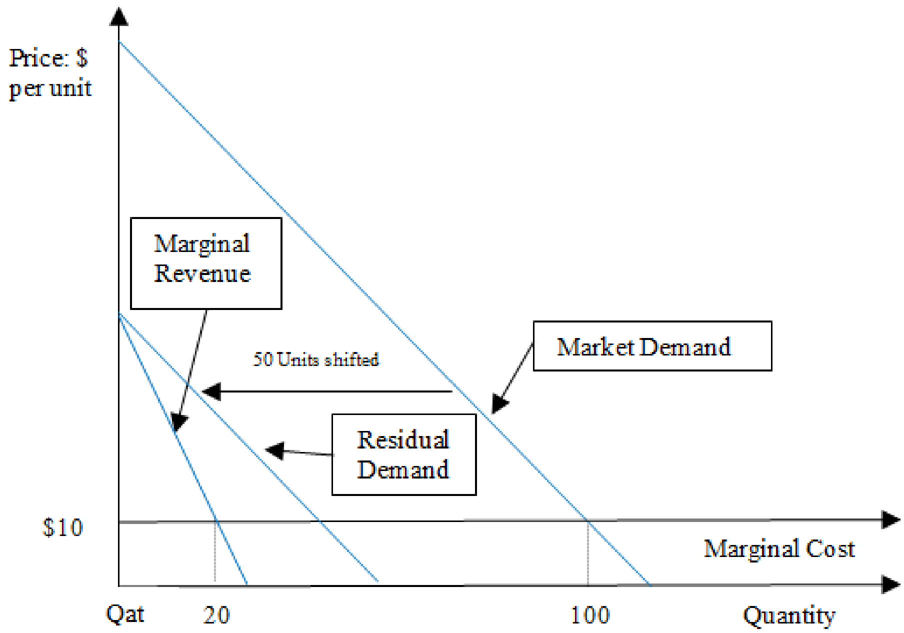

Figure 5-3: Oligopolistic Market – Firm's response to its Rival Firm's decision on supply quantities

In the case of the oligopolistic market, the tax effect will be different compared to it in perfect competition. For instance, addition of one dollar tax on a product price in a non-perfectly competitive market can be larger than the tax margin itself. A simple inverse demand function illustrating the tax incident can be represented as: $p(Q)=Q^{1/\varepsilon}$. The total revenue corresponding to the given function would be $TR(Q)=pQ=Q\times Q^{1/\varepsilon}=Q^{1+1/\varepsilon}$, and from here the marginal revenue $(MR)=(1+1/\varepsilon)\times Q^{1/\varepsilon}$. Suppose that the marginal cost of a product is $MC(Q)=c$, which after the tax becomes $MC(Q)=c+\delta$. By making MR=MC we get $(1+1/\varepsilon)\times Q^{1/\varepsilon}=c+\sigma$ and solving for Q we get $Q=((c+\sigma)/(1+1/\varepsilon))^{\varepsilon}$. We find the corresponding price using the inverse demand function to be $p=(c+\sigma)/(1+1/\varepsilon)$. From this function it is clear that depending on the tax (σ) the impact might be larger or smaller than the value of the tax. To observe the change in the price from change in the tax, we take the derivative of the price with respect to the tax: $dp/d\sigma=1/(1+1/\varepsilon)$. The numerical example makes this statement clearer. If we consider ε

=-2.5, then dp/dσ =1/(1-0.4)=1.667, and, therefore, one dollar tax induces a 1.667 dollar increase in price. In other instances, only a portion of the tax may be transferred to the consumer. Similar observations can be made from the results of scenarios discussed in this research and analyzed by WGM, considering multiple players and countries that eventually achieve equilibrium.

The next section provides the details of the extended WGM formulation.

5.5 Problem and Formulation

We make some assumptions in the original WGM formulation that will allow the analysis of the impact of carbon policies on the natural gas market. This is done by proportionally transferring the direct assignment of a carbon cost from suppliers to consumers. The revised WGM formulation includes changes in the objective functions of the various market agents. The details of the original WGM formulation are described in Gabriel et al. (2012) and the country-node mapping along with KKT conditions of the various players also available in Gabriel et al. (2012) are presented in Appendix 5-A.

5.5.1 The Problem

Policy makers apply carbon taxes, cap and trade programs and emission allowances to limit or reduce the amount of GHG emissions. In most cases, these policies can be expressed in terms of a monetary value per unit of emissions and act as incentives or disincentives for both producers and large energy consumers inducing a switch to cleaner energy sources or improved technologies. As illustrated in Section 5.4, under non-perfect competition the carbon pricing can have significant negative impact on the price and consequently as shown in case studies on some market players. Therefore, there is a need to develop a model that can support proportional assignment of carbon costs, and, hence, allow the development of more desirable carbon policies (either from a consumers' or suppliers' perspective). The existing decision-support models do not provide analysis options for assessing the effectiveness of carbon pricing on the natural gas industry. We allocate carbon emissions to players in WGM based on their shares in the total supply. Specifically, 27% of 0.37 metric tons per thousand cubic meters of natural gas emissions were allocated to production, 12% to processing, 28% to transmission, 24% to distribution, and 9% to storage related pollution of the supply chain players. The emissions from the final consumption of 2.39 metric tons per thousand cubic meters of natural gas were also applied to producers, storage operators and traders as part of the gas supply chain that delivers natural gas to its users through the marketer (EIA 1998; INGAA 2000).

This modification of the standard WGM allows for inclusion of carbon costs per ton corresponding to the desired carbon policy. The approach implemented in this chapter is different from existing techniques by means of assigning carbon costs simultaneously to the suppliers and the consumers in varying proportions depending on the modeler's choice. In contrast to perfectly competitive markets, consideration of the WGM structure as a Nash-Cournot game provides non-intuitive outcomes depending on the given parameters per policy scenario and the equilibrium point. The next section provides the details of formulation and explains what is added to the model to account for carbon emissions.

5.5.2 The Formulation

The formulation presents the details for each player in WGM. The market-clearing conditions are included at the end of the section before the Case Study.

5.5.3 Notation

For consistency with the original formulation of WGM, the terms for carbon emissions and carbon costs used in the extension follow the same structure. For instance, market player indices are the first letters of their full names. For example, $SALES^{X}$ are the total sales of a market agent of type X. Also, $SALES^{X\rightarrow Y}$are the sales of an agent of type X to an agent of type Y and $PURCH^{Y\rightarrow X}$ are the purchases of an agent of type Y from agents of type X. Country nodes are denoted by indices from the set N, and subsets of nodes where a player X is present, by $N(x)$; to denote individual nodes in this set, we write $n(x)$. To denote the subset of agents X present at node n, a $X(n)$ is used; for individual set elements, $x(n)$ was used. Units used in the model are provided in more detail in Appendix 5-A.

In general, the following terms are used: market prices π, inverse demand function $\Pi(\cdot)$, shadow prices of constraints in lower case Greek symbols with superscripts representing the relevant player type (describing the player in the supply side of the market, such as producers, traders, transmission system operators, storage operators and marketers), and subscripts representing the players, nodes, seasons and years (e.g., α_{pdm}^{P}, the dual of the producer ($\cdot^{P}$) capacity constraint for producer p in year m and season d).

The following are the sets used in the original model formulation (Gabriel et al. 2012):

$a \in A$ Gas transportation arcs, e.g., {NNED_GER, LNOR_FRA, RGER_GER}[13]

[13] The first letter indicates the type of arc; combinations of three letters denote the region or country name. NNED_GER represents a pipeline from the Netherlands to Germany; LNOR_FRA is an LNG shipping arc from the Norwegian liquefaction node to the regasification node of France and RGER_GER the arc from

$d \in D$ Demand seasons, e.g., {low, high}

$p \in P$ Producers, e.g., {P_NOR, P_RUW, P_RUE}[14]

$m \in M$ Years, e.g., {2005, 2010, 2015, 2020}

$n \in N$ Model nodes[15], e.g., {N_NOR, N_RUW}

The complete list of notation is provided in Appendix 5-A.

5.5.4 Producer's Problem

The first player in the natural gas supply chain is the producer that extracts the gas (either onshore or off-shore) and after processing makes it available to the trader (i.e. the producer's marketing arm dedicated only to a particular producer). It is assumed that all the production costs are included in the model by the given production function. This is a simplification of reality in which the actual costs may be fairly complicated to compute and may not have desirable mathematical properties such as convexity or differentiability with respect to quantities produced.

The formulation presents a discounted profit maximization problem for the producer p, where profits are represented as the difference between sales $SALES^{P}_{pdm}$ and production and investment costs. Cash flows in year m are discounted by a factor of γ_m. Since sale rates are per day and may differ by season, those are multiplied by the number of days in the season d. Also, $days_d$. cc^{ton}_{pm} denotes the carbon cost per ton of CO_2e for

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the German regasification node to the German country node. NNIG_LNG denotes the arc from the country node Nigeria to the Nigerian liquefaction node.

[14] Indicating the producers in Norway, Russia West and East and in other countries

[15] Model nodes represent geographical regions in the world (see Appendix 5-A). They can be defined flexibly in the model data set. Due to the limited relevance and impact of countries that only produce and consume small amounts, several countries have been grouped with neighboring ones and are represented in the model data set on an aggregate level. For some countries the opposite is true: their consumption or production is so high, and the geographical distances so large, that a division of the countries in several regions is warranted.

the producer p in year m. The factor CE^P is the carbon emissions factor associated with the production process per unit of natural gas. The superscript of this factor changes for other players in the supply chain (i.e. for traders or storage operators). To account for the proportional application of carbon costs along the supply chain, the term Ω is included as the weight per node. Here Ω is a value in [0, 1].

The objective function of the producer's problem, with carbon costs applied to both the supply side and the consumer side is:

$$\max_{SALES^P_{pdm}}$$

$$\sum_{m\in M} \gamma_m \left\{ \sum_{d\in D} days_d \left[\left(\pi^P_{n(p)dm} + \Omega_{pm} \cdot cc^{ton}_{pm} \cdot CE^P \right) SALES^P_{pdm} - c^P_{pm}\left(SALES^P_{pdm}\right) - \left(1-\Omega_{pm}\right) cc^{ton}_{pm} \cdot SALES^P_{pdm} \cdot CE^P \right] \right\} \qquad (5-1)$$

In this function, the price $\pi^P_{n(p)dm}$ is multiplied by the $SALES^P_{pdm}$ and summed up over days. Similarly, the costs $c^P_{pm}\left(SALES^P_{pdm}\right)$ are deducted from revenues, where the difference is the profit that is being maximized. The new added terms for carbon costs are $\Omega_{pm} \cdot cc^{ton}_{pm} \cdot CE^P$ which represents the proportion of carbon cost being assigned to the consumer. Here the term cc^{ton}_{pm} is multiplied by CE^P the carbon emissions factor CE^P. When these terms are multiplied by the amount of sales, we get the cost of carbon corresponding to the traded amount of gas. When the carbon cost is transferred to the producer and deducted from its revenues, the term $(1-\Omega_{pm})$ is used together with $cc^{ton}_{pm} \cdot SALES^P_{pdm} \cdot CE^P$ and then is subtracted from the revenues. Finally, we find the total discounted profits by multiplying all terms by the number of days per high and low seasons, and sum over time periods.

Before the modification, the objective function for the producer's problem without consideration of carbon costs in WGM was given as:

$$\max_{SALES^P_{pdm}}$$

$$\sum_{m\in M}\gamma_m\{\sum_{d\in D} days_d[(\pi^P_{n(p)dm})SALES^P_{pdm} - c^P_{pm}(SALES^P_{pdm})]\} \quad (5-1')$$

The producers' and other players' constraints were not modified, but are shown for completeness.

The sales are restricted to the maximum production capacity $\overline{PR}^P_{pm}$, which can vary over time:

$$s.t. \quad SALES^P_{pdm} \le \overline{PR}^P_{pm} \quad \forall d,m \quad \left(\alpha^{PR}_{pdm}\right) \quad (5\text{-}2)$$

Due to reserve limitations and regulatory requirements, the total production of natural gas in a considered time period is limited to the production ceiling $\overline{PH}_p$.

$$\sum_{m\in M}\sum_{d\in D} days_d SALES^P_{pdm} \le \overline{PH}_p \quad \forall m \quad \left(\alpha^{PH}_p\right) \quad (5\text{-}3)$$

Lastly, sales must be nonnegative:

$$SALES^P_{pdm} \ge 0 \quad \forall d,m \quad (5\text{-}4)$$

5.5.5 Trader's Problem

The trader buys gas from its producer, and resells it to its marketer through the transmission system, which eventually delivers natural gas to the final user or consumer. In WGM, carbon costs related to the transmission of traded natural gas (through transmission system) are partially applied to the trader's problem, since the transmission system operator is modeled using arcs in between nodes. This excludes application of country or region specific carbon costs to that player. The other portion of the transmission system related emissions is applied to the storage operator.

Profit maximization of the trader is based on the amount of gas sold to marketers ($SALES^{T}_{tndm}$), gas purchasing costs and the costs that represent regulated transmission fees $\tau^{A,reg}_{adm}$ plus a congestion fee τ^{A}_{adm}, to transport the gas ($FLOW^{T}_{tadm}$) (which is the amount of gas flowing between the origin and destination linked by arc *a*) over high pressure pipelines and LNG vessels. The parameter $\delta^{C}_{tn} \in [0,1]$ represents the market power of the trader and is exerted at a consumption node, with 0 representing perfectly competitive behavior and 1 representing perfect Nash-Cournot oligopolistic behavior. Values between 0 and 1 indicate that some market power is exerted by the trader, but diluted relative to Cournot competition. The expression $(\delta^{C}_{tn}\Pi^{W}_{ndm}(\cdot) + (1 - \delta^{C}_{tn})\pi^{W}_{ndm})$ is a weighted combination of market prices resulting from the inverse demand function $\Pi^{W}_{ndm}(\cdot)$ and a perfectly competitive market-clearing wholesale price π^{W}_{ndm}. The price term $(\delta^{C}_{tn}\Pi^{W}_{ndm}(\cdot) + (1 - \delta^{C}_{tn})\pi^{W}_{ndm})$ in the trader's problem gets affected due to the inclusion of the carbon cost term $(\Omega_{tm} \cdot cc^{ton}_{tm} \cdot CE^{T} + \Omega_{pm} \cdot cc^{ton}_{pm} \cdot CE^{P} + \Omega_{sm}(cc^{ton}_{sm} \cdot CE^{SI} + cc^{ton}_{sm} \cdot CE^{SX}))$ in the market-clearing conditions presented at the end of the formulation section. Here, the additional portion of carbon terms is transferred to the consumer as the total price per unit of traded natural gas. The trader also decides how much gas to inject (INJ^{T}_{tndm}) and extract (XTR^{T}_{tndm}) from storage and therefore, acts as a player interacting with all other players. The injection costs represent the sum of the regulated fee and congestion rate ($\tau^{SI,reg}_{sndm} + \tau^{SI}_{sndm}$)while the extraction costs are represented only by the congestion rate (τ^{SX}_{sndm}). Thus, trader *t* will have the following objective function:

$$\max_{SALES^{T}_{tndm}, PURCH^{T}_{tndm}, INJ^{T}_{tndm}, XTR^{T}_{tndm}, FLOW^{T}_{tadm}}$$

$$\sum_{m\in M}\gamma_m \sum_{p\in P}\sum_{d\in D} days_d \left\{ \sum_{n\in N(t)} [(\delta^{C}_{tn}\Pi^{W}_{ndm}(\cdot) + (1-\delta^{C}_{tn})\pi^{W}_{ndm})SALES^{T}_{tndm} \right.$$

$$- \left(\pi^{P}_{ndm} + \Omega_{pm}\cdot cc^{ton}_{pm}\cdot CE^{P}\right)PURCH^{T}_{tndm}$$

$$- \sum_{s\in S(t)} \left(\left(\tau^{SI,reg}_{sndm} + \tau^{SI}_{sndm} + \Omega_{sm}\cdot cc^{ton}_{sm}\cdot CE^{SI}\right)INJ^{T}_{tndm}\right.$$

$$\left. + (\tau^{SX}_{sndm} + \Omega_{sm}\cdot cc^{ton}_{sm}\cdot CE^{SX})XTR^{T}_{tndm}\right) - (1-\Omega_{tm})$$

$$\cdot cc^{ton}_{tm} SALES^{T}_{tndm}\cdot CE^{T}]$$

$$\left. - \left(\sum_{a\in A(t)} \left(\tau^{A,reg}_{adm} + \tau^{A}_{adm}\right) FLOW^{T}_{tadm}\right)\right\} \qquad (5-5)$$

Before this extension, the objective function of the trader's problem was given as:

$$\max_{SALES^T_{tndm},\,PURCH^T_{tndm},\,INJ^T_{tndm},\,XTR^T_{tndm},\,FLOW^T_{tadm}}$$

$$\sum_{m\in M}\gamma_m\sum_{d\in D}days_d\Bigg\{\sum_{n\in N(t)}[(\delta^C_{tn}\Pi^W_{ndm}(\cdot)+(1-\delta^C_{tn})\pi^W_{ndm})SALES^T_{tndm}$$

$$-(\pi^P_{ndm})PURCH^T_{tndm}$$

$$-\sum_{s\in S(t)}\Big((\tau^{SI,reg}_{sndm}+\tau^{SI}_{sndm})INJ^T_{tndm}+(\tau^{SX}_{sndm})XTR^T_{tndm}\Big)]$$

$$-\left(\sum_{a\in A(t)}\left(\tau^{A,reg}_{adm}+\tau^{A}_{adm}\right)FLOW^T_{tadm}\right)\Bigg\} \qquad (5-5')$$

Constraints of the trader's problem are from Gabriel et al. (2012). More specifically, traders need to preserve the mass balance at every node *n* in every season *d* of every year *m*:[16]

$$s.t.\quad \begin{aligned}&PURCH^T_{tndm}+\sum_{a\in a^+(n)}\left(1-loss_a\right)FLOW^T_{tadm}+XTR^T_{tndm}=\\ &SALES^T_{tndm}+\sum_{a\in a^-(n)}FLOW^T_{tadm}+INJ^T_{tndm}\quad \forall n,d,m\ \left(\varphi^T_{tndm}\right)\end{aligned} \qquad (5\text{-}6)$$

In each annual storage cycle, the total extracted volumes must equal the loss-corrected injection volumes:

$$\left(1-loss_s\right)\sum_{d\in D}days_d INJ^T_{tsdm}=\sum_{d\in D}days_d XTR^T_{tsdm}\quad \forall n,s\in S\left(N\left(t\right)\right),d,m\ \left(\varphi^S_{tsdm}\right) \qquad (5\text{-}7)$$

Traders must meet contractual obligations, (CON^T_{tndm}) modeled as follows:

[16] Pipeline losses are accounted for in this mass-balance equation; in contrast, the storage loss-rate is accounted for in the storage-cycle constraint, equation (5-7).

$$FLOW_{tadm}^{T} \geq CON_{tadm}^{T} \quad \forall a,d,m \quad \left(\varepsilon_{tadm}^{T}\right) \tag{5-8}$$

Lastly, all variables are nonnegative:

$$SALES_{tndm}^{T} \geq 0 \quad \forall n,d,m \tag{5-9}$$

$$PURCH_{tndm}^{T} \geq 0 \quad \forall n,d,m \tag{5-10}$$

$$FLOW_{tadm}^{T} \geq 0 \quad \forall a,d,m \tag{5-11}$$

$$INJ_{tndm}^{T} \geq 0 \quad \forall n,d,m \tag{5-12}$$

$$XTR_{tndm}^{T} \geq 0 \quad \forall n,d,m \tag{5-13}$$

Note: the inverse demand curve $\Pi_{ndm}^{W}(\cdot)$ is presented later.

The next section describes the transmission system operator, who is responsible for assigning available capacities to the traders needing transport capacity for exporting gas, and for expansions of the international transportation capacities. The international high pressure pipelines as well as the various steps of the LNG supply chain are represented as arcs with appropriate costs, losses and capacities. The underlying assumption is that all transportation infrastructure agents are price-taking players.

5.5.6 Transmission System Operator's Problem

The transmission system is formulated as a set of connections (arcs) between nodes representing countries or regions, which make it impossible to apply carbon costs specific to a country or region to the TSO. This obstacle could have been avoided if the TSO's problem was reformulated using nodes. In fact, the initial formulation of WGM used nodes for TSO's problem formulation, but due to computational efficiencies it was reformulated using arcs. To account for effects of emissions related to the transmission system, the emission quantities were proportionally added to the trader and the storage system operator.

The TSO provides an economic mechanism to efficiently allocate international transport capacity to traders. It maximizes the discounted profit resulting from selling arc capacity to traders ($SALES^A_{adm}$) minus investment costs for capacity expansions (Δ^A_{am}). Regulators base the maximum infrastructure usage charges (*regulated fees*) on the long-term marginal costs, which are the operating and maintenance costs plus a margin to earn a return on investment. In the WGM, a simplified assumption is made that the regulated fees collected from the traders equal the costs; therefore the profit margin is equal to the congestion fee (τ^A_{adm}). Note that these congestion fees are not paid in actuality, but merely facilitate the efficient allocation of a scarce capacity in the model. The following is the objective function for the TSO followed by the set of constraints as given in Gabriel et al. (2012).

$$\max_{\substack{SALES^A_{adm} \\ \Delta^A_{am}}} \quad \sum_{m \in M} \gamma_m \left\{ \sum_{d \in D} days_d \sum_a \tau^A_{adm} SALES^A_{adm} - \sum_a b^A_{am} \Delta^A_{am} \right\} \tag{5-14}$$

The assigned capacity is restricted by the available capacity. Available arc capacity at arc a is the sum of the initial arc capacity ($\overline{CAP}^A_{am}$) and capacity expansions in the previous years ($m' < m$) ($\sum_{m'<m} \Delta^A_{am'}$).

$$SALES^A_{adm} \leq \overline{CAP}^A_{am} + \sum_{m'<m} \Delta^A_{am'} \quad \forall a,d,m \quad \left(\alpha^A_{adm}\right) \tag{5-15}$$

There may be budgetary or other limits to the yearly capacity expansions:

$$\Delta^{A}_{am} \le \overline{\Delta}^{A}_{am} \quad \forall a,m \qquad \left(\rho^{A}_{am}\right) \tag{5-16}$$

Lastly, all variables are nonnegative:

$$SALES^{A}_{adm} \ge 0 \tag{5-17}$$

$$\Delta^{A}_{am} \ge 0 \tag{5-18}$$

The storage operator problem is presented next, which in comparison to other players has carbon emissions associated with two stages of operation, namely injection and extraction.

5.5.7 Storage Operator's Problem

The storage operator maximizes the discounted profit resulting from selling injection capacity ($SALES^{SI}_{sdm}$) and extraction volumes ($SALES^{SX}_{sdm}$) to traders. In equilibrium, the rates for ($SALES^{SI}_{sdm}$) and ($SALES^{SX}_{sdm}$) must be equal to the aggregate injection and extraction rates (loses are captured as described in constraints (5-6) and (5-7) in the trader's problem and in footnote 4). Similarly to the TSOs' problem, a starting point that the regulator or a private company sets is selected as a maximum capacity usage fee based on the long-term marginal costs. Depending on the country the capacity usage fee can be assigned either by the regulator, where the system belongs to the regulator as government or a private company. This simplified assumption is due to the fact that the regulated fees collected from the traders equal the operating costs, and, therefore, in the model the profit margin is equal to the congestion fees for injection (τ^{SI}_{sdm}) and extraction (τ^{SX}_{sdm}). Besides the regulated tariffs for injection and extraction, costs may be accrued to expand capacities for injection, extraction and total working gas: $(b_{sm}^{SI}\Delta_{sm}^{SI} + b_{sm}^{SX}\Delta_{sm}^{SX} + b_{sm}^{SW}\Delta_{sm}^{SW})$, where ("$b$") as in other player's problems is the corresponding capacity expansion costs in units of thousand dollars per million cubic meters.

During the injection and extraction processes of natural gas into and out of storage some technological stages and flaring result into a certain amount of emissions per unit of processed gas. To capture the economic effect of these emissions in the Storage Operator's problem the terms $(\Omega_{sm} \cdot cc_{sm}^{ton} \cdot CE^{SI})$ for injection and $(\Omega_{sm} \cdot cc_{sm}^{ton} \cdot CE^{SX})$ for extraction related processes were added to the objective function. The values related to carbon emission terms are discussed in Section 5.1 and also can be found in EIA (1998) and INGAA (2000). Similar to the other players' problems here again the carbon cost is added proportionally to the price or subtracted from the revenues of the storage operator. When applying carbon costs only the emissions corresponding to the sold amount of gas is considered. The effects of emissions from gas storage in low season are considered in the next extraction in the high season following the low season extraction.

$$\max_{SALES_{sdm}^{SI}, SALES_{sdm}^{SX}, \Delta_{sm}^{SI}, \Delta_{sm}^{SX}, \Delta_{sm}^{SW}} \sum_{m \in M} \gamma_m \sum_{d \in D} days_d \Big\{ \Big((\tau_{sdm}^{SI}) SALES_{sdm}^{SI} + (\tau_{sdm}^{SX} + \Omega_{sm} \cdot cc_{sm}^{ton}(CE^{SI} + CE^{SX})) SALES_{sdm}^{SX} \Big) - b_{sm}^{SI}\Delta_{sm}^{SI} - b_{sm}^{SX}\Delta_{sm}^{SX} - b_{sm}^{SW}\Delta_{sm}^{SW} - (1 - \Omega_{sm})(cc_{sm}^{ton}(CE^{SI} + CE^{SX})) SALES_{sdm}^{SX} \Big\} \qquad (5-19)$$

Before modification the Storage Operator's objective function was given as in (5-19'):

$$\max_{SALES^{SI}_{sdm}, SALES^{SX}_{sdm}, \Delta^{SI}_{sm}, \Delta^{SX}_{sm}, \Delta^{SW}_{sm}}$$

$$\sum_{m\in M}\gamma_m \sum_{d\in D} days_d \left\{\left((\tau^{SI}_{sdm})SALES^{SI}_{sdm} + (\tau^{SX}_{sdm})SALES^{SX}_{sdm}\right) - b^{SI}_{sm}\Delta^{SI}_{sm} - b^{SX}_{sm}\Delta^{SX}_{sm} - b^{SW}_{sm}\Delta^{SW}_{sm}\right\} \quad (5-19')$$

Constraints of the storage operator's problem are provided below without any change from the original formulation of WGM (Gabriel et al. 2012). The injection rate in any season is restricted by the injection capacity given as in (5-20). Injection capacities can be expanded; therefore the overall previous yearly expansions ($\sum_{m'<m}\Delta^{SI}_{sm'}$) must be added to the initial capacity ($\overline{INJ}^{S}_{s}$) to determine the total capacity. Equation (5-21) provides the limits to extraction from storage and condition (5-22) represents the working gas limitations.

For example,

$$SALES^{SI}_{sdm} \le \overline{CAP}^{SI}_{s} + \sum_{m'<m}\Delta^{SI}_{sm'} \quad \forall m,d \quad \left(\alpha^{SI}_{sdm}\right) \quad (5\text{-}20)$$

$$SALES^{SX}_{sdm} \le \overline{CAP}^{SX}_{s} + \sum_{m'<m}\Delta^{SX}_{sm'} \quad \forall m,d \quad \left(\alpha^{SX}_{sdm}\right) \quad (5\text{-}21)$$

$$\sum_{d\in D} days_d SALES^{SX}_{sdm} \le \overline{WG}^{S}_{s} + \sum_{m'<m}\Delta^{SW}_{sm'} \quad \forall m \quad \left(\alpha^{SW}_{sm}\right) \quad (5\text{-}22)$$

The limitations to capacity expansions are modeled as the following:

$$\Delta^{SI}_{sm} \le \bar{\Delta}^{SI}_{sm} \quad \forall m \quad \left(\rho^{SI}_{sm}\right) \quad (5\text{-}23)$$

$$\Delta^{SX}_{sm} \le \bar{\Delta}^{SX}_{sm} \quad \forall m \quad \left(\rho^{SX}_{sm}\right) \quad (5\text{-}24)$$

$$\Delta_{sm}^{SW} \leq \overline{\Delta}_{sm}^{SW} \quad \forall m \quad \left(\rho_{sm}^{SW}\right) \tag{5-25}$$

Since there are losses in storage facilities similar to transmission processes, the mass balance for each storage facility (the *storage cycle* constraint) considers losses which are dealt with equation (5-7).

Similar to other players' problems here also all variables are nonnegative:

$$SALES_{sdm}^{SI} \geq 0 \quad \forall m, d \tag{5-26}$$

$$SALES_{sdm}^{SX} \geq 0 \quad \forall m, d \tag{5-27}$$

$$\Delta_{sm}^{SI} \geq 0 \quad \forall m \tag{5-28}$$

$$\Delta_{sm}^{SX} \geq 0 \quad \forall m \tag{5-29}$$

$$\Delta_{sm}^{SW} \geq 0 \quad \forall m \tag{5-30}$$

5.5.8 Marketer's Problem

The last participant in of the natural gas supply chain in the WGM is the marketer. The marketer is responsible for delivery of natural gas to consumers. It buys natural gas from traders and sells it to all consumers in various sectors. The main sectors included in WGM are industrial, residential and commercial users. Since the purpose of WGM was not to analyze the marketers' interaction with each user in detail for each country the marketer's problem is not formulated as a profit-maximizing player. This also helped in computational efficiency of the WGM due to decreased number of variables, because in contrast to optimization problems the consumption is represented as an inverse demand curve. To allow the effect of carbon costs to be transferred to the Trader's problem as part of the equilibrium price the inverse demand function is given as:

$$(\Pi^{W}_{ndm}(\cdot) =)\pi^{W}_{ndm}$$

$$= INT^{W}_{ndm} + SLP^{W}_{ndm} \cdot \sum_{t} SALES^{T}_{tndm}$$

$$+ \left(\sum_{p} (\Omega_{pm} \cdot cc^{ton}_{pm} \cdot CE^{P}) + \sum_{t} \Omega_{tm} \cdot cc^{ton}_{tm} \cdot CE^{T} \right.$$

$$\left. + \sum_{s} \Omega_{sm} (cc^{ton}_{sm} \cdot CE^{SI} + cc^{ton}_{sm} \cdot CE^{SX}) \right) \quad \forall n, d, m \; (\pi^{W}_{ndm}) \quad (5-31)$$

In the marketers problem π^{W}_{ndm} is the price that appears in the Trader's problem to maximize profits. To make sure that from proportional allocation of carbon costs the share of other players is not deducted from the Trader's profits (when the cost is applied to the consumers) the final transfer of the cost to the consumer is achieved through (5-31). In this function the carbon costs from producers, traders and storage operators along with the corresponding Ω values representing the carbon costs are added to the price.

As in the case of the other players, the original form of market-clearing condition is also presented and was given as (5-31')

$$(\Pi^{W}_{ndm}(\cdot) =)\pi^{W}_{ndm}$$

$$= INT^{W}_{ndm} + SLP^{W}_{ndm} \cdot \sum_{t} SALES^{T}_{tndm} \qquad \forall n, d, m \; (\pi^{W}_{ndm}) \qquad (5-31')$$

The following are the market-clearing conditions. These conditions for all gas markets under consideration are not changed from the original formulation given in Gabriel et al. (2012) other than the market-clearing conditions for the marketer, which supplies price information to the trader and therefore includes additions of carbon costs from all players.

Market-clearing between producers and traders:

$$SALES^{P}_{pdm} = \sum_{t(p)} PURCH^{T}_{tn(p)dm} \quad \forall p,d,m \quad \left(\pi^{P}_{n(p)dm}\right) \tag{5-32}$$

Market-clearing for storage injection capacity and volumes:

$$SALES^{SI}_{sdm} = \sum_{t \in T(N(s))} INJ^{T}_{tsdm} \quad \forall s,d,m \quad \left(\tau^{SI}_{sdm}\right) \tag{5-33}$$

Market-clearing for storage extraction capacity and volumes:

$$SALES^{SX}_{sdm} = \sum_{t \in T(N(s))} XTR^{T}_{tsdm} \quad \forall s,d,m \quad \left(\tau^{SX}_{sdm}\right) \tag{5-34}$$

Market-clearing between the TSO and the traders for arc capacity and flows:

$$SALES^{A}_{adm} = \sum_{t} FLOW^{T}_{tadm} \quad \forall a,d,m \quad \left(\tau^{A}_{adm}\right) \tag{5-35}$$

The next section presents the case study analyzed to assess the impact of carbon policies when applied to suppliers and on consumers proportionally.

5.6 Study Design

The extended model, particularly the modification of the objective functions of the players and the market-clearing conditions of the marketer in equations (5-1), (5-5), (5-19), (5-31) permits the evaluation of the impact of carbon policies. This is due by proportionally applying the carbon cost along the supply chain as a flat rate not responsive to quantity changes in the amount of traded natural gas. The applied approach for inclusion of carbon costs directly into the model formulation rather than the adjustment of inverse demand curves in response to tax addition is found to be more accurate. This is even more important for the game-theoretic structure of the model where the addition of the carbon tax may or may not affect the equilibrium price of the traded natural gas, and therefore make the adjustment even more difficult. The adjustment of the inverse demand curve parameters would not be practical for each policy scenario since the impact on the natural gas market had not been analyzed in other studies and therefore reference factors for inverse demand curve adjustment might not be readily available. The approach applied in this chapter is also considered to be more practical since the original formulation of WGM already has a well calibrated inverse demand function parameters to represent the global natural gas market. Since for any decision-maker it is important to evaluate the impact of proposed policies compared to the reference state of the market the given formulation allows a proportional addition of emissions tax on players in the WGM by country/region and by specific time periods.

5.6.1 Hypotheses

The natural gas market may change its behavior due to many external factors. Carbon emission restricting regulations are thought to be one of those factors. Until now the impact of such policies on the natural gas market is not exactly clear as discussed in Section 5.1. As a result of the case study we will try to answer the following question:

- Does a carbon tax have the same economic effect depending on where it is applied in the natural gas supply chain?

The following study consists of using and evaluating two carbon policy scenarios conducted as part of the LinkS (CIER, 2012) project in that used the Global Change Assessment Model (GCAM), a multi-industry general equilibrium model developed by the Joint Global Change Research Institute (GCAM 2012). The set of cases in this study consist of Base Case, 650ppm Case, and 20-20-20 Case. 650ppm and 20-20-20 Cases have specific requirements for carbon emissions concentration in the atmosphere and accordingly suggest application of different carbon costs per country/region and per time period compared to Base Case where no carbon cost is considered.

5.6.2 Base Case (named as 650ppm-0CO_2 and 20-20-20-0CO_2)

The Base Case represents the natural gas market without inclusion of carbon costs. The WGM as given in Gabriel et al. (2012) is calibrated according to the databases presented in Table 5-1.

Table 5-1. Assumptions for Base Case

Summary Case Assumptions						
Case	Consumption North America	Production North America	Consumption Rest of the World	Production Rest of the World	Alaska Pipeline	AK LNG Export Terminal
Base	AEO 2009 April ARRA Update		EC Trends IEA WEO 2008		Option 2020	Phase Out 2015

The inclusion of this case allows comparison of effects from suggested natural gas-related carbon policies.

5.6.3 650ppm Case

The 650ppm Case differs from the Base Case *(named as 650ppm-0CO_2)* by inclusion of carbon policy requirements. The requirement of this policy assumes a limitation of pollution levels in the atmosphere to 650 parts per million (650 ppm) by 2095, which is considered as a relaxed requirement compared to more aggressive policies such as the European 20-20-20 Case. The corresponding carbon costs for this case are obtained from the LinkS project from resulting GCAM runs (Table 5-2) and used as input data.

Table 5-2. Costs of Carbon Dioxide Equivalents per metric ton in U.S. Dollars (2005) for 650ppm

Region	Considered Time Periods											
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Africa	-	-	-	-	-	-	-	-	-	14.12	35.70	64.75
Australia/NZ	-	-	7.54	10.22	12.91	15.60	21.22	26.84	32.46	44.12	55.79	67.45
Canada	-	-	7.54	10.22	12.91	15.60	21.22	26.84	32.46	44.12	55.79	67.45
China	-	-	-	-	-	10.76	16.97	24.15	32.46	44.12	55.79	67.45
Eastern Europe	-	-	7.54	10.22	12.91	15.60	21.22	26.84	32.46	44.12	55.79	67.45
Former Soviet Union	-	-	-	-	-	10.76	16.97	24.15	32.46	44.12	55.79	67.45
India	-	-	-	-	-	10.76	16.97	24.15	32.46	44.12	55.79	67.45
Japan	-	-	7.54	10.22	12.91	15.60	21.22	26.84	32.46	44.12	55.79	67.45
Korea	-	-	-	-	-	-	-	-	-	14.12	35.70	64.75
Latin America	-	-	-	-	-	10.76	16.97	24.15	32.46	44.12	55.79	67.45
Middle East	-	-	-	-	-	-	-	-	-	14.12	35.70	64.75
Southeast Asia	-	-	-	-	-	-	-	-	-	14.12	35.70	64.75
USA	-	-	7.54	10.22	12.91	15.60	21.22	26.84	32.46	44.12	55.79	67.45
Western Europe	-	-	7.54	10.22	12.91	15.60	21.22	26.84	32.46	44.12	55.79	67.45

The data in Table 5-2 are comparably low from carbon costs proposed for the stricter 20-20-20 Case. Nevertheless the costs in Table 5-2 come on-line earlier than the 20-20-20 Case and hence provide interesting economic insights described in the numerical results and analyses section. Also, it should be noted that the carbon prices for the last time periods under the 650 ppm Case become more consistent over the different regions in the world.

5.6.4 The 20-20-20 Case

Similar to 650ppm Case, the 20-20-20 case differs from the Base Case (named as *20-20-20-0*CO_2) by enforcement of carbon costs which were obtained again from GCAM output (LinkS project). This case includes the European Climate Policy that requires Europe to achieve a 20% carbon emissions reduction by 2020 below 1990 levels, 20% energy efficiency, 20% renewable energy supply and 10% of transportation energy efficiency by 2020. What is new versus the conventional 20-20-20 policy is that in the LinkS project, this policy is extended to the rest of the world and not just Europe (the conventional case). The conventional case was designed as model for the rest of the world showing that such emissions reductions are possible. In this 20-20-20 Case scenario, the requirements are much stricter. This policy is designed to limit the global warming temperature to 2°C compared to pre-industrial levels. The expansion of this policy assumes that 80 to 95% of developed countries should participate in implementing this policy for reaching the overall goal. The Table 5-3 presents the detailed requirements for the 20-20-20 policy scenario for various countries/regions by certain time periods. The carbon cost values for 20-20-20 policy case are presented in Table 5-4.

Table 5-3. The timing of implementation of the 20-20-20 policy in different countries

Policy 20-20-20	2020	2035	2050
E. Europe W. Europe	GHG (20%) EE (20%) RES (20%) TE (10%)	GHG (50%) EE (50%) RES (50%) TE (25%)	GHG (80%) EE (80%) RES (80%) TE (50%)
Australia/NZ Canada China Japan USA	-//-	GHG (20%) EE (20%) RES (20%) TE (10%)	GHG (50%) EE (50%) RES (50%) TE (25%)
Former Soviet Union India L. America	-//-	-//-	GHG (20%) EE (20%) RES (20%) TE (10%)
Africa Mid. East Korea S.E. Asia	-//-	-//-	-//-

*-//- Indicates no policy comes on-line at given year

In particular, Table 5-3 presents the emissions reduction and technological improvement targets by country/region applied to GCAM to generate the data for carbon costs given in Table 5-4. Specifically, the policy goals are first applied to Western and Eastern Europe where 20% reduction of greenhouse gas emissions, 20% of energy efficiency improvement, 20% share of supply by renewables in total energy demand and 10% of transport efficiency is expected by 2020. For the next two 15-year time intervals, further stricter requirements are enforced. The other countries/regions of the world become participants in this policy later in the time horizon, but some others including part of the developing world does not face any carbon emission related restrictions until after 2050.

Table 5-4. Costs of Carbon Dioxide Equivalents per metric ton in U.S. Dollars (2005) for 20-20-20

Region	Considered Time Periods											
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Africa	-	-	-	-	-	-	-	-	-	-	-	64.20
Australia/NZ	-	-	-	-	-	68.94	74.50	77.32	90.91	105.57	127.83	171.20
Canada	-	-	-	-	-	67.45	59.64	51.83	50.24	52.78	66.95	104.58
China	-	-	-	-	-	55.56	65.42	68.09	66.91	67.37	67.09	64.95
Eastern Europe	-	-	50.49	60.52	65.81	65.31	63.10	58.44	50.39	43.46	40.93	51.90
Former Soviet Union	-	-	-	-	-	-	-	-	22.08	22.71	26.39	32.25
India	-	-	-	-	-	-	-	-	113.67	103.19	91.06	83.39
Japan*	-	-	-	-	-	1.08	-	-	0.55	-	6.19	1.66
Korea	-	-	-	-	-	-	-	-	-	-	-	5.57
Latin America	-	-	-	-	-	-	-	-	90.83	98.47	103.46	139.66
Middle East	-	-	-	-	-	-	-	-	-	-	-	53.74
Southeast Asia	-	-	-	-	-	-	-	-	-	-	-	61.67
USA	-	-	-	-	-	39.84	44.27	45.33	42.79	45.11	50.37	78.46
Western Europe	-	-	43.45	52.53	57.93	59.35	61.30	60.20	51.01	50.06	47.11	43.99

* The fluctuating carbon costs for Japan from zero to non-zero values until 2055 is explained due to reached equilibrium in GCAM as a necessity.

In Table 5-4 for regions that does not have any carbon requirement by 2050 the carbon costs start from 2060. The effect from this last-term costs is not analyzed with WGM since it reports results in five year increments and only until 2050 (but considers time periods until 2060), due to the end of the time horizon effect when the results from the last two periods (2055 and 2060) are dropped.

For each country/region in the considered scenarios where the carbon cost is applicable, a set of weights had been used for a range analysis to compare the impact of proportional assignment of carbon costs on market behavior. Weights changed from 0 to 1 in 0.1 increments indicating switching of carbon costs from suppliers to consumers. The next section presents the findings of this study.

5.7 Numerical Results and Analyses

5.7.1 Overview

This section presents the results of the case study. In particular, we show that the carbon cost policy implementation may significantly affect the equilibrium prices and quantities in the natural gas market depending on where it is applied in the natural gas supply chain. Changes in the average wholesale prices together with production and consumption levels due to a shifted equilibrium become more noticeable when the carbon costs from carbon policies get relatively high. The proportional assignment of carbon costs is found to be helpful for designing better policies depending on whether it is from suppliers' or consumers' perspective. If the tax can be applied equally to the supply chain, prices remain relatively unchanged. This fact was observed for the U.S., Germany and Russia. The reason these three countries were picked was to compare the carbon policy effects across the different market structures. The U.S. in the WGM is a perfectly competitive market that is self-sufficient. Germany has relatively little of its own supply of natural gas and has a mixture of perfectly and imperfectly competitive suppliers. Lastly, Russia represents a supply-rich producer with significant market power. Some non-intuitive changes also occur in regions where the carbon policy was not adopted by the time considered for comparison. In fact, it is found that the early adopters of carbon policies may not be the most adversely affected regions.

5.7.2 Scientific Hypotheses

The hypothesis testing is addressed in detail in the next subsections.

5.7.3 Does a carbon tax have the same economic effect depending on where it is applied in the natural gas supply chain?

From economic theory (Osborn 1997) it is known that depending on the market structure the impact of taxation may be either easy or difficult to answer. Possible answers for various markets are summarized in Table 5-5.

Table 5-5. Market structure and corresponding possible impact from tax addition

Market Type	Notes	Tax on the Supply Side	Tax on the Consumer Side	Shared Tax between Consumers and Suppliers	Impact
Perfectly competitive market	Multiple fuels with some level of substitution	Shifts the supply curve upwards by the amount of tax	Shifts the demand curve downwards based on level of substitution	Shifts both curves: demand curve downwards based on the level of substitution and supply curve upwards by the amount of shared tax	From the governments' perspective no difference. For the market it depends on the elasticity of curves
Perfectly competitive market	Single fuel	Shifts the supply curve upwards by the amount of tax	Shifts the demand curve downwards by the amount of tax	Shifts both curves: demand curve downwards and supply curve upwards	From the governments' perspective no difference. For the market no difference
Imperfect competition –monopolistic	May consider either one type of fuel or substitutes	Shifts the marginal cost upwards, the impact on price can be higher than the tax	May shift the demand curve downwards by the amount of tax, depends on the fuel types	A mixed reaction: the demand curve shifts downwards along with marginal cost curve shifting upwards	The impact is negative since monopolist can assert a strong market power and maximize its own profits
Oligopolistic: Nash-Cournot representation of the market	Nash equilibrium if Cournot's model where players act according to reaction curves and get to equilibrium.	Not known a priori	Not known a priori	Not known a priori	Not known a priori

From Figure 5-2 in the case of perfect competition for a product with some level of substitution the demand curve can be shifted downwards subject to the marginal rate of substitution if the tax is applied to the consumer. If the tax is applied to the supplier then prices increase due to the supply curve shift corresponding to the amount of tax. When the shared tax is applied again the same amount of tax is being collected. Due to the elasticity of supply and demand curves the tax portion may be either deducted from consumer's surplus or from producer's surplus.

If the product is homogeneous then there is no effect of marginal rate of substitution and therefore the tax addition would be directly reflected on the equilibrium prices and quantities indifferently on whom and by what proportions it is applied. Figure 5-2 can be again considered for given comparison where even if we keep the slopes of the curves constant any aggregate shift of demand and supply curves would lead to the same equilibrium price.

Monopolistic and oligopolistic market structures can be pictured as given in Figure 5-3. Figure 5-3 represents the existence of two rival firms where after exclusion of the supply quantities from the total demand one of the rival firms decides on its production quantities as a single firm. As discussed in Section 5-3 the impact on price in this case is due to the inverse demand elasticity.

The technique exercised in this research may help in answering the questions not addressed in Table 5-5, specifically in the last row. Even though the model developed answers some of the unknown items from Table 5-5 there are some complications. In particular, the inverse demand function parameters for each node have different values. Due to those differences the market response to a given policy is not consistent among regions and countries. Another complication is related to the timing when each region adopts the carbon policy. Additionally, there is a potential of having multiple solutions in the model making the comparisons of results against the Base Case harder.

To measure the effect of the impact from carbon policies on the natural gas market the following metrics are used: the consumer and producer surpluses and average wholesale prices. Before presenting the specifics for the U.S. it is important to realize the global impact of carbon policy implementation on the natural gas markets. As such the average wholesale price changes in 2015 and 2050 for all regions for 650ppm Case scenarios are presented in Figure 5-4.

From Table 5-2 it is known that only few regions adopt the proposed 650ppm carbon policy by 2015. Moreover, by 2015 the cost, for regions adopting the policy, is relatively low. In contrast, by 2050 all regions have this policy adopted and therefore the impact of carbon costs is much more noticeable compared to 2015. The numerical values for the presented cases and scenarios are given in Table 5-B1 in the Appendix 5-B.

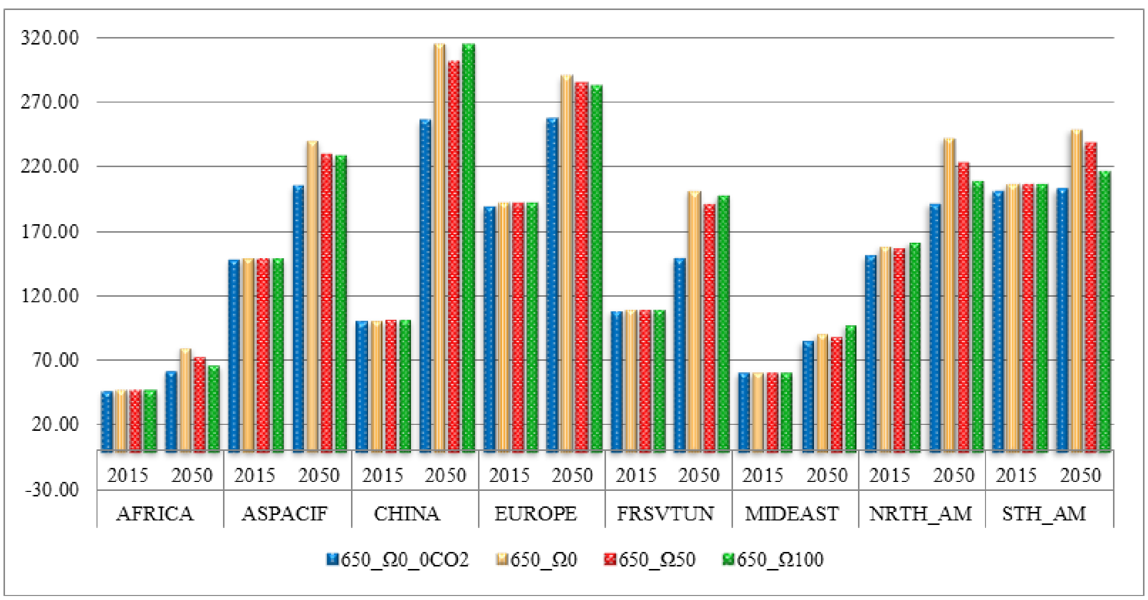

Figure 5-4: Average Wholesale Prices in 2015 and 2050 $/KCM ($2005) (650ppm Case)[17]

[17] _0CO2 indicates a no carbon cost case.
Ω 0 is when the carbon cost is subtracted from the suppliers' revenues directly, when it is Ω 1 then the consumer faces the direct addition of the tax to the total price. Although it should be noted that as described

Similarly, the results from the 20-20-20 Case are depicted in Figure 5-5. We can observe the impact of carbon costs on the natural gas market. Under this case the only region adopting carbon policy by 2015 is Europe (Table 5-3). In the 20-20-20 Case most of the regions have that carbon policy adopted by 2050. It is found that in certain regions such as Russia that adopt the 20-20-20 carbon policy later than the 650ppm carbon policy huge gains are possible. For example in the 20-20-20 Case the losses in total surplus are only 10 to 17% of what they would be under the 650ppm Case. However this result is not uniform across countries and policies.

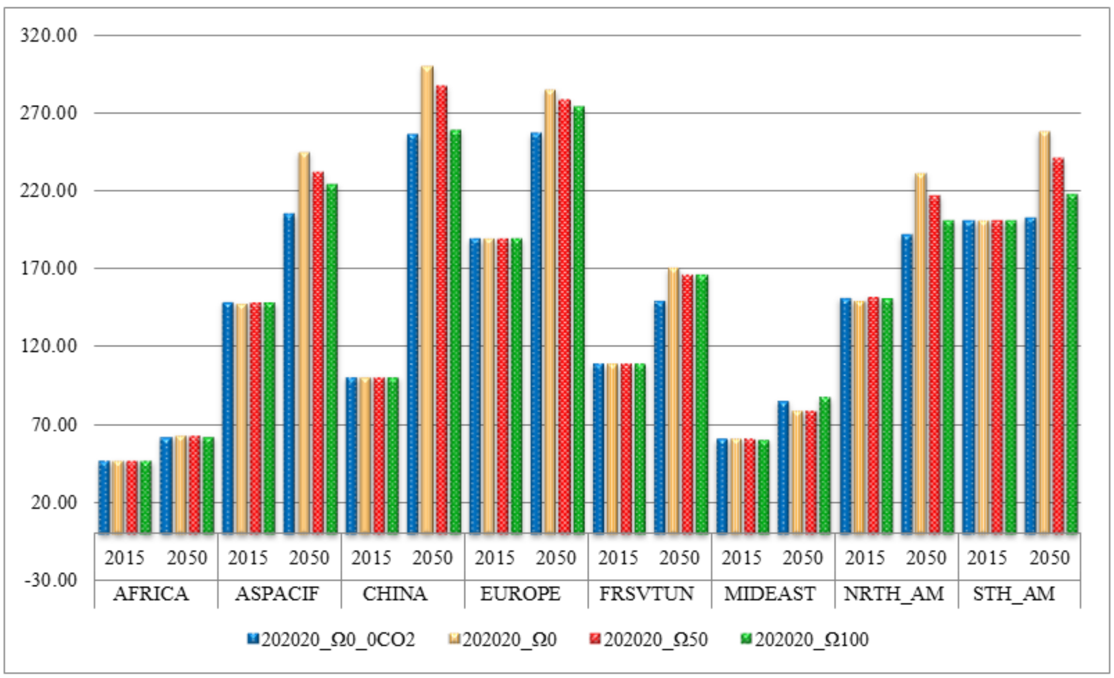

Figure 5-5: Average Wholesale Prices in 2015 and 2050 $/KCM ($2005) (20-20-20 Case)

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in Section 5.4, the impact of such carbon cost applications may vary from region to region and from case to case due to non-perfect competition and the elasticity of inverse demand functions.

5.7.4 Analyses for the U.S.

More specific details for market change comparisons for both cases are presented in Figure 5-6 for years 2015 to 2050 for the U.S.

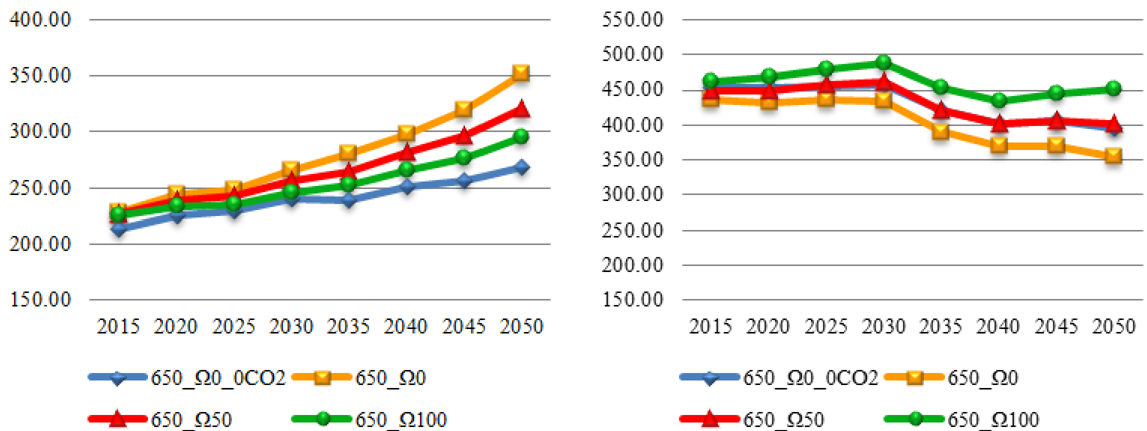


Figure 5-6: Average Wholesale Prices $/KCM ($2005) (left) and Production in BCM/Y in the U.S. (650ppm Case) (right)

In particular, Figure 5-6 shows the change in average wholesale price and production levels in the U.S. from 2015 (as a first year of carbon policy adoption in at least one region) to 2050 (the time horizon for which the results of the model are reported).

Numerical results of these cases are presented in Table 5-6.

Table 5-6. Average Wholesale Prices and Production Volumes in the U.S. (650ppm Case)

Year	$/KCM ($2005) 650ppm Case Scenarios				Production in BCM/Y 650ppm Case Scenario			
	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100
2015	214.12	228.22	227.43	225.12	453.40	435.83	448.79	461.33
2020	225.99	244.47	238.89	233.63	453.67	431.59	449.75	467.48
2025	229.72	248.20	242.75	234.39	455.38	436.56	458.05	480.01
2030	240.29	265.26	256.33	245.79	457.45	433.19	461.67	488.07
2035	238.60	280.51	264.94	252.34	421.90	390.05	421.31	453.20
2040	250.86	297.94	282.20	265.74	401.06	368.86	401.09	435.00
2045	256.36	319.26	296.94	277.14	405.31	369.74	406.38	444.32
2050	268.21	351.98	320.51	295.88	395.11	354.00	402.77	450.63

From the above information the loss in consumer surplus when comparing the impact of carbon policy results due to a no carbon policy case through proportional allocation of carbon costs between suppliers and consumers is given in Table 5-7. The loss of consumer surplus is given in Figure 5-7 and is equal to the total surface given by B plus C. To compute the loss of consumer surplus one can take the equilibrium price and quantity differences between scenarios and find the difference of the consumer surpluses (same as the sum of area B plus C).

$$B + C = \frac{1}{2}(p_c^e - p_b^e)(q_c^e + q_b^e)$$

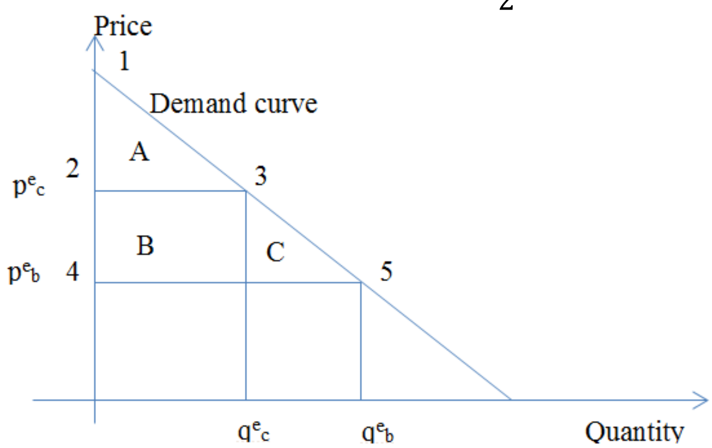


Figure 5-7: Loss of Consumer Surplus as the area of B+C.

Table 5-7. Loss of Consumer Surplus in the U.S. from the carbon cost allocation

Year	10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	6.27	6.00	5.03
2020	8.18	5.83	3.52
2025	8.24	5.95	2.18
2030	11.12	7.37	2.60
2035	17.01	11.11	6.01
2040	18.12	12.57	6.22
2045	24.38	16.47	8.83
2050	31.38	20.86	11.70

The table shows to have the least loss of consumer surplus it is preferable from policy perspective to apply the carbon cost to the consumers. This happens because of the oligopolistic structure of the market where the rival firms operate in the elastic region of the demand curve and therefore the impact from the tax might be higher. Table 5-8 presents the total production costs in each considered time period. Conversely as shown in Table 5-9 the producers do better, but only at smaller amount if the 100% of the tax is applied to the consumers. Lastly, the loss of the total surplus is minimized using the same approach to carbon tax allocation as shown in Table 5-10.

Table 5-8. Total Production Costs in the U.S. x$10^9 (650ppm Case)

Year	x$10^9 ($2005) 650ppm Case Scenarios			
	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100
2015	48.18	49.59	49.46	49.20
2020	49.27	51.33	51.14	50.76
2025	53.25	56.71	56.50	56.16
2030	57.74	62.35	61.76	60.51
2035	56.00	60.85	60.01	58.83
2040	56.67	62.24	61.59	60.66
2045	60.44	67.09	66.68	65.52
2050	62.81	73.25	72.53	69.90

From the information in Table 5-6 and 5-8 the loss of producer surplus is computed and presented in Table 5-9.

Table 5-9. Loss of Producer Surplus in the U.S. x$10^9 (650ppm Case)

Year	10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	3.35	1.78	0.18
2020	4.57	2.30	0.01
2025	5.78	2.93	0.03
2030	7.89	3.47	1.06
2035	9.45	4.09	1.28
2040	10.55	4.91	0.78
2045	12.53	6.08	0.70
2050	17.95	8.42	1.63

The corresponding total loss in surplus is the sum of the losses of producer and consumer surpluses given in Table 5-10:

Table 5-10. Total Loss of Surplus in the U.S. x$10^9 (650ppm Case)

Year	10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	9.62	7.78	5.21
2020	12.75	8.13	3.53
2025	14.03	8.88	2.21
2030	19.01	10.84	3.66
2035	26.46	15.19	7.29
2040	28.68	17.48	7.00
2045	36.90	22.55	9.53
2050	49.33	29.28	13.33

The results of Table 5-10 indicate for the U.S. in 650ppm Case the worst option of policy implementation would be if the tax is applied on the suppliers. The best case would be if the tax is imposed on consumers. This is due to the fact that in the oligopolistic market similar to the monopolistic market discussed in Section 5.4 the rival firms operate in the elastic region of the inverse demand curve.

The market structure in the U.S is modeled as a perfect competition although within the model the market also interacts with other players from other regions. As an example of a region that exerts market power on the market the impact of carbon policy adoption in Europe is considered next.

5.7.5 Analyses for Germany

Germany is selected for detailed analysis due to its geographic location and market structure. Specifically, it does not have much natural gas, and is highly dependent on Russian supplies as opposed to the U.S. which is more self-sufficient. First we present the difference in average wholesale prices and the production levels for Germany in Figure 5-8.

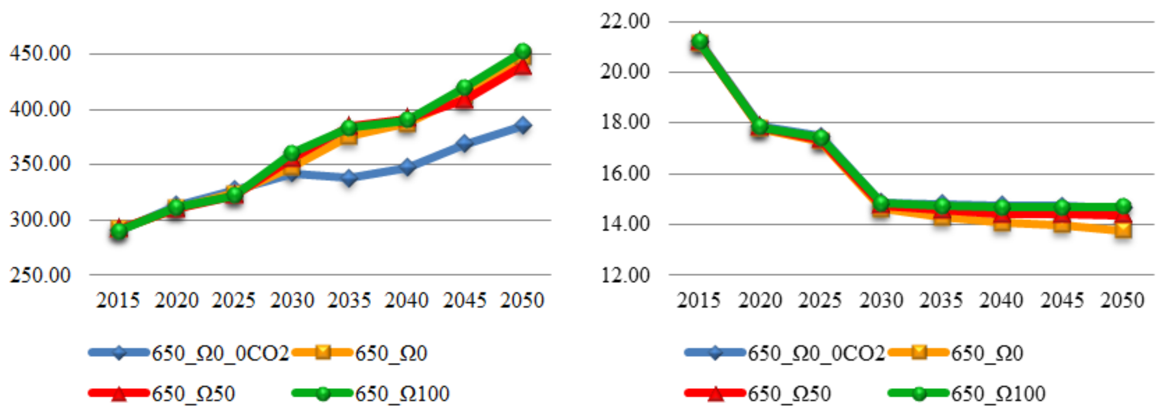


Figure 5-8: Average Wholesale Prices $/KCM ($2005) (left) and Production in BCM/Y in Germany (650ppm Case) (right)

Table 5-11. Average Wholesale Prices and Production Volumes in Germany (650ppm Case)

Year	$/KCM ($2005) 650ppm Case Scenarios				Production in BCM/Y 650ppm Case Scenario			
	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100
2015	290.28	291.53	291.83	289.93	21.21	21.16	21.18	21.19
2020	313.50	311.02	310.29	311.71	17.86	17.78	17.82	17.84
2025	327.04	323.90	322.06	322.11	17.48	17.27	17.35	17.42
2030	342.46	348.37	355.61	361.01	14.86	14.61	14.76	14.83
2035	338.18	376.10	384.95	383.83	14.80	14.28	14.55	14.72
2040	347.34	387.04	391.62	390.18	14.74	14.06	14.40	14.67
2045	369.18	412.38	408.89	420.31	14.72	13.97	14.39	14.67
2050	385.69	447.66	439.25	452.28	14.65	13.76	14.36	14.69

Similar to the U.S. case the loss of consumer surplus is computed and is given in Table 5-12. The loss in consumer surplus is equal to the total surface given by B plus C in Figure 5-7.

Table 5-12. Loss of Consumer Surplus in Germany

Year	10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	0.03	0.03	-0.01
2020	-0.04	-0.06	-0.03
2025	-0.05	-0.09	-0.09
2030	0.09	0.19	0.28
2035	0.55	0.69	0.67
2040	0.57	0.65	0.63
2045	0.62	0.58	0.75
2050	0.88	0.78	0.98

*(-) means gains in the surplus.

The production costs of producers in Germany are given in Table 5-13.

Table 5-13. Total Production Costs in Germany x$10^9 (650ppm Case)

Year	x$10^9 ($2005) 650ppm Case Scenarios			
	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100
2015	3.01	3.15	3.08	3.01
2020	2.73	2.88	2.80	2.73
2025	2.88	3.03	2.95	2.86
2030	2.64	2.78	2.71	2.62
2035	2.82	2.97	2.89	2.80
2040	3.02	3.19	3.11	3.00
2045	3.24	3.45	3.37	3.23
2050	3.47	3.77	3.67	3.49

From the information in Table 5-11 and 5-13 the loss of producer surplus is computed and presented in Table 5-14.

Table 5-14. Loss of Producer Surplus in Germany x$10^9 (650ppm Case)

Year	10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	0.145	0.073	0.000
2020	0.163	0.080	0.001
2025	0.192	0.094	0.006
2030	0.193	0.094	0.008
2035	0.250	0.122	0.009
2040	0.315	0.159	0.006
2045	0.385	0.198	0.004
2050	0.055	0.020	0.008

The corresponding total loss is the sum of the producer and consumer losses given in Table 5-15:

Table 5-15. Total Loss of Surplus in Germany x$10^9 (650ppm Case)

Year	10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	0.171	0.105	-0.007
2020	0.119	0.023	-0.031
2025	0.138	0.007	-0.080
2030	0.280	0.288	0.283
2035	0.802	0.808	0.683
2040	0.887	0.804	0.636
2045	1.005	0.776	0.756
2050	1.410	1.056	0.985

These results indicate that for Germany in the 650ppm Case the best option for carbon policy adoption would be if the tax is dynamically adjusted between consumers and producers from one time period to another. As an example it might be better to apply the entire tax on consumers in 2015 then on suppliers in 2030. Due to such strategy the total loss of surplus can be lessened. One reason for this dynamic result might be the combination of the elastic range of inverse demand curve where the rival firms operate and get to equilibrium. From an oligopolistic market perspective a firm can maximize its revenues up to the point where the unit elasticity on the inverse demand curve is negative 1 (Figure 5-9). This means that when rival firms are in the market for profit maximization and they have no incentive to deviate from equilibrium price and quantity the equilibrium is reached. The equilibrium can be reached by adjusting the quantity and prices in the elastic region (from negative infinity to negative 1elasticity) and as presented in Section 5.4 the impact of taxation can be even higher than the tax itself. By allocating the tax on the supplier and considering the flexibility of each firm for is production levels the impact on price may not be predicted *a priori*.

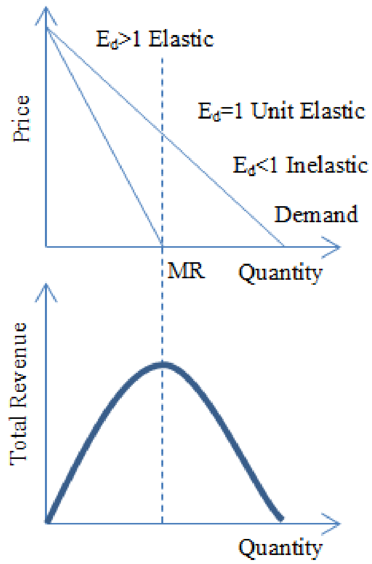


Figure 5-9: The inverse demand curve for a firm in an oligopolistic market

Results for Germany are also affected due to the mixed structure of the market where some part is subject to the market power from suppliers (e.g., Russia and Norway) and some not. The consideration of a mixed structure creates additional difficulty in understanding the exact cause of the change but in this case some firms are price-takers, while others set the price from an oligopolistic perspective. The decisions made by rival firms that also set the price consequently affect the supply decisions of price-taker firms. For Germany actual gains in consumer surplus versus the no carbon policy scenario occurred in 2020 and 2025 contrary to the U.S. This can be explained since the German suppliers are not affected by the carbon policy adoption as indicated in Table 5-14. The weight Ω influences somewhat the loss in consumer surplus as shown in Table 5-12. Once all nations have adopted the carbon policy by 2050 the impact on consumer surplus is minimized by allocation of carbon cost when Ω is 50% as shown in Figure 5-10. From consumers perspective the best carbon tax allocation is for 50/50 case until after 2030 then it is best apply the tax on the supplier. From Figure 5-10 we observe that when the

650ppm carbon policy is adopted in Germany a difference in loss in consumer surplus is already noticeable from the start. In fact the policy impact is in favor of consumers in years 2020 and 2025 where the loss in consumer surplus is negative meaning that the consumer surplus is larger. In 2030 when the German consumers bear 100 percent of the tax they lose more in surplus versus when they share the tax equally with producers. In fact for 2030 the best for consumer surplus is to have producers to pay 100 percent of the tax.

Why does this happen? For 2030 for Germany the following logic prevails. First, due in part to producers paying 100 percent of the tax with resulting higher production cost the production for German producers is lowest among carbon policy scenarios (see Figure 5-8). Also, at the same time producers (via their traders) from other countries ramp up to compensate (Figure 5-10). Some of these producers presumably have lower production costs due to non-adoption of carbon policies resulting in the lowest average wholesale prices for all the carbon cost allocation scenarios. Lower prices leads to higher consumer surplus. Other years are different such as 2050.

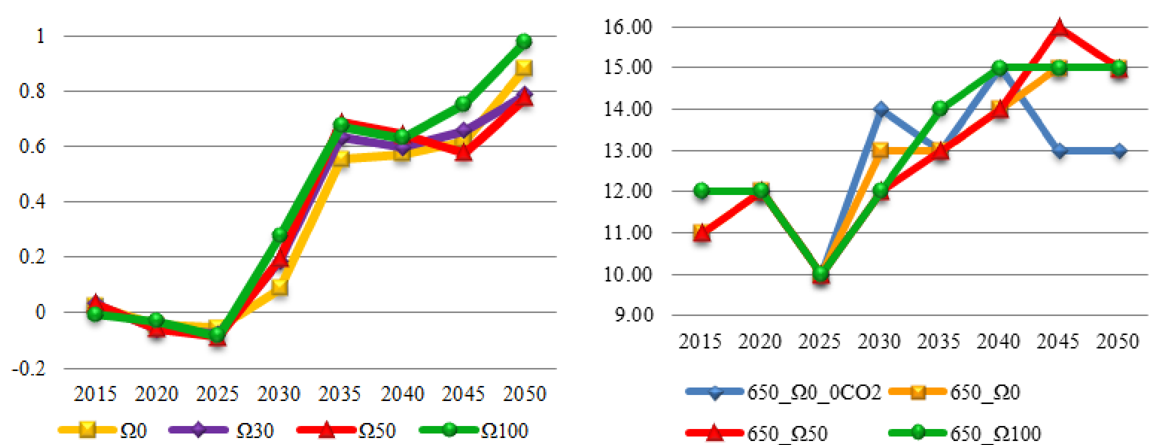
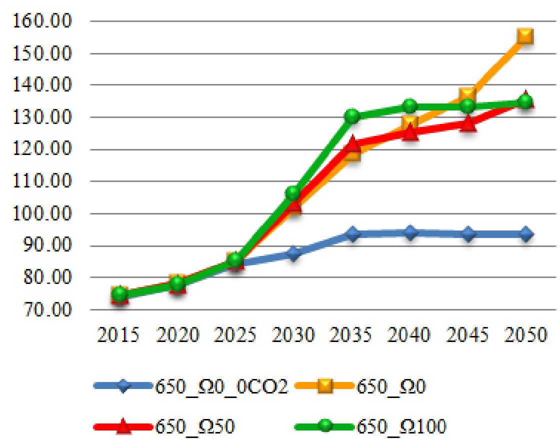


Figure 5-10: Loss of consumer surplus from carbon cost allocation through Ω along the supply chain (left) and daily sales by traders in Germany million cubic meters per day (right)

5.7.6 Analyses for Russia

Next we analyze the market dynamics for Russia. Average wholesale prices and production volumes in Russia are presented in Figure 5-11.



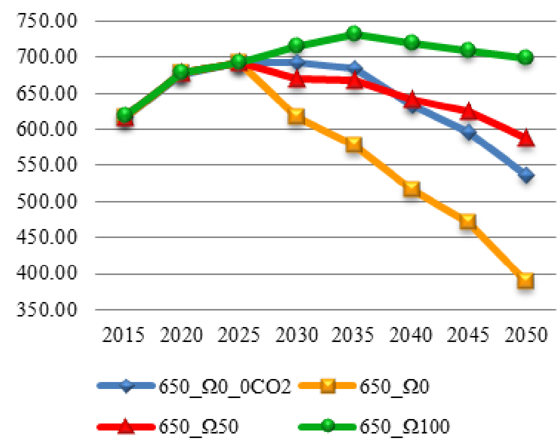


Figure 5-11: Average Wholesale Prices $/KCM ($2005) (left) and Production in BCM/Y in Russia (650ppm Case) (right)

Table 5-16. Average Wholesale Prices and Production Volumes in Russia (650ppm Case)

Year	$/KCM ($2005) 650ppm Case Scenarios				Production in BCM/Y 650ppm Case Scenario			
	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100
2015	74.15	74.40	74.43	74.44	616.79	616.96	617.58	618.20
2020	77.69	78.09	78.03	77.91	676.94	677.58	677.93	678.02
2025	84.28	85.25	85.19	85.01	691.40	692.92	693.06	693.14
2030	87.54	102.02	103.29	105.87	693.25	617.41	670.40	715.69
2035	93.46	118.44	121.49	129.78	685.02	576.86	666.91	730.74
2040	94.03	127.50	125.48	133.24	633.55	516.29	642.10	719.42
2045	93.69	136.44	128.03	133.11	596.73	471.24	624.12	709.82
2050	93.32	154.98	135.40	134.71	536.99	388.77	586.92	698.25

The loss of consumer surplus is computed for the Russian region as well and is given in Table 5-17.

Table 5-17. Loss of Consumer Surplus in Russia

Year	10^9 \$ (\$2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	0.15	0.17	0.18
2020	0.27	0.23	0.15
2025	0.67	0.63	0.51
2030	9.49	10.74	12.91
2035	15.76	18.95	25.71
2040	19.24	20.06	26.52
2045	22.83	20.96	25.75
2050	28.54	23.65	25.56

In Russia the loss of consumer surplus increases dramatically starting in 2030 which according to Table 5-2 is when the carbon policy is adopted. From the loss of consumer surplus perspective the policy should be adjusted almost in every time period (Table 5-20) similar to the case of Germany (Figure 5-10). The production costs in Russia are given in Table 5-18.

Table 5-18. Total Production Costs in Russia x\$10^9 (650ppm Case)

Year	x\$10^9 (\$2005) 650ppm Case Scenarios			
	650_Ω0_0CO_2	650_Ω0	650_Ω50	650_Ω100
2015	31.32	31.39	31.47	31.32
2020	37.46	37.55	37.59	37.49
2025	41.67	41.82	41.86	41.79
2030	45.18	46.95	47.44	45.78
2035	48.34	53.74	53.20	51.15
2040	47.48	56.74	56.22	50.53
2045	47.34	59.69	58.92	50.47
2050	44.86	62.00	61.92	47.42

From the information in Table 5-17 and 5-18 the loss of producer surplus is calculated and presented in Table 5-19.

Table 5-19. Loss of Producer Surplus in Russia x$10^9 (650ppm Case)

Year	x10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	0.060	0.105	0.076
2020	0.051	0.073	0.027
2025	0.058	0.089	0.009
2030	7.121	3.811	0.847
2035	14.258	6.217	0.401
2040	20.093	8.041	3.183
2045	25.281	9.200	5.373
2050	35.155	12.348	9.649

The corresponding total loss is the sum of the producers and consumers losses given in Table 5-20:

Table 5-20. Total Loss of Surplus in Russia x$10^9 (650ppm Case)

Year	x10^9 $ ($2005) 650ppm Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 650ppm 100% to consumers (Ω100)
2015	0.214	0.278	0.255
2020	0.322	0.304	0.176
2025	0.730	0.719	0.515
2030	16.610	14.549	13.759
2035	30.019	25.164	26.111
2040	39.336	28.101	29.708
2045	48.109	30.162	31.125
2050	63.696	35.995	35.212

The results of Table 5-20 indicate that for Russia to lessen the loss of total surplus the consumers should bear the brunt of the carbon tax starting in 2030 corresponding to the time period when Russia adopts the carbon policy. In 2045 and 2050 the total surplus is significantly higher when both consumers and suppliers are equally share the tax, or only consumers take the carbon tax. One possible explanation for this dynamic carbon policy is the simultaneous adjustment of the marginal cost curve and the inverse demand curve where the change in slopes may result in a smaller deadweight loss as discussed in Sections 5.3 and 5.4 for perfectly and non-perfectly competitive markets.

Next we present the experiments by region for the 20-20-20 Case.

5.7.7 Analysis

We first present the results for the U.S. and then compare them with results for Germany and Russia. The average wholesale prices and the production levels for the U.S. are given in Figure 5-12.

Figure 5-12: Average Wholesale Prices $/KCM ($2005) (left) and Production in BCM/Y in the U.S. (20-20-20 Case) (right)

In 2030 the U.S. adopts the 20-20-20 carbon tax policy. Producers paying the greater share of the tax results in proportionally higher prices and lower production (Figure 5-12). Consequently, the consumers paying 100 percent of the tax results in the highest consumer surplus (Table 5-22).

Why might this happen? One of the possible reasons for this is the amplified effect of the tax due to the elasticity of the inverse demand curve (Figure 5-9).

Table 5-21. Average Wholesale Prices and Production Volumes in the U.S. (20-20-20 Case)

Year	$/KCM ($2005) 20-20-20 Case Scenarios				Production in BCM/Y 20-20-20 Case Scenario			
	202020_Ω0_0CO_2	202020_Ω0	202020_Ω50	202020_Ω100	202020_Ω0_0CO_2	202020_Ω0	202020_Ω50	202020_Ω100
2015	214.12	211.68	216.28	219.91	453.40	453.69	457.24	460.42
2020	225.99	225.63	225.49	228.40	453.67	458.20	459.12	458.90
2025	229.72	230.09	229.54	234.73	455.38	459.18	461.23	460.88
2030	240.29	305.36	287.98	272.72	457.45	394.61	463.19	531.55
2035	238.60	320.44	295.82	267.38	421.90	358.67	419.93	487.60
2040	250.86	332.15	305.47	276.29	401.06	337.51	395.54	454.09
2045	256.36	341.97	317.22	283.96	405.31	387.15	433.37	478.59
2050	268.21	352.54	326.21	299.37	395.11	380.81	425.98	464.13

The loss of consumer surplus is computed for the U.S. and is given in Table 5-22.

Table 5-22. Loss of Consumer Surplus in the U.S.

Year	10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 100% to consumers (Ω100)
2015	-1.11	0.98	2.65
2020	-0.16	-0.23	1.10
2025	0.17	-0.08	2.30
2030	27.72	21.95	16.04
2035	31.94	24.08	13.09
2040	30.02	21.75	10.87
2045	33.92	25.52	12.20
2050	32.72	23.81	13.39

Before 2030 when the U.S. adopts the carbon policy the Ω value is almost negligible. Then in 2030 highest consumer surplus (smallest loss) is to put the entire tax on the consumers (Table 5-22). A similar phenomenon occurs for the total surplus (Table 5-25) since the producer surplus is small. Also, the total surplus is highest for Germany (Table 5-24) and Russia (Table 5-25) when consumers pay the entire tax. This fact is again explained with the same approach as for the U.S. and as discussed in Sections 5.3 and 5.4 although the effects of the market power in German and Russian markets could also influence.

The production cost and loss of producer's surplus for the U.S. are given in Appendix 5-C (Table 5-C1 and 5-C2). The corresponding total loss is the sum of the producers and consumers losses given in Table 5-23.

Table 5-23. Total Loss of Surplus in the U.S. x$10^9 (20-20-20 Case)

Year	x10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 100% to consumers (Ω100)
2015	-0.60	1.35	2.88
2020	0.06	-0.13	1.22
2025	0.51	0.07	2.34
2030	46.58	26.51	18.14
2035	50.07	29.34	14.68
2040	47.76	26.26	11.94
2045	50.56	33.40	13.84
2050	50.03	32.03	14.93

The supplemental details for Germany and Russia including the average wholesale prices, production levels, production costs along with loss of consumer and producer surpluses can be found in Appendix 5-C in Figures 5-C1 and 5-C2 as well as in Tables 5-C3 to 5-C10.

Table 5-24. Total Loss of Surplus in Germany x$10^9 (20-20-20 Case)

Year	x10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 100% to consumers (Ω100)
2015	0.911	0.593	0.136
2020	1.019	0.567	0.075
2025	1.068	0.607	0.100
2030	0.940	0.585	0.180
2035	1.009	0.636	0.333
2040	0.916	0.679	0.256
2045	1.366	1.193	1.057
2050	1.374	1.135	0.866

Table 5-25. Total Loss of Surplus in Russia x$10^9 (20-20-20 Case)

Year	x10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost ($\Omega0\_0CO_2$) vs. 20-20-20 0% to consumers ($\Omega0$)	No Carbon Cost ($\Omega0\_0CO_2$) vs. 20-20-20 50% to consumers ($\Omega50$)	No Carbon Cost ($\Omega0\_0CO_2$) vs. 20-20-20 100% to consumers ($\Omega100$)
2015	0.931	0.827	0.908
2020	1.092	0.980	1.148
2025	1.372	1.239	1.254
2030	1.604	1.519	1.589
2035	1.001	0.767	0.940
2040	0.951	0.662	1.032
2045	31.995	22.716	19.907
2050	33.608	19.184	15.326

Russia significantly benefits from the 20-20-20 policy due to a later adoption (2045) than the 650ppm Case (2030). This has far-reaching policy implications for Russia to adopting 20-20-20 policy than 650ppm policy.

The addition of carbon costs to the WGM allows more flexibility in its applications and also provides a platform for a more flexible carbon policy development for the natural gas industry. The potential beneficiaries of this work are the government agencies and private consulting companies that are involved in a policy development or decision-making practice.

5.8 Future Work

The future work related to carbon policy impact analysis, specifically on natural gas, may include addition of a new player into the WGM as a Carbon Trader, which will try to maximize profits from the market subject to the amount of generated emissions from both suppliers and consumers. This player can also help in the development of an emission policy, where its carbon costs variables may suggest certain values to help reaching given goals, such as limiting the amount of emissions from the supply chain and the consumption of natural gas. Additional work/scenarios can be implemented with an application of proportional assignment techniques of emissions cost in WGM for assessing the effects in different countries. Such analyses may be of interest to many national and international agencies that try to evaluate the impact of emissions policies in international trade. For instance, it may help in evaluation of trade volumes for exports from the U.S. to Europe or to Asia, which when considering the low cost of U.S. supply may initiate profitable contractual agreements.

Appendix 5-A

Table 5-A. ***Mapping of Nodes, Countries, Sub Regions and Regions in WGM***

Node	Country	Sub region	Region
ALG	Algeria	AfrNorth	Africa
NIG	Angola	AfrWest	Africa
ALG	Egypt	AfrNorth	Africa
NIG	Equatorial Guinea	AfrWest	Africa
ALG	Libya	AfrNorth	Africa
ALG	Morocco	AfrNorth	Africa
NIG	Mozambique	AfrWest	Africa
NIG	Nigeria	AfrWest	Africa
NIG	South Africa	AfrWest	Africa
ALG	Tunisia	AfrNorth	Africa
AUS	Australia	Australia	AsiaPacific
CHN	Birma	AsPacOther	AsiaPacific
IDO	Brunei	AsPacGECF	AsiaPacific
CHN	China	AsPacOther	AsiaPacific
IDA	India	AsPacOther	AsiaPacific
IDO	Indonesia	AsPacGECF	AsiaPacific
JAP	Japan	JPKor	AsiaPacific
IDO	Malaysia	AsPacGECF	AsiaPacific
AUS	New Zealand	Australia	AsiaPacific
IDA	Pakistan	AsPacOther	AsiaPacific
CHN	Singapore	AsPacOther	AsiaPacific
JAP	SouthKorea	JPKor	AsiaPacific
CHN	Taiwan	AsPacOther	AsiaPacific
CHN	Thailand	AsPacOther	AsiaPacific
KZK	Armenia	Caspian	Caspian
KZK	Azerbaijan	Caspian	Caspian
KZK	Georgia	Caspian	Caspian
KZK	Kazakhstan	Caspian	Caspian
KZK	Turkmenistan	Caspian	Caspian
KZK	Uzbekistan	Caspian	Caspian
UKR	Belarus	UkrBelarus	Eurasia
UKR	Ukraine	UkrBelarus	Eurasia
GER	Austria	EurOther	Europe
POL	BalticRegion	EurOther	Europe
FRA	Belgium & Luxembourg	EurOther	Europe
ROM	Bulgaria	EurOther	Europe
GER	CzechRepublic	EurOther	Europe
GER	Denmark	EurOther	Europe
POL	Finland	EurOther	Europe
FRA	France	EurSouthWest	Europe
GER	Germany	EurOther	Europe
ROM	Greece	EurOther	Europe
ROM	Hungary	EurOther	Europe
UKD	Ireland	UK Eire	Europe
ITA	Italy	EurSouthWest	Europe
NED	Netherlands	NoNL	Europe
NOR	Norway	NoNL	Europe
POL	Poland	EurOther	Europe
SPA	Portugal	EurSouthWest	Europe
ROM	Romania	EurOther	Europe
POL	SlovakRepublic	EurOther	Europe
ITA	Slovenia	EurOther	Europe
SPA	Spain	EurSouthWest	Europe
POL	Sweden	EurOther	Europe
GER	Switzerland	EurOther	Europe
TRK	Turkey	Turkey	Europe
UKD	UnitedKingdom	UK Eire	Europe
QAT	Iran	MidEastGECF	MiddleEast
YMN	Kuwait	MidEastOther	MiddleEast
YMN	Oman	MidEastOther	MiddleEast
QAT	Qatar	MidEastGECF	MiddleEast
YMN	SaudiArabia	MidEastOther	MiddleEast
YMN	UAE	MidEastOther	MiddleEast
YMN	Yemen	MidEastOther	MiddleEast
CAE	Canada-East	CAN	NorthAmerica
CAW	Canada-West	CAN	NorthAmerica
MEX	Mexico	USAMex	NorthAmerica
ULS	USA Alaska	USAMex	NorthAmerica
ULN	USA Alaska NorthSlope	USAMex	NorthAmerica
US3	USA East NCentral	USAMex	NorthAmerica
US6	USA East SCentral	USAMex	NorthAmerica
US2	USA Middle Atlantic	USAMex	NorthAmerica
US8	USA Mountain	USAMex	NorthAmerica
US1	USA New England	USAMex	NorthAmerica
US9	USA Pacific	USAMex	NorthAmerica
US5	USA South Atlantic	USAMex	NorthAmerica
US4	USA West N Central	USAMex	NorthAmerica
US7	USA West S Central	USAMex	NorthAmerica
RUE	Russia-East	RusEast	Russia
RUL	Russia-Sakhalin	RusEast	Russia
RUW	Russia-Volga-Uralsk	RusWest	Russia
RUW	Russia-West	RusWest	Russia
BRA	Argentina	LatinEast	SouthAmerica
TRI	Bolivia	LatinGECF	SouthAmerica
BRA	Brazil	LatinEast	SouthAmerica
CHL	Chile	LatinWest	SouthAmerica
CHL	Ecuador	LatinWest	SouthAmerica
CHL	Peru	LatinWest	SouthAmerica
TRI	Trinidad & Tobago	LatinNonGECF	SouthAmerica
TRI	Venezuela	LatinGECF	SouthAmerica

The Original Formulation of WGM in Complete Form

This Appendix presents the optimization problems and market-clearing conditions that constitute the World Gas Model. The modeled market agents include producers (P), traders (T), liquefiers (L), LNG shipment, regasifiers (R), transmission system operator, storage operators (S), marketers (M) and several consumption sectors (K1, K2, K3).

Producers sell gas to their trading arms. Traders ship gas to consumer markets, domestically via distribution networks, or internationally via high pressure pipeline networks or LNG terminals, ships and regasifiers in other countries. Traders make use of storage services to balance their flows among seasons.

Nomenclature

This subsection lists the symbols used.

Sets

$a \in A$	Gas transportation arcs, e.g., {NNED_GER, LNOR_FRA, RGER_GER}[18]
$d \in D$	Demand seasons, e.g., {low, high}
$p \in P$	Producers, e.g., {P_NOR, P_RUW, P_RUE}
$m \in M$	Years, e.g., {2005, 2010, 2015, 2020}
$n \in N$	Model nodes[19], e.g., {N_NOR, N_RUW}
$s \in S$	Storage facilities, e.g., {S_NED, S_GER}
$t \in T$	Traders, e.g., {T_NOR, T_RUS}

[18] The first letter indicates the type of arc; combinations of three letters denote the region or country name. NNED_GER represents a pipeline from the Netherlands to Germany; LNOR_FRA is an LNG shipping arc from the Norwegian liquefaction node to the regasification node of France and RGER_GER the arc from the German regasification node to the German country node. NNIG_LNG denotes the arc from the country node Nigeria to the Nigerian liquefaction node.

[19] Model nodes represent geographical regions in the world. They can be defined flexibly in the model data set. Due to the limited relevance and impact of countries that only produce and consume small amounts, several countries have been grouped with neighboring ones and are represented in the model data set on an aggregate level. For some countries the opposite is true: their consumption or production is so high, and the geographical distances so large, that a division of the countries in several regions is warranted.

$a^{+}(n)$ Inward arcs

$a^{-}(n)$ Outward arcs

For subsets of nodes where a player *x* is present, we use *N(x)*. To refer to individual nodes in this set, we write *n(x)*. Similarly, to denote the subset of agents *X* present at node *n*, we use: *X(n)*, (e.g., *T(n)* are the traders with access to node *n)*; and to refer to individual set elements of this set, we write *x(n)*.

The set elements are used as subscripts and superscripts in the other symbols.

Input parameters

b_{am}^{A}	Arc capacity expansion costs (k$/mcm/d)[20]
b_{sm}^{SI}	Storage injection capacity expansion costs (k$/mcm)
b_{sm}^{SX}	Storage extraction capacity expansion costs (k$/mcm)
b_{sm}^{SW}	Storage working gas capacity expansion costs (k$/mcm)
$c_{pm}^{P}(.)$	Production costs (k$/mcm)
$\overline{CAP}_{am}^{A}$	Arc capacity (mcm/d)[21]
$\overline{CAP}_{sm}^{SI}$	Storage injection capacity (mcm/d)
$\overline{CAP}_{sm}^{SX}$	Storage extraction capacity (mcm/d)
CON_{tadm}^{T}	Contractual supply obligation (mcm/d)
δ_{tn}^{C}	Level of market power exerted by trader in a market, $\delta_{tn}^{C} \in [0,1]$; 0 is perfectly competitive, 1 is fully Cournot.
$days_{d}$	Number of days in season, e.g., days_{low}=183

[20] Units of measurement for costs are thousands of USD$ (k$) and for volumes million cubic meters (per day) (mcm/d).

[21] Subscript *m* is to account for the year for expansions approved or under construction.

$\overline{\Delta}_{am}^{A}$	Upper bound of arc capacity expansion (mcm/d)
$\overline{\Delta}_{sm}^{SI}$	Upper bound of storage injection capacity expansion (mcm/d)
$\overline{\Delta}_{sm}^{SX}$	Upper bound of storage extraction capacity expansion (mcm/d)
$\overline{\Delta}_{sm}^{SW}$	Upper bound of storage working gas capacity expansion (mcm)
γ_m	Discount rate in year, $\gamma_m \in (0,1]$
INT_{ndm}^{W}	Intercept of inverse demand curve (mcm/d)
$loss_a$	Loss rate of gas in transport arc, $l_a \in [0,1)$
$loss_s$	Loss rate of gas storage injection, $l_s \in [0,1)$
$\overline{PR}_{pm}^{P}$	Daily production capacity (mcm/d)
$\overline{PH}_{p}^{P}$	Total producible reserves in time horizon (mcm)
SLP_{ndm}^{W}	Slope of inverse demand curve (mcm/d/k$)
$\tau_{adm}^{A,reg}$	Regulated fee for arc usage (k$/mcm)
$\tau_{sdm}^{SI,reg}$	Regulated fee for storage injection (k$/mcm)
$\overline{WG}_{sm}^{S}$	Storage working gas capacity (mcm/d)

Variables (all variables are taken to be nonnegative)

Δ_{am}^{A}	Arc capacity expansion (mcm/d)
Δ_{snm}^{SI}	Storage injection capacity expansion (mcm/d)
Δ_{snm}^{SX}	Storage extraction capacity expansion (mcm/d)
Δ_{snm}^{SW}	Storage working gas capacity expansion (mcm/d)
$FLOW_{tadm}^{T}$	Arc flow by trader (mcm/d)
INJ_{tndm}^{T}	Quantity injected to storage by trader (mcm/d)

$PURCH^{T}_{tndm}$ Quantity bought from producer by trader (mcm/d)

$SALES^{A}_{adm}$ Pipeline capacity assigned to trader (mcm/d)

$SALES^{P}_{pdm}$ Quantity sold by producer to traders (mcm/d)

$SALES^{SI}_{sdm}$ Storage injection capacity assigned for use to traders (mcm/d)

$SALES^{SX}_{sdm}$ Storage extraction capacity assigned for use to traders (mcm/d)

$SALES^{T}_{tndm}$ Quantity sold to end-user markets by trader (mcm/d)

XTR^{T}_{tndm} Quantity extracted from storage by trader (mcm/d)

When presenting restrictions in the formulations below, Greek symbols in parentheses represent the dual variables used in the KKT derivation.[22]

Dual variables

$\alpha, \beta \geq 0$ dual variables to capacity restrictions

φ *free* dual variables to mass balance constraints

$\rho \geq 0$ dual variables to capacity expansion limitations

π *free* duals to market-clearing conditions for sold and bought quantities

τ *free* duals market-clearing conditions for capacity assignment and usage.

In what follows, we describe the representation of the producer and other players.

Producer Problem

A producer p is modeled as maximizing his discounted profits, which are the result of revenues from sales $SALES^{P}_{pdm}$ minus production costs. Cash flows in year m are discounted with a factor γ_m. Since sales-rates are per day and may differ by season, the

[22] KKT: Karush Kuhn Tucker conditions

sales-rates and production costs are multiplied by the number of days in the season: $days_d$.

$$\max_{SALES^P_{pdm}} \sum_{m \in M} \gamma_m \sum_{d \in D} days_d \left[\pi^P_{n(p)dm} SALES^P_{pdm} - c^P_{pm}(SALES^P_{pdm}) \right] \quad \textbf{(A. 1)}$$

The sales-rate is restricted by a production capacity $\overline{PR}^P_{pm}$ (that can vary by year):

$$s.t. \quad SALES^P_{pdm} \leq \overline{PR}^P_{pm} \quad \forall d, m \quad \left(\alpha^{PR}_{pdm} \right) \quad \textbf{(A. 2)}$$

Due to reserve limitations or governmental restrictions the aggregate production over all years in a time period is restricted by a production ceiling $\overline{PH}_p$.

$$\sum_{m \in M} \sum_{d \in D} days_d SALES^P_{pdm} \leq \overline{PH}_p \quad \forall m \quad \left(\alpha^{PH}_p \right) \quad \textbf{(A. 3)}$$

Lastly, the sales-rate must be nonnegative:

$$SALES^P_{pdm} \geq 0 \quad \forall d, m \quad \textbf{(A. 4)}$$

The KKT conditions for the producer and all other agents can be found at the end of this Appendix. The market player described in the following sub-section is the trader.

Trader Problem

The trader maximizes profits resulting from selling gas to marketers ($SALES^T_{tndm}$), net of the gas purchasing costs and the costs: a regulated fee $\tau^{A,reg}_{adm}$ plus a congestion fee τ^A_{adm}, to transport the gas ($FLOW^T_{tadm}$) over high pressure pipelines *a*. The parameter $\delta^C_{tn} \in [0,1]$ indicates the level of market power exerted by a trader at a consumption node, with 0 representing perfect competitive behavior and 1 representing perfect Nash-Cournot oligopolistic behavior. Values between 0 and 1 indicate that we assume that some market power is exerted by the trader, but diluted relative to Cournot competition. The expression $\left(\delta_{tn}^{C}\Pi_{ndm}^{W}\left(\cdot\right)+(1-\delta_{tn}^{C})\pi_{ndm}^{W}\right)$ can be viewed as a weighted average of market prices resulting from the inverse demand function $\Pi_{ndm}^{W}\left(\cdot\right)$ and a perfectly competitive market-clearing wholesale price π_{ndm}^{W}. The trader also decides how much gas to inject in and extract from storage. The costs for injection are a regulated fee and a congestion rate; costs for extraction are a congestion rate only. Thus, trader *t* is modeled as solving the following optimization problem.

$$\max_{\substack{SALES_{tndm}^{T}\\ PURCH_{tndm}^{T}\\ FLOW_{tadm}^{T}\\ INJ_{tndm}^{T}\\ XTR_{tndm}^{T}}} \sum_{m\in M}\gamma_m\sum_{d\in D} days_d \left\{ \begin{array}{l} \sum\limits_{n\in N(t)}\left[\begin{array}{l}\left(\delta_{tn}^{C}\Pi_{ndm}^{W}\left(\cdot\right)+(1-\delta_{tn}^{C})\pi_{ndm}^{W}\right)SALES_{tndm}^{T}\\ -\pi_{ndm}^{P}PURCH_{tndm}^{T}\\ -\sum\limits_{s\in S(t)}\left(\begin{array}{l}\left(\tau_{sndm}^{SI,reg}+\tau_{sndm}^{SI}\right)INJ_{tndm}^{T}\\ +\quad\tau_{sndm}^{SX}XTR_{tndm}^{T}\end{array}\right)\end{array}\right]\\ -\left(\sum\limits_{a\in A(t)}\left(\tau_{adm}^{A,reg}+\tau_{adm}^{A}\right)FLOW_{tadm}^{T}\right)\end{array}\right\} \tag{A. 5}$$

Traders need to preserve mass balance at every node *n* in every season *d* of every year *m*:[23]

$$\text{s.t.}\quad \begin{array}{l} PURCH_{tndm}^{T}+\sum\limits_{a\in a^{+}(n)}\left(1-loss_a\right)FLOW_{tadm}^{T}+XTR_{tndm}^{T}=\\ SALES_{tndm}^{T}+\sum\limits_{a\in a^{-}(n)}FLOW_{tadm}^{T}+INJ_{tndm}^{T}\quad\forall n,d,m\ \left(\varphi_{tndm}^{T}\right)\end{array} \tag{A. 6}$$

In each yearly storage cycle the total extracted volumes must equal the loss-corrected injection volumes:

$$\left(1-loss_s\right)\sum_{d\in D}days_d INJ_{tsdm}^{T}=\sum_{d\in D}days_d XTR_{tsdm}^{T}\quad\forall n,s\in S\left(N\left(t\right)\right),d,m\quad\left(\varphi_{tsdm}^{S}\right) \tag{A. 7}$$

Some traders have contractual obligations, that can be modeled as follows:[24]

[23] Pipeline losses are accounted for in this mass-balance equation; in contrast the storage loss-rate is accounted for in the storage-cycle constraint, equation **(A. 7)**.

$$FLOW^T_{tadm} \geq CON^T_{tadm} \quad \forall a,d,m \quad \left(\varepsilon^T_{tadm}\right) \tag{A. 8}$$

All other constraints are nonnegativity of variables:

$$SALES^T_{tndm} \geq 0 \quad \forall n,d,m \tag{A. 9}$$

$$PURCH^T_{tndm} \geq 0 \quad \forall n,d,m \tag{A. 10}$$

$$FLOW^T_{tadm} \geq 0 \quad \forall a,d,m \tag{A. 11}$$

$$INJ^T_{tndm} \geq 0 \quad \forall n,d,m \tag{A. 12}$$

$$XTR^T_{tndm} \geq 0 \quad \forall n,d,m \tag{A. 13}$$

The inverse demand curve $\Pi^W_{ndm}(\cdot)$ is presented later.

The next section describes the transmission system operator, who is responsible for assigning available capacities to the traders needing transport capacity for exporting gas; and for expansions of the international transportation capacities. The international high pressure pipelines as well as the various steps of the LNG supply chain are represented as arcs with appropriate costs, losses and capacities. The underlying assumption is that all transportation infrastructure agents are regulated players.

Transmission system operator problem

The transmission system operator (TSO) provides an economic mechanism to efficiently allocate international transport capacity to traders. The TSO maximizes the discounted profit resulting from selling arc capacity to traders $SALES^A_{adm}$ minus investment costs for capacity expansions Δ^A_{am}. Loosely speaking, regulators base the maximum infrastructure usage charges (*regulated fees*) on the long-term marginal costs, i.e. the operating and maintenance costs plus a margin to earn a return on investment. In the model we make

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the simplified assumption that the regulated fees collected from the traders are to equal the costs; therefore the profit margin is equal to the congestion fee τ^A_{adm}. Note that these congestion fees are not paid in actuality, but merely facilitate the efficient allocation of a scarce capacity in the model.

$$\max_{\substack{SALES^A_{adm} \\ \Delta^A_{am}}} \sum_{m \in M} \gamma_m \left\{ \sum_{d \in D} days_d \sum_a \tau^A_{adm} SALES^A_{adm} - \sum_a b^A_{am} \Delta^A_{am} \right\} \quad \textbf{(A. 14)}$$

The assigned capacity is restricted by the available capacity. Available arc capacity at arc a is the sum of the initial arc capacity $\overline{CAP}^A_{am}$ and capacity expansions in the previous years $\sum_{m'<m} \Delta^A_{am'}$.

$$SALES^A_{adm} \le \overline{CAP}^A_{am} + \sum_{m'<m} \Delta^A_{am'} \quad \forall a,d,m \quad \left(\alpha^A_{adm}\right) \quad \textbf{(A. 15)}$$

There may be budgetary or other limits to the yearly capacity expansions:

$$\Delta^A_{am} \le \bar{\Delta}^A_{am} \quad \forall a,m \quad \left(\rho^A_{am}\right) \quad \textbf{(A. 16)}$$

Lastly, all variables are nonnegative:

$$SALES^A_{adm} \ge 0 \quad \textbf{(A. 17)}$$

$$\Delta^A_{am} \ge 0 \quad \textbf{(A. 18)}$$

The following presents the storage operator problem.

Storage Operator Problem

The storage operator provides an economic mechanism to efficiently allocate storage capacity to traders. The storage operator maximizes the discounted profit resulting from selling injection capacity $SALES^{SI}_{sdm}$ and extraction capacity $SALES^{SX}_{sdm}$ to traders. In equilibrium the capacity sales-rates $SALES^{SI}_{sdm}$ and $SALES^{SX}_{sdm}$ must be equal to the aggregate injection and extraction rates. Similarly as for the TSO, we take as a starting point that the regulator sets a maximum capacity usage fee based on the long-term marginal costs. Our simplified assumption is that the regulated fees collected from the traders equal the operating costs and therefore in the model the profit margin is equal to the congestion fees for injection τ_{sdm}^{SI} and extraction τ_{sdm}^{SX}. Note that these congestion fees are not paid in actuality, cf. the pipeline congestion fees. Besides the regulated tariffs for injection and extraction, costs may be accrued to expand capacities for injection, extraction and total working gas: $b_{sm}^{SI}\Delta_{sm}^{SI} + b_{sm}^{SX}\Delta_{sm}^{SX} + b_{sm}^{SW}\Delta_{sm}^{SW}$.

$$\max_{\substack{SALES_{sdm}^{SI},\\ SALES_{sdm}^{SX},\\ \Delta_{sm}^{SI},\Delta_{sm}^{SX},\Delta_{sm}^{SW}}} \sum_{m\in M}\gamma_m \sum_{d\in D} days_d \begin{Bmatrix} \tau_{sdm}^{SI} SALES_{sdm}^{SI} + \tau_{sdm}^{SX} SALES_{sdm}^{SX} \\ -b_{sm}^{SI}\Delta_{sm}^{SI} - b_{sm}^{SX}\Delta_{sm}^{SX} - b_{sm}^{SW}\Delta_{sm}^{SW} \end{Bmatrix} \quad \textbf{(A. 19)}$$

The aggregate injection rate in any season is restricted by the injection capacity (5-20). Injection capacities can be expanded; therefore the aggregate previous yearly expansions $\sum_{m'<m}\Delta_{sm'}^{SI}$ must be added to the initial capacity $\overline{INJ}_s^S$ to determine the total capacity. Equation (5-21) provides the limits to extraction from storage and condition (5-22) represents the working gas limitations.

s.t. $$SALES_{sdm}^{SI} \le \overline{CAP}_s^{SI} + \sum_{m'<m}\Delta_{sm'}^{SI} \quad \forall m,d \quad \left(\alpha_{sdm}^{SI}\right) \quad \textbf{(A. 20)}$$

$$SALES_{sdm}^{SX} \le \overline{CAP}_s^{SX} + \sum_{m'<m}\Delta_{sm'}^{SX} \quad \forall m,d \quad \left(\alpha_{sdm}^{SX}\right) \quad \textbf{(A. 21)}$$

$$\sum_{d\in D} days_d SALES_{sdm}^{SX} \le \overline{WG}_s^S + \sum_{m'<m}\Delta_{sm'}^{SW} \quad \forall m \quad \left(\alpha_{sm}^{SW}\right) \quad \textbf{(A. 22)}$$

The limitations to allowable capacity expansions are modeled as follows:

$$\Delta_{sm}^{SI} \le \bar{\Delta}_{sm}^{SI} \quad \forall m \quad \left(\rho_{sm}^{SI}\right) \quad \textbf{(A. 23)}$$

$$\Delta_{sm}^{SX} \leq \bar{\Delta}_{sm}^{SX} \quad \forall m \quad \left(\rho_{sm}^{SX}\right) \qquad \textbf{(A. 24)}$$

$$\Delta_{sm}^{SW} \leq \bar{\Delta}_{sm}^{SW} \quad \forall m \quad \left(\rho_{sm}^{SW}\right) \qquad \textbf{(A. 25)}$$

Note that mass balance for each storage facility (the *storage cycle* constraint) including accounting for losses, is dealt with (for each separate trader) in equation (A. 7).

Lastly, all variables are nonnegative:

$$SALES_{sdm}^{SI} \geq 0 \quad \forall m, d \qquad \textbf{(A. 26)}$$

$$SALES_{sdm}^{SX} \geq 0 \quad \forall m, d \qquad \textbf{(A. 27)}$$

$$\Delta_{sm}^{SI} \geq 0 \quad \forall m \qquad \textbf{(A. 28)}$$

$$\Delta_{sm}^{SX} \geq 0 \quad \forall m \qquad \textbf{(A. 29)}$$

$$\Delta_{sm}^{SW} \geq 0 \quad \forall m \qquad \textbf{(A. 30)}$$

Market-Clearing Conditions

The following are the market-clearing conditions that tie the various optimization problems together into one equilibrium problem.

Market-clearing between producers and traders:

$$SALES_{pdm}^{P} = \sum_{t(p)} PURCH_{tn(p)dm}^{T} \quad \forall p, d, m \quad \left(\pi_{n(p)dm}^{P}\right) \qquad \textbf{(A. 31)}$$

Market-clearing for storage injection capacity and volumes:

$$SALES_{sdm}^{SI} = \sum_{t \in T(N(s))} INJ_{tsdm}^{T} \quad \forall s, d, m \quad \left(\tau_{sdm}^{SI}\right) \qquad \textbf{(A. 32)}$$

Market-clearing for storage extraction capacity and volumes:

$$SALES_{sdm}^{SX} = \sum_{t \in T(N(s))} XTR_{tsdm}^{T} \quad \forall s, d, m \quad \left(\tau_{sdm}^{SX}\right) \qquad \textbf{(A. 33)}$$

Market-clearing between the TSO and the traders for arc capacity and flows:

$$SALES^{A}_{adm} = \sum_{t} FLOW^{T}_{tadm} \quad \forall a,d,m \quad \left(\tau^{A}_{adm}\right) \tag{A. 34}$$

The clearing of the final demand is represented as the inverse demand curve:

$$\left(\Pi^{W}_{ndm}(\cdot) =\right) \pi^{W}_{ndm} = INT^{W}_{ndm} + SLP^{W}_{ndm} \cdot \sum_{t} SALES^{T}_{tndm} \quad \forall n,d,m \quad \left(\pi^{W}_{ndm}\right) \tag{A. 35}$$

Karush-Kuhn-Tucker Conditions

In the KKT's the left-hand sides (relative to the $\perp$-sign) are the equations, the right-hand sides the variables. Most primal variables are denoted as normal words in capitals, except for capacity expansions, which are denoted by Greek letter □; all dual variables are written as Greek symbols.

KKT conditions for the producer's problem

$$0 \le \gamma_m days_d \left(-\pi^{P}_{n(p)dm} + \frac{\partial c^{P}_{pm}(SALES^{P}_{pdm})}{\partial SALES^{P}_{pdm}} \right) + \alpha^{PR}_{pdm} + days_d \alpha^{PH}_{pdm} \perp SALES^{P}_{pdm} \ge 0, \forall d,m \tag{A. 36}$$

$$0 \le \overline{PR}^{P}_{pm} - SALES^{P}_{pdm} \quad \perp \quad \alpha^{PR}_{pdm} \ge 0, \quad \forall d,m \tag{A. 37}$$

$$0 \le \overline{PH}_{p} - \sum_{m \in M} \sum_{d \in D} days_d SALES^{P}_{pdm} \quad \perp \quad \alpha^{PH}_{pdm} \ge 0 \tag{A. 38}$$

KKT conditions for the trader's problem

$$0 \le days_d \gamma_m \begin{pmatrix} \delta^{C}_{t,n} SLP^{W}_{ndm} SALES^{T}_{tndm} \\ -\left(\delta^{C}_{t,n} \Pi^{W}_{ndm} + (1-\delta^{C}_{t,n}) \pi^{W}_{ndm}\right) \end{pmatrix} + \phi^{T}_{tndm} \perp SALES^{T}_{tndm} \ge 0, \quad \forall n,d,m \tag{A. 39}$$

$$0 \le days_d \gamma_m \pi^{P}_{ndm} - \phi^{T}_{tndm} \quad \perp \quad PURCH^{T}_{tndm} \ge 0, \quad \forall n \in N(p(t)), d, m \tag{A. 40}$$

$$0 \le days_d \gamma_m \left(\tau^{SI,reg}_{ndm} + \tau^{SI}_{ndm}\right) + \phi^{T}_{tndm} - \left(1 - loss_n\right) days_d \phi^{S}_{tnm} \perp INJ^{T}_{tdnm} \ge 0, \quad \forall n,m \tag{A. 41}$$

$$0 \le days_d \gamma_m \tau^{SX}_{ndm} - \phi^{T}_{tndm} + days_d \phi^{S}_{tnm} \perp XTR^{T}_{tndm} \ge 0, \quad \forall n,m \tag{A. 42}$$

$$0 \le \begin{matrix} days_d \left[\gamma_m \left(\tau^{A}_{adm} + \tau^{A,reg}_{adm} \right) \right] \\ + \phi^{T}_{tn_{a-}dm} - (1 - loss_a) \phi^{T}_{tn_{a+}dm} - \varepsilon^{T}_{tadm} \end{matrix} \quad \perp \quad FLOW^{T}_{tadm} \ge 0, \quad \forall a = \left(n_{a-}, n_{a+}\right), d, m \tag{A. 43}$$

$$0=\begin{pmatrix} PURCH_{tndm}^{T}+\sum_{a\in a^{+}(n)}\left(1-loss_{a}\right)FLOW_{tadm}^{T}+XTR_{tndm}^{T} \\ -SALES_{tndm}^{T}-\sum_{a\in a^{-}(n)}FLOW_{tadm}^{T}-INJ_{tndm}^{T} \end{pmatrix},\quad \varphi_{tndm}^{T} free,\quad \forall n,d,m \qquad \textbf{(A. 44)}$$

$$0=\left(1-loss_{s}\right)\sum_{d}days_{d}INJ_{tsdm}^{T}-\sum_{d}days_{d}XTR_{tsdm}^{T},\quad \varphi_{tsm}^{S}\ free,\forall n,s\in S\left(N\left(t\right)\right),d,m \qquad \textbf{(A. 45)}$$

$$0\leq FLOW_{tadm}^{T}-CON_{tadm}^{T}\quad \perp \varepsilon_{tadm}^{T}\geq 0,\forall a,d,m \qquad \textbf{(A. 46)}$$

KKT conditions for the transmission system operator's problem

$$0\leq -days_{d}\gamma_{m}\tau_{adm}^{A}+\alpha_{adm}^{A}\quad \perp \quad SALES_{adm}^{A}\geq 0\quad \forall a,d,m \qquad \textbf{(A. 47)}$$

$$0\leq \overline{CAP}_{am}^{A}+\sum_{m'<m}\Delta_{am'}^{A}\quad -SALES_{adm}^{A}\perp \quad \alpha_{adm}^{A}\geq 0\quad \forall a,d,m \qquad \textbf{(A. 48)}$$

$$0\leq \gamma_{m}b_{am}^{A}-\sum_{d\in D}\sum_{m'>m}\alpha_{adm'}^{A}+\rho_{am}^{A}\quad \perp \quad \Delta_{am}^{A}\geq 0\quad \forall a,m \qquad \textbf{(A. 49)}$$

$$0\leq \overline{\Delta}_{am}^{A}-\Delta_{am}^{A}\quad \perp \quad \rho_{am}^{A}\geq 0\quad \forall a,m \qquad \textbf{(A. 50)}$$

KKT conditions for storage operator's problem

$$0\leq -days_{d}\gamma_{m}\tau_{sdm}^{SI}+\alpha_{sdm}^{SI}\perp SALES_{sdm}^{SI}\geq 0,\quad \forall d,m \qquad \textbf{(A. 51)}$$

$$0\leq -days_{d}\gamma_{m}\tau_{sdm}^{SX}+\alpha_{sdm}^{SX}+days_{d}\alpha_{sm}^{SW}\perp SALES_{sdm}^{SX}\geq 0,\quad \forall d,m \qquad \textbf{(A. 52)}$$

$$0\leq \gamma_{m}b_{sm}^{SI}-\sum_{d\in D}\sum_{m'>m}\alpha_{sdm'}^{SI}+\rho_{sm}^{SI}\quad \perp \quad \Delta_{sm}^{SI}\geq 0,\quad \forall m \qquad \textbf{(A. 53)}$$

$$0\leq \gamma_{m}b_{sm}^{SX}-\sum_{d\in D}\sum_{m'>m}\alpha_{sdm'}^{SX}+\rho_{sm}^{SX}\quad \perp \quad \Delta_{sm}^{SX}\geq 0,\quad \forall m \qquad \textbf{(A. 54)}$$

$$0\leq \gamma_{m}b_{sm}^{SW}-\sum_{d\in D}\sum_{m'>m}\alpha_{sm'}^{SW}+\rho_{sm}^{SW}\quad \perp \quad \Delta_{sm}^{SW}\geq 0,\quad \forall m \qquad \textbf{(A. 55)}$$

$$0\leq \overline{CAP}_{sm}^{SI}+\sum_{m'<m}\Delta_{sm'}^{SI}-SALES_{sdm}^{SI}\ \perp \ \alpha_{sdm}^{SI}\geq 0\qquad \forall m,d \qquad \textbf{(A. 56)}$$

$$0\leq \overline{CAP}_{sm}^{SI}+\sum_{m'<m}\Delta_{sm'}^{SX}-SALES_{sdm}^{SX}\ \perp \ \alpha_{sdm}^{SX}\geq 0\qquad \forall m,d \qquad \textbf{(A. 57)}$$

$$0\leq \overline{WG}_{s}^{S}+\sum_{m'<m}\Delta_{sm'}^{SW}-\sum_{d\in D}days_{d}SALES_{sdm}^{SX}\ \perp \ \alpha_{sm}^{SW}\geq 0\quad \forall m \qquad \textbf{(A. 58)}$$

$$0 \le \overline{\Delta}_{sm}^{SI} - \Delta_{sm}^{SI} \quad \perp \quad \rho_{sm}^{SI} \ge 0 \quad \forall m \tag{A. 59}$$

$$0 \le \overline{\Delta}_{sm}^{SX} - \Delta_{sm}^{SX} \quad \perp \quad \rho_{sm}^{SX} \ge 0 \quad \forall m \tag{A. 60}$$

$$0 \le \overline{\Delta}_{sm}^{SW} - \Delta_{sm}^{SW} \quad \perp \quad \rho_{sm}^{SW} \ge 0 \quad \forall m \tag{A. 61}$$

Market-clearing conditions

$$0 = SALES_{pdm}^{P} - \sum_{t(n) \in T(p)} PURCH_{t(n)n(p)dm}^{T} \quad , \quad \pi_{n(p)dm}^{P} \; free \quad \forall p,d,m \tag{A. 62}$$

$$0 = SALES_{adm}^{A} - \sum_{t} FLOW_{tadm}^{T} \quad , \; \tau_{adm}^{A} \; free \quad \forall a,d,m \tag{A. 63}$$

$$0 = SALES_{sdm}^{SI} - \sum_{t \in T(N(s))} INJ_{tsdm}^{T} \quad , \quad \tau_{sdm}^{SI} \; free \quad \forall s,d,m \tag{A. 64}$$

$$0 = SALES_{sdm}^{SX} - \sum_{t \in T(N(s))} XTR_{tsdm}^{T} \quad , \quad \tau_{sdm}^{SX} \; free \quad \forall s,d,m \tag{A. 65}$$

$$0 = \pi_{ndm}^{W} - \left(INT_{ndm}^{W} - SLP_{ndm}^{W} \cdot \sum_{t \in T(n)} SALES_{tndm}^{T} \right) \quad , \pi_{ndm}^{W} free \;\; \forall n,d,m \tag{A. 66}$$

The combination of all the Karush-Kuhn-Tucker conditions, the market-clearing conditions and inverse demand curves form the MCP. All minimization objective functions are convex and differentiable and all feasible regions are polyhedral, thus, the KKT points for this system are necessary and sufficient for optimal solutions.

Appendix 5-B

Table 5-B1. Average Wholesale Prices for 650ppm Case and 20-20-20 Case

Region	Year	$/KCM ($2005) Case Scenarios							
		650_Ω0_0CO₂	650_Ω0	650_Ω50	650_Ω100	202020_Ω0_0CO₂	202020_Ω0	202020_Ω50	202020_Ω100
AFRICA	2015	46.98	47.92	47.89	47.93	46.98	47.42	47.36	47.32
	2050	62.16	80.54	73.1	66.77	62.16	63.44	63.06	62.98
ASPACIF	2015	148.87	149.59	149.74	149.7	148.87	148.23	148.58	148.76
	2050	205.84	240.61	230.11	229.53	205.84	245.48	232.48	224.89
CHINA	2015	101.26	101.26	101.98	102.72	101.26	101.26	101.26	101.26
	2050	256.49	315.74	302.2	315.36	256.49	300.55	288.04	259.86
EUROPE	2015	189.98	192.58	192.7	193.02	189.98	189.91	190.08	190.17
	2050	257.81	291.02	285.74	283.85	257.81	285.64	278.83	274.33
FRSVTUN	2015	109.51	109.9	109.98	110.04	109.51	109.43	109.44	109.45
	2050	149.72	202.04	191.96	198.95	149.72	170.79	167.09	167.03
MIDEAST	2015	61.29	61.37	61.43	61.5	61.29	61.34	61.26	61.21
	2050	85.53	90.93	89.34	98.45	85.53	79.35	79.4	87.95
NRTH_AM	2015	151.89	158.85	158.11	162.36	151.89	150.29	152.58	151.62
	2050	192.35	242.45	224.23	209.32	192.35	231.74	217.39	201.71
STH_AM	2015	201.71	207.01	207.13	207.04	201.71	201.35	201.54	201.66
	2050	203.56	249.65	239	217.75	203.56	258.41	241.21	218.65

Appendix 5-C

Table 5-C1. Total Production Costs in the U.S. x$10^9 (20-20-20 Case)

Year	x$10^9 ($2005) 20-20-20 Case Scenarios			
	20-20-20_Ω0_0CO₂	20-20-20_Ω0	20-20-20_Ω50	20-20-20_Ω100
2015	48.18	48.72	48.22	49.16
2020	49.27	49.98	49.96	49.95
2025	53.25	54.04	54.09	53.95
2030	57.74	67.27	63.05	69.36
2035	56.00	64.27	60.98	66.42
2040	56.67	63.91	60.38	65.30
2045	60.44	73.99	72.77	73.14
2050	62.81	77.53	76.25	75.45

Table 5-C2. Loss of Producer Surplus in the U.S. x$10^9 (20-20-20 Case)

Year	10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO₂) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO₂) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO₂) vs. 20-20-20 100% to consumers (Ω100)
2015	0.51	0.36	0.23
2020	0.22	0.10	0.12
2025	0.34	0.15	0.05
2030	18.86	4.56	2.11
2035	18.13	5.26	1.59
2040	17.74	4.51	1.07
2045	16.64	7.88	1.64
2050	17.31	8.22	1.54

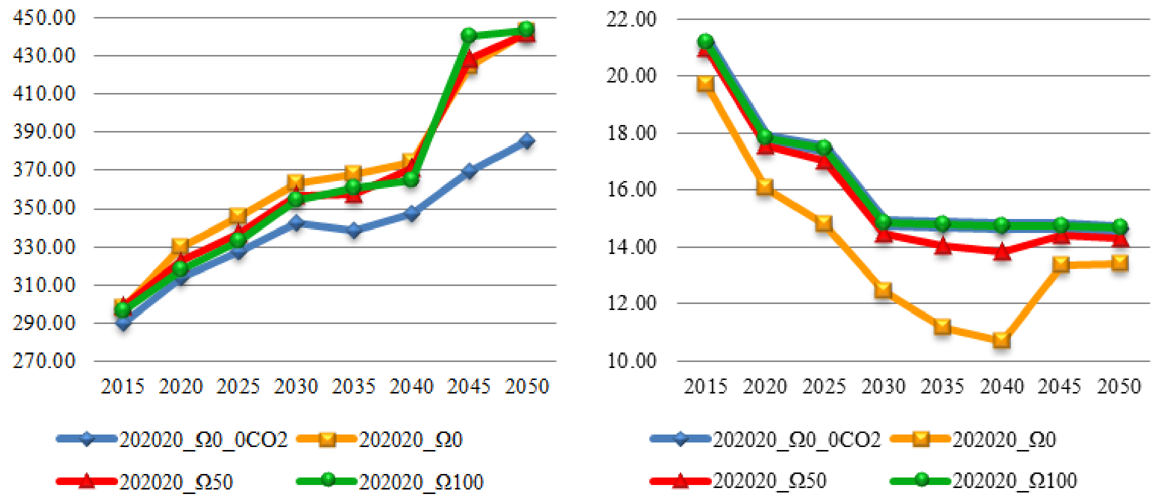

Figure 5-C1: Average Wholesale Prices \$/KCM (\$2005) (left) and Production in BCM/Y in Germany (20-20-20 Case) (right)

Table 5-C3. Average Wholesale Prices and Production Volumes in Germany (20-20-20 Case)

Year	\$/KCM (\$2005) 20-20-20 Case Scenarios				Production in BCM/Y 20-20-20 Case Scenario			
	202020_Ω0_0CO_2	202020_Ω0	202020_Ω50	202020_Ω100	202020_Ω0_0CO_2	202020_Ω0	202020_Ω50	202020_Ω100
2015	290.28	297.93	299.02	296.64	21.21	19.71	20.98	21.19
2020	313.50	329.45	322.17	317.63	17.86	16.10	17.59	17.84
2025	327.04	345.86	337.16	332.53	17.48	14.82	17.04	17.46
2030	342.46	363.39	356.90	354.28	14.86	12.46	14.48	14.86
2035	338.18	368.27	357.31	360.51	14.80	11.18	14.06	14.79
2040	347.34	374.05	371.01	364.57	14.74	10.71	13.81	14.72
2045	369.18	424.47	428.85	440.55	14.72	13.38	14.42	14.76
2050	385.69	442.59	442.17	443.98	14.65	13.39	14.34	14.70

Table 5-C4. Loss of Consumer Surplus in Germany

Year	10^9 \$ (\$2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 100% to consumers (Ω100)
2015	0.16	0.18	0.13
2020	0.27	0.15	0.07
2025	0.30	0.17	0.10
2030	0.29	0.21	0.18
2035	0.39	0.28	0.33
2040	0.34	0.34	0.25
2045	0.78	0.87	1.05
2050	0.80	0.82	0.86

Table 5-C5. Total Production Costs in Germany x$10^9 (20-20-20 Case)

Year	x$10^9 ($2005) 20-20-20 Case Scenarios			
	20-20-20_Ω0_0CO_2	20-20-20_Ω0	20-20-20_Ω50	20-20-20_Ω100
2015	3.01	3.52	3.38	3.01
2020	2.73	3.17	3.10	2.73
2025	2.88	3.14	3.23	2.87
2030	2.64	2.81	2.94	2.63
2035	2.82	2.66	3.03	2.82
2040	3.02	2.68	3.16	3.01
2045	3.24	3.51	3.50	3.26
2050	3.47	3.72	3.71	3.49

Table 5-C6. Loss of Producer Surplus in Germany x$10^9 (20-20-20 Case)

Year	10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 100% to consumers (Ω100)
2015	0.754	0.409	0.001
2020	0.748	0.413	0.001
2025	0.764	0.432	0.004
2030	0.654	0.374	0.004
2035	0.618	0.360	0.002
2040	0.576	0.342	0.002
2045	0.589	0.324	0.005
2050	0.576	0.316	0.011

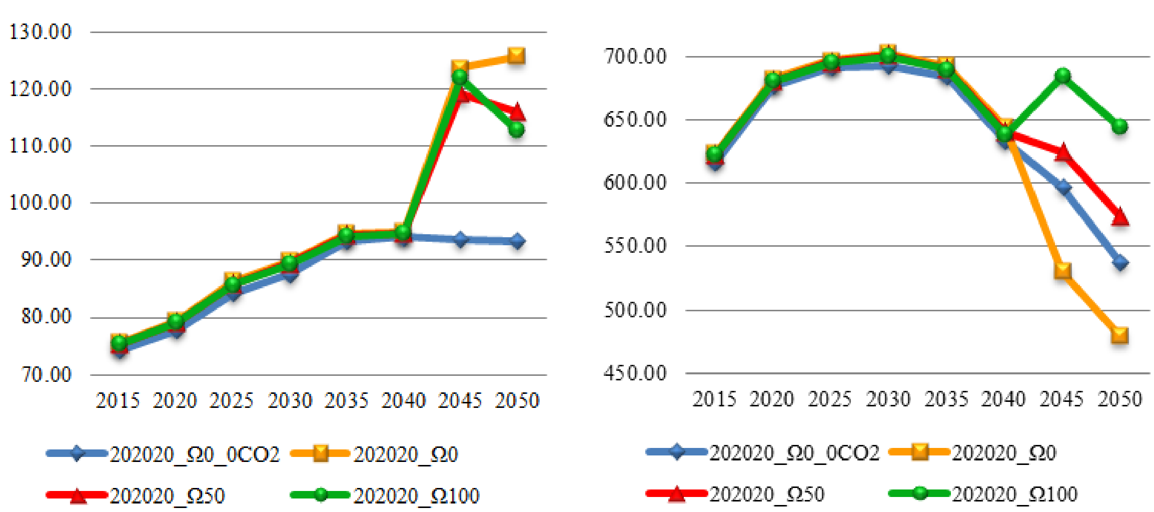

Figure 5-C2: Average Wholesale Prices $/KCM ($2005) (left) and Production in BCM/Y in Russia (20-20-20 Case) (right)

Table 5-C7. Average Wholesale Prices and Production Volumes in Russia (20-20-20 Case)

Year	$/KCM ($2005) 20-20-20 Case Scenarios				Production in BCM/Y 20-20-20 Case Scenario			
	202020_Ω0_0CO_2	202020_Ω0	202020_Ω50	202020_Ω100	202020_Ω0_0CO_2	202020_Ω0	202020_Ω50	202020_Ω100
2015	74.15	75.57	75.29	75.27	616.79	623.43	622.16	622.07
2020	77.69	79.29	78.97	78.99	676.94	682.71	681.21	680.76
2025	84.28	86.24	85.88	85.69	691.40	697.34	696.13	695.60
2030	87.54	89.76	89.45	89.31	693.25	702.81	701.44	700.93
2035	93.46	94.75	94.40	94.25	685.02	693.25	690.98	690.13
2040	94.03	95.05	94.78	94.58	633.55	643.98	640.78	638.35
2045	93.69	123.64	119.23	121.94	596.73	530.19	625.07	684.74
2050	93.32	125.69	115.95	112.69	536.99	478.32	574.14	644.77

Table 5-C8. Loss of Consumer Surplus in Russia

Year	10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 100% to consumers (Ω100)
2015	0.88	0.71	0.69
2020	1.09	0.87	0.88
2025	1.36	1.11	0.98
2030	1.55	1.33	1.23
2035	0.89	0.65	0.54
2040	0.65	0.48	0.35
2045	16.88	15.60	18.10
2050	16.43	12.57	11.45

Table 5-C9. Total Production Costs in Russia x$10^9 (20-20-20 Case)

Year	x$10^9 ($2005) 20-20-20 Case Scenarios			
	20-20-20_Ω0_0CO_2	20-20-20_Ω0	20-20-20_Ω50	20-20-20_Ω100
2015	31.32	31.71	31.72	31.80
2020	37.46	37.77	37.81	37.94
2025	41.67	42.04	42.09	42.20
2030	45.18	45.86	45.90	46.04
2035	48.34	48.81	48.88	49.10
2040	47.48	47.96	48.21	48.52
2045	47.34	56.29	56.86	52.39
2050	44.86	56.14	54.79	49.63

Table 5-C10. Loss of Producer Surplus in Russia x$10^9 (20-20-20 Case)

Year	10^9 $ ($2005) 20-20-20 Case Scenarios		
	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 0% to consumers (Ω0)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 50% to consumers (Ω50)	No Carbon Cost (Ω0_0CO_2) vs. 20-20-20 100% to consumers (Ω100)
2015	0.050	0.121	0.214
2020	0.004	0.111	0.266
2025	0.011	0.129	0.277
2030	0.055	0.187	0.355
2035	0.112	0.120	0.397
2040	0.299	0.184	0.682
2045	15.120	7.114	1.806
2050	17.176	6.612	3.881

CHAPTER 6: CONCLUSIONS AND EXTENSIONS

6.1 Contributions

Problems related to global climate change and resource scarcity are main concerns for a society trying to build a sustainable infrastructure. These problems are targeted from many perspectives, including government-enforced policies and regulations that call for energy efficiency and transportation efficiency to build a sustainable infrastructure. Even though the directions for improvement are defined, the methods and techniques for reaching these specified goals are not yet well developed. Decision-makers do not have sufficient and accurate models to evaluate the impact of proposed carbon policies supporting sustainable infrastructure.

In this dissertation an interdisciplinary approach is used with the aim of analyzing programs geared at reducing emissions and costs, and determining optimal allocation of resources along with profit maximization by developing and employing optimization, regression and game-theoretic models for three strategically important industries. Specifically, this dissertation addresses specific problems and provides tools to support informed decision-making in the construction, energy and transportation industries. Decisions made in any of these industries are complementary to each other and can be directed toward the common goal of building a sustainable infrastructure. The set of developed models can aid in carbon policy developments and evaluations in these industries.

In each of these industries, specific problems were identified related to sustainability and emissions minimization. Specifically, it was noticed that for the construction industry to be more sustainable and emit less, the contractors must either replace the old construction equipment or retrofit existing equipment pieces, since the old equipment fleets are major sources of environmental pollution. Unfortunately, both options are expensive, and, therefore, the identified objective was to minimize emissions from construction equipment, while satisfying all task-specific requirements for construction projects in a cost-efficient way. This problem was addressed in a novel mixed integer program. The program aids in the construction equipment selection process that simultaneously satisfies all the necessary conditions of cost and emission minimization. The model can also aid in bid preparation for construction projects given increasing public sentiment for “green” construction The output of the model is a list of construction equipment to be used for project activities at a given time interval. The model is helpful both to the private sector and government agencies interested in cost and emissions minimization from construction projects.

In the energy sector, the identified problems are for the natural gas industry that when solved successfully can contribute to informed decision-making towards sustainable development. The first problem identified in this area is the complexity related to the decisions for supply network capacity expansion and investment. Natural gas demand is increasing, which also assumes more supply requiring reconstruction of the existing natural gas supply infrastructure. It is very costly to invest in energy supply networks and, together with the issue of security of supplies, the decisions for such investments become more difficult and are highly strategic. The decisions made for energy supply networks are affected by the market structure where some market representatives have a leader position and others act as followers. The bi-level mathematical problem with equilibrium constraints was developed. The objective function of the leader's profit maximization problem considers issues pertaining to both construction related costs and environmental pollution. Feedback from the model allows for more informed negotiations between suppliers and consumers, and, therefore, can be used for planning sustainable development benefiting society. This model can be used by both the private sector and government agencies for supply network expansion decisions and financing, in addition to defining specific aspects of contractual agreements between suppliers and consumers.

Not only in the U.S., but also around the world, owners of vehicles used in on-road transportation is purchasing to environmentally friendlier vehicle models. In this process, new technologies are being developed. Hybrid vehicles that use renewable energy sources in combination with fossil fuels, including natural gas, are thus entering the market. In many instances, the integration of these vehicles employing new technologies is supported by government incentives and policies, but the improvement in terms of reduced emissions due to these vehicles in everyday usage has not been quantified. The expected improvement in the amount of emissions is mostly based on laboratory tests or scientifically calculated values, but the collective effect of an increase in these vehicles in the vehicle mix in conjunction with driving conditions has not been analyzed in detail. These details may allow for specific policy or incentive recommendations towards a more sustainable transportation system. Given the mix of vehicles in the vehicle composition, the impact of new technology vehicles on the amount of emissions can vary from ideal conditions. The impact of road type and driving conditions together with vehicle specifics need to be considered for more accurate or representative results (compared to idealistic single vehicle performance testing). Since it is time consuming and costly to model and simulate each and every possible incentive and policy assessing the cost effectiveness of investments (supporting the integration of new vehicular technologies), a set of regression models was developed to aid in predicting the impact of newer and alternative technology vehicles on the amount of emissions on freeways and arterial roads. These models would help in policy development, determining the level of incentive that might be warranted, incentivizing consumers to purchase newer technology vehicles, and would also help in reaching certain goals for emission minimization from on-road traffic. Similarly, these models can be used by private organizations and companies or by government agencies responsible for developing incentives that aim at lowering emissions from on-road traffic.

Given the expected increase in the usage of natural gas and the importance of understanding the impact of carbon policies on the natural gas industry, a novel technique was developed allowing such assessments. This part of the dissertation extends previously developed natural gas industry model (called World Gas Model) at the University of Maryland. The extension was done through a practical reformulation of objective functions, allowing the assignment of carbon costs to both suppliers and consumers simultaneously. This technique enables development of a whole range of new carbon policies for the natural gas industry. It is found that for some regions in the world there is a potential for carbon policy adoption without significantly affecting the equilibrium average wholesale prices or quantities. The impact on loss of consumer's and producer's surplus can be improved through a proper allocation of carbon costs along the supply chain of natural gas. Previously, detailed impact analyses of carbon policies along the gas supply chain were not generally available. The applied formulation enables the analyses of carbon cost effects on natural gas markets. Such analyses can be conducted either by the private sector or by governments that will decide on the sufficient magnitude of restrictions and costs or application of carbon policies to support emissions minimization related to the natural gas market.

The value added of this research is the development of more accurate feedback for informed decision-making and policy development, focusing on sustainable infrastructure in specific industries. This is done through an efficient formulation of problems by considering industry-specific details that cover engineering, economic and environmental aspects of sustainable practices. As such, the engineering aspects considered in the construction model are included in the optimization problem. The developed mixed integer model is flexible enough to be applied practically to any construction project. In the case of natural gas industry, the earlier models did not use a two-level MPEC problem structure for the natural gas supply network expansion problems. The model developed in this dissertation allows for better representation of the natural gas market than one-level models and also builds a relationship with construction industry and the environment. The on-road traffic emission estimation models are structured as polynomial functions that consider vehicle-specific parameters and road gradient that in a combined function allow analyses in on-road traffic emission estimation. Finally, the WGM extension that captures carbon cost analyses are implemented through a technique that allows proportional application of carbon costs not previously used in a setting.

6.2 Assumptions, Shortcomings and Extensions

The developed models and case studies are based on certain assumptions and, therefore, have some shortcomings. In particular, the construction equipment selection model is well structured, but some linearity assumptions were made for overall productivity considerations of equipment pieces. For the case study on the actual ICC project, the entire data for construction tasks was not provided in every specific detail due to confidentiality. This difficulty was overcome by using some scientific estimation and practical judgment to compute values for specific tasks from contractor-provided aggregate quarterly data. Also, equipment cycle times and, thus, the amount of work each piece of available equipment could complete in a given day were estimated from equipment specifications assuming 75% "duty days" and eight-hour workdays. The amount of work to be completed in each work category was calculated from provided total work estimates, prior knowledge of construction processes, categories of equipment assigned to tasks, and equipment productivity.

In the natural gas supply network expansion model, the assumption of linear inverse demand function was made for computational- and formulation-related purposes. This assumption was a deviation from reality, because the linear approach is a simplified representation of almost any market. For the case study, some assumptions were made in terms of identifying the reasonable set of parameters of the inverse demand functions including the slope and intercept values, because real world data for those parameters for a natural gas supply network expansion were not available. Specifically, the slope and the intercept for the Chinese natural gas demand function were based on a data available for only a few regions and do not represent the entire country's response to price change.

Similar assumptions were also made for the demand elasticity of supply capacity expansions in China. Due to a lack of information the cost estimations for supply capacity expansions were made based on Russian values and adjusted with the data from the U. S. Census Bureau.

The on-road transportation emission estimation models also have some assumptions and limitations in terms of accuracy and applicability. These models were developed based on estimated data obtained from ORSEEM. The set of runs were limited to freeway and arterial networks within a specific set of parameters, making the models useful for conditions observed on specified roadways. There are a number of limitations in this study and, hence, in the use of the developed regression models. For example, traffic volume increases by up to 20% from the 2005 base year levels. Moreover, an increase of only 5.3% was assumed between 2005 and 2010. This might constrain the traffic volumes in future years, as an increase by more than 20% could be possible. However, it is not likely to be a limiting factor for near-term future analyses. Even though the models were developed using millions of data points, only one change in vehicle composition was tested. Systematic study of vehicular technology changes is required to draw more general conclusions. Findings given herein were developed from numerical experiments. Field tests would be needed to validate the findings and estimates generated through VISSIM and ORSEEM. Comprehensive field tests would be required, which are very difficult and expensive to conduct.

Finally, some assumptions were made regarding the carbon policy analyses in the natural gas industry. Specifically, it was assumed that per ton carbon costs in suggested policies were known. If a modeler desires to make a suggestion for a new policy, the model would not be able to provide information on the equilibrium prices of carbon.

An interesting extension to the construction equipment selection model might be the inclusion of a human factor as an iterative optimization process in the productivity of construction processes, using the available set of construction equipment. Another extension could be the consideration of a learning curve expressed as a function of productivity improvement, if the model is used for repetitive projects. To support applications with large numbers of equipment pieces, the proposed tools can be embedded within a decision-support framework where other aspects of construction activities, including the design and technological differences affecting the amount of emissions, can be analyzed.

Improvements are also possible for the natural gas supply network expansion model. To improve the formulation, the security of the supply factor giving the consumer a choice of being dependent on any supplier (already considered in the model) can be endogenized. This approach would allow the model to determine the dependences from suppliers and suggest preferable actions for contractual negotiations. Additionally, the values for resource availability can be endogenized as a function of technological advancements, which will allow dynamic, endogenized availability of resources subject to technology.

A possible extension of on-road traffic emission estimation models can be further tuning of regression parameters through extra simulation runs for other types of roads. The selected set of parameters in the models can also be adjusted. However, the existing parameters were found to be representative of vehicle-related emissions.

There are also some interesting possibilities for the extension of the WGM model, such as endogenizing the weights for proportional assignment of carbon costs to the suppliers and consumers. Such extension would require addition of a new player in the WGM model. The dual variables of certain players' constraints could be considered in the current extended forms of the objective functions accounting for carbon costs. Otherwise, the inclusion of weights (as a new set of endogenous variables) would create nonlinearity in the objective functions of each player's problem.

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