# Modeling and Analysis of Energy Production Systems for Environmentally Conscious Supply Chain Management

by

Ahu SOYLU

A Thesis Submitted to the
Graduate School of Engineering
in Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in

Industrial Engineering

Koç University

July 2005

Koç University

Graduate School of Sciences and Engineering

This is to certify that I have examined this copy of a master's thesis by

Ahu Soylu

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Ceyda OĞUZ, Ph. D.

Serpil SAYIN, Ph. D.

Metin TÜRKAY, Ph. D. (Advisor)

Date:

*to "the one"…*

## ABSTRACT

The energy sector is a high-cost and high-emission sector. With the demanding environmental regulations, the energy producing companies must find new solutions continuously to decrease emissions while satisfying the energy demand. It was shown that collaboration by exchanging steam among the companies may create synergy both in environmental and economical criteria. In this thesis, the analysis of the synergy created by collaboration is examined in detail; the conditions that can create synergy and the behavior of synergy under specific cases are examined. Moreover, optimization models that resemble real characteristics of cogeneration systems are developed. Cogeneration systems include boilers that are crucial equipments in the sense they incur most of the operating costs and harmful gas emissions. Therefore, performance maintenance of boilers is an important aspect in the management of energy systems. A modeling technique is developed for performance maintenance with two approaches. Then, the optimization model is extended to reflect the contradicting multi-objective nature of the energy systems: minimize the total cost and minimize the emissions of environmentally harmful gases. The incentives of companies under the economy - environment contradiction are examined. This contradiction requires making new technology investments to reduce emissions to desired levels. Therefore, a model for planning the transition to new technologies has been developed for the energy production system. It is found on the example system that, in addition to collaboration, companies must make investments in new technologies in order to achieve the required emission reductions in the long run.

**ACKNOWLEDGEMENTS**

I would like to thank Asst. Prof. Metin Türkay not only for his guidance in my study but also for his positive attitude and confidence in me. I would also like to thank Assoc. Prof. Serpil Sayın and Assoc. Prof. Ceyda Oğuz for their participation in the thesis committee and for their supportive comments on my thesis.

I'd like to present my deepest appreciation to all of my professors from Koç University and Bilkent University, for their teaching and guidance in my academic studies.

To all of my dear friends, thank you for sharing life under any circumstances. Impossible to name you all, but a few, Semra, Fadime, Zeynep, Başak, Tuğrul, Ertunç, Göker… And Aysun, my friend forever, thank you for days and nights together, being with me and being your perfect self…

Finally, I want to thank my dear family for their endless love and support.

**TABLE OF CONTENTS**

## LIST OF TABLES

## LIST OF FIGURES

## NOMENCLATURE

**Parameters**

| | |
|---|---|
| $1/\eta$ | boiler efficiency [kJ/kg] |
| $cc$ | calorific value of the fuel |
| $a$ | consumption parameter for HP generation |
| $s_{Sox}$ | $SO_x$ emission parameter [$m^3$/ton of fuel] |
| $s_{GHG}$ | GHG emission parameter [$m^3$/ton of fuel] |
| $e$ | coefficient of electricity generation vs. HP steam input |
| $g$ | coefficient of electricity generation vs. MP-LP steam generation |
| $I^U$ | storage capacity of a fuel tank [ton] |
| $I_0$ | initial inventory in a fuel tank [ton] |
| $\delta$ | safety stock parameter (defined as a fraction of $I^U$) |
| $X^L_{HP,GEN}$, $X^U_{HP,GEN}$ | lower and upper limits on HP generation in a boiler |
| $p^L$,$p^U$ | lower and upper limits on fuel purchase [ton/order] |
| $c$ | cost of unit amount of fuel [$/ton] |
| $v$ | fixed cost of purchasing fuel [$/order] |
| $h$ | unit holding cost of fuel [$/ton of fuel] |
| $d$ | demand of a certain product [kWh/hr or ton/hr] |
| $\xi$ | capacity of exchange structure of a certain product at a specific mode |
| $\tau$ | lifetime of a certain type of exchange structure |
| $\varphi$ | cost of exchange structure construction for a certain product at a specific mode |
| $\omega$ | proportion of company in the cost of exchange structure construction |
| $n$ | length of a period [hours] |
| $X^U_{Sox}$ | upper limit on $SO_x$ emission [$m^3$] |
| $X^U_{GHG}$ | upper limit on GHG emission [$m^3$] |
| $\varsigma_{Sox}$ | penalty cost of $SO_x$ release [$ /$m^3$] |
| $\varepsilon$ | price of unit electricity [$ / kWh] |
| ο | fixed cost for operating |
| σ | fixed cost for the startup operation |
| λ | depreciation rate of boiler with age |
| κ | maximum age that a boiler can be used |
| θ | minimum capacity that a boiler can have |
| $\mu$ | cost of device change in a boiler |
| $\ell$ | depreciation rate with cumulative HP production |
| $GP^U_{iy}$ | the maximum amount of GHG emission limits that can be purchased by company *i* at year *y* |

| | |
|---|---|
| $cbn_f$ | the cost of a new boiler in a period of five years, *f* |
| $ctn_f$ | the cost of a new turbine in a period of five years, *f* |
| $cng_f$ | the cost of a switching an existing boiler to natural gas in a period of five years, *f* |
| $IC^U_{if}$ | the maximum investment that can be spent by company *i* in a period of five years, *f* |
| $pg_y$ | price of unit GHG emission permit in year *y* |

**Variables**

| | |
|---|---|
| $X_{ijklt}$ | the amount of material *k* in the unit *j* that belongs to company *i* in state *l* at any period *t* |
| $XHF_{ijkt}$ | the amount of HP steam generated in boiler *j* of company *i* at period *t* by using fuel *k* |
| $YFU_{ijkt}$ | binary variable representing if the fuel *k* is used in boiler *j* of company *i* in period *t* |
| $Y_{ijt}$ | binary variable for modeling unit *j* (boiler, turbine)of company *i* is operating in period *t* |
| $YS_{ijt}$ | binary variable for modeling unit *j* (boiler, turbine)of company *i* is at startup in period *t* |
| $I_{ijkt}$ | the amount of fuel *k* in tank *j* of company *i* at period *t* |
| $C_i$ | the total cost of purchased fuel by company *i* |
| $YP_{ijkt}$ | binary variable for modeling fuel purchase for tank *j* of company *i* in period *t*. |
| $CP_i$ | the total fixed fuel purchasing cost of company *i* |
| $HC_i$ | the total fuel holding cost of company *i* |
| $XE_{iji'j't}$ | the amount of material exchange from unit *j* of company *i* to unit *j'* of company *i'* in period *t* |
| $XEC_{iji'j't}$ | the maximum available capacity of material exchange between unit *j* of company *i* and unit *j'* of company *i'* period *t* |
| $YEC_{iji'j'mt'}$ | binary variable for the construction of exchange structure at mode *m* between company *i* and *i'* to exchange resources in units *j* and *j'* in period *t'* |
| $CE_i$ | proportion of the investment required for company i to establish a link between two companies *i* and *i'* in units *j* and *j'* |
| $CS_i$ | the total $SO_x$ release penalty of company *i* |
| $CEL_i$ | the total electricity purchase cost of company *i* |
| $YO_{ijbt}$ | 1, if the device *b* is on company *i*'s boiler *j* at period *t*; 0, o.w. |
| $YW_{ijbt}$ | 1, if the device *b* on company *i*'s boiler *j* is working at period *t*; 0, o.w. |
| $YN_{ijbt}$ | 1, if the device *b* for company *i*'s boiler *j* is not used yet at period *t*; 0, o.w. |
| $YX_{ijbt}$ | 1, if the device *b* for company *i*'s boiler *j* has been taken off and is old at period *t*; 0, o.w. |
| $YC_{ijbt}$ | 1, if the device *b* for company *i*'s boiler *j* is set up at period *t*; 0, o.w. |
| $XHFD_{ijkbt}$ | the amount of HP steam generated in boiler *j* of company *i* at period *t* by using fuel *k* using device *b* |
| $FD_{ijkbt}$ | the amount of fuel *k* consumed in boiler *j* of company *i* at period *t* using device *b* |

| | |
|---|---|
| $A_{ijbt}$ | the age of device *b* in boiler *j* of company *i* at period *t* |
| $CM_i$ | the total maintenance cost of company *i* |
| $YBN_{ijt'}$ | 1, if the company *i* purchases new boiler *j* at period *t'*; 0, o.w. |
| $YTN_{ijt'}$ | 1, if the company *i* purchases new turbine *j* at period *t'*; 0, o.w. |
| $YNG_{ijt'}$ | 1, if the company *i* existing boiler *j* is switched to natural gas at period *t'*; 0, o.w. |
| $G_{ijkct}$ | the amount of GHG released from company *i*'s boiler *j* changing with the type of fuel used and the existence of CCS at period *t* |
| $CCE_{it}$ | 1, if CCS system exists at the company *i* at period *t*; 0, o.w. |
| $CC_{it'}$ | 1, if CCS system is constructed at the company *i* at period *t'*; 0, o.w. |
| $XC_{ijklct}$ | the amount of materials used or produced in company *i*'s turbine *j* changing with the existence of CCS at period *t* |
| $GP_{iy}$ | the amount of GHG emission limits purchased by company *i* at year *y* |
| $IC_{if}$ | the investment cost that is spent by company *i* in a period of five years, *f* |
| $OC_{iy}$ | the operation cost that is spent by company *i* at year *y* |

**Indices**

| | |
|---|---|
| *i* | index representing the company, *i* = Company 1, Company 2, Company 3, Company 4, Company 5, Company 6 |
| *j* | index representing the unit, *j* = Boiler 1, Turbine1, Mixer/SplitterHP1,… |
| *k* | index representing the material, *k* = HP, LP, Fuel 1, Biodiesel, electricity, GHG,... |
| *l* | index representing state of the material, *l* = in, out, gen, con |
| *m* | mode of exchange structure *m* = High, Medium, Low |
| *t, y, f* | indices representing different time periods |
| *b* | index representing the device on a boiler, *b* =Device 1, Device 2, Device 3, Device 4 |
| *c* | index representing the existence of CCS *c* =CCS, NoCCS |

# Chapter 1

## INTRODUCTION

Energy is a fundamental entity of modern life that has strong influence on social, industrial and economic activities in a society. As such per capita energy consumption is an important measure in the quality of life in different regions of the world. Electricity constitutes a major proportion of the energy requirements. Electricity has to be produced in the right amount at the right time since it cannot be stored in large quantities for extended periods. This is a distinct feature of energy that differentiates it from other materials.

Fossil fuel based energy systems are the dominating electricity production technologies in the world. An important aspect of fossil fuel based energy systems is the inevitable release of harmful substances to the environment. Energy production systems release a large quantity of environmentally harmful substances such as, $SO_x$ and Green House Gases (GHG). Therefore, environmental protection must be treated as an important factor in the energy supply chain. The Kyoto Protocol [1] demands for reductions in greenhouse gas emissions by the industrialized countries. The energy sector will be seriously affected with Kyoto Protocol since it requires countries to have an air pollution management strategy. The amount of substances released to environment will be restricted. This restriction can be achieved by reducing the energy consumption, changing energy production technologies to environmentally friendlier ones or taking some remedy actions in energy supply chain management.

Supply chain management involves all of the activities in industrial organizations from raw material procurement to final product delivery to customers. The main aim in supply chain management is to satisfy production requirements, while optimizing the economic objectives. Moreover, environmental improvements are performance measures of a company. After it has been realized that integration can be beneficial for performance measures of companies, many companies are integrating their operations in order to benefit from the performance improvement that can be achieved by better coordination.

Since all of the systems require energy for production, there usually exist a number of energy production companies in an industrial area. Since these companies are in geographical proximity, process integration and collaboration among them is viable. Electricity production in cogeneration facilities are known to be the most efficient thermal energy producing systems. Cogeneration facilities consume fuel in electricity production and produce steam as well. They emit environmentally harmful substances by fuel consumption in electricity production. Therefore, environmental performance of an energy producing company is important. It has already been shown that collaboration by exchanging steam among the energy producing companies may create synergy both in environmental and economical criteria by Türkay et. al.[2] and Oruç [3].

## 1.1 Overview of the Thesis

In this thesis, the analysis of the synergy created is examined in detail. An analytical derivation for the financial synergy that is created by collaboration in a simplified version of the energy production companies is conducted. After that derivation, the analysis is enlarged to examine the effects of differences in specific parameters on collaboration benefit. The conditions that can create synergy and the behavior of collaboration under specific cases are examined. It has been verified that, in order to benefit from collaboration, the companies must have some parameters that are not identical and some idle capacity in their units.

In order to examine the synergy created by collaboration, in a setting that includes many real life aspects of the energy systems, the model developed by Türkay et. al. [2] and Oruç [3] is enhanced; new improvements as well as modifications on the model are conducted. With the model enhanced with significant details, the financial synergy analysis is performed in order to verify the finding that synergy is created under existence of special differences between companies. In the existence of synergy, it is realized that it requires one company lose and the other one gain. Therefore, it is necessary to examine if collaboration can be beneficial for both companies. With some modifications in the model to reflect two contracts, it is shown that collaboration can be financially beneficial for both companies. Another analysis regarding the environmental performance is conducted such that collaboration enables companies perform environmental improvements without sacrificing from the minimal costs of their non-collaborated solutions.

During the analyses of the cost structures of the companies, it is realized that the fuel purchasing costs constitute a large proportion of the total costs. Moreover, the idle capacity of the boilers is an important feature in obtaining synergy with collaboration. Therefore, the behavior of the boilers is important in energy systems. The capacity of the boilers decreases with the precipitation of materials in the fuels used. In order to be able to model performance decay and maintenance in the model, a new model is developed that schedules the performance maintenances and boiler states. The model is able to reflect the behavior of the boilers under performance maintenance requirements. The modeling technique for performance maintenance with decaying performance is new and it is open for improvements.

The multi-objective nature of the energy systems is modeled by considering the limits on GHG emissions as a second objective rather than a constraint. This is because with the increasing environmental demands of the environmentalists, government and the nature itself, environmental consideration is no more a limit but an objective to be minimized. The $SO_x$ release is kept as a constraint because its limits are strict and the release costs are well quantified in terms of penalties paid to the governments. The impact of GHG emissions on global warming can be measured in units of metric tons of carbon dioxide ($CO_2$) equivalent units. The Kyoto protocol [1] puts emission decrease targets from the year 1990 emission levels of countries to achieve and the governments put individual decrease targets on companies. But the limits are not so strict in the sense of the existing $CO_2$ trading availability [4]. $CO_2$ trading is a major concept in international relations stating that countries and individual companies can exchange their $CO_2$ release permits. For example, since 1 January 2005, some 12,000 large industrial plants in the EU have been able to buy and sell permits to release $CO_2$ into the atmosphere. By this way, investments in cleaner technologies can then be turned into profits while helping to meet Kyoto commitments. The prices of the permits are not known for certain and they are expected to follow an open market behavior. According to Energy Information Administration (EIA)'s Report [5], the carbon prices are projected to be between $67/ton and $348/ton in 2008-2012 period, rising with higher emission reductions. Therefore, it is worthwhile to know, with a cost benefit approach, how much it costs for the companies to conduct a pre-specified decrease in greenhouse gas emissions. This value can be useful to determine the amount of $CO_2$ that they can trade or emit. In order to assess that, the efficient frontier regarding the economy – environment conflict has been put into effect.

With the increasing demand of energy by growing population and requirements for higher quality of life, the projections in EIA's report [5] suggest that without transition, it is impossible to reduce the emissions to the year 1990 levels or less. The researchers are in the search of new technologies that will reduce the emissions of harmful gases to the atmosphere. Renewable energy technologies are promising in the sense that they release almost no emissions to the atmosphere [6]. They constitute a large group of technologies including, solar photovoltaic cells, wind turbines, and biodiesel usage in energy production. The weakness of renewable energy sources is that their high costs of investment and unreliable output changing with the shining rate, wind speed, etc. That is why the solutions like using the renewable energy technologies together with conventional electricity production techniques are emerging. There are also other emission reduction techniques that extensive research is conducted on. Carbon Capture and Sequestration (CCS) is a technique mainly involving capturing the carbon from the fuel and injecting it underground. Another technique is switching the boilers to burn natural gas which has less emission than oil and coal technologies.

Biodiesel usage, CCS and switching to natural gas can be regarded as transition technologies that can be applied to fossil fuel based cogeneration systems. As an urgent action, biodiesel usage is suggested in the short run of emission reduction targets. For examination of the long-run emission reduction, transition to new technologies together with $CO_2$ trading has been modeled in the energy production systems model for a 20 years time period with using anticipated increases in costs, and decreases in emission limits. It is found out that in addition to collaboration, the companies must invest to new technologies and purchase $CO_2$ in the future to satisfy increasing reductions on limits.

As a summary, within this thesis models are developed and necessary analyses are conducted for energy production systems to provide decision makers with necessary tools in the route of decreasing emissions, without sacrificing from energy requirements. In order to model the energy systems model, modeling techniques of MILP, disjunctive programming and propositional logic has been conducted. Multi-objective programming is used to illustrate the conflicting nature of two objectives in energy systems: minimizing cost and environmental emissions.

The main contributions of the thesis can be listed as follows:

i. analysis of synergy generated by collaboration between energy producing systems using analytical and numerical methods,

ii. construction of detailed models for the process units that exhibit performance decay with use,

iii. development of a multi-objective optimization model for the energy production system, solution of the resulting problem to illustrate the conflicting behavior of minimization of economy - environment objectives and suggestion of using the results in $CO_2$ trading markets,

iv. construction of models with $CO_2$ trading flexibility to incorporate new technologies into energy systems: the usage of biodiesel as an urgent act in emission reduction by blending to existing fuels, investments for carbon reduction systems.

**1.2 Outline of the Thesis**

Chapter 2 provides literature review on energy - economy interactions and methodologies used to examine them. General information on the systems is avoided and they are distributed within the text.

The synergy analysis arising from collaboration in energy companies has been conducted in Chapter 3, by analytical analysis on a simplified version of the energy system.

Chapter 4 introduces the energy systems model enriched with discrete exchange structures, biodiesel, unit startup and operating costs, etc. Synergy analysis is performed on the model by experimenting in order to test the findings of Chapter 3. Afterwards, rationality of collaboration is analyzed for individual companies.

In Chapter 5, advanced modeling techniques have been applied to the energy systems model. A new modeling approach for boiler performance maintenance is developed for incorporating decaying capacity of boilers. Another advanced modeling technique, multi objective programming approach, has been used on the energy systems model in order to support a tool for economy – environment challenge of energy systems.

In Chapter 6, a decision tool for the long-run investments of the energy companies is developed. Transition to less carbon technologies together with $CO_2$ trading has been modeled in the energy production systems model.

In Chapter 7, the thesis is concluded with a short summary of the study and recommendations for future research.

# Chapter 2

## LITERATURE REVIEW

Energy supply chain consists of raw materials, production facilities and demands for end products, i.e. energy. According to Energy Information Administration (EIA)'s Report [5], over one-third of all primary energy consumption goes into producing and delivering electricity and most of the world's primary energy consumption comes from fossil fuels, such as coal, natural gas and oil. Burning fossil fuels release emissions that are harmful to the environment. These emissions can be classified into two main groups: $SO_x$ and $CO_2$ equivalent emissions. $SO_x$ equivalent emissions are the particles that are quantified strictly and limited with certain regulations. The case with $CO_2$ equivalent emissions is different; these are gases that have effect on global warming, i.e. greenhouse gases (GHG). The Kyoto Protocol [1] sets obligatory limits on the emission of GHG's by the industrialized countries during the period 2008-2012. The limits apply to an aggregate of emissions of six gases covered in the protocol in $CO_2$ equivalent units.

According to Energy Information Administration (EIA)'s Report [5], more than 80 percent of the human-originated greenhouse gas emissions are energy related. Thus, electricity production and consumption is likely to be a major focus in meeting Kyoto Targets. The electricity production systems and the researchers are in the search for recipe solutions for reducing emissions without sacrificing from the amount of energy production and low prices of production.

Since production and management of energy are very important, there has been extensive research on planning and decision making in the energy supply chain. Using the existing infrastructure more effectively can benefit quickly in the quest of low emissions and low prices. Integrating energy companies in order to have better environmental and economical performance criteria has already been suggested [2], [3]. Türkay et al. [2] and Oruç [3] analyzed the benefits of collaboration with financial and environmental objectives. These studies show that improvements are possible both in environmental and economic performances by establishing collaboration between energy production systems but without considering the cost of investment required to establish such collaboration. The work of Soylu et al. [7] is an extension of this paper. The energy production companies are modeled with the addition of fixed investment costs for establishing collaboration structures. It has been shown that synergy in terms of both environmental and economic criteria can be created with collaboration, in the existence of investment costs. In this thesis, the model in [2], [3] and [4] is extended and the synergy created by collaboration is examined in detail.

Financial synergy analysis is studied by Fluck and Lynch [8] in the literature who show that merging two firms results in better results in financial performance. The synergy captured by inter-functional and inter-organizational integration in Supply Chain Management has been studied by Min and Zhou [9]. They present the benefits of integrated supply chain and analyze the efforts in supply chain modeling. Integration benefits should be achieved by some kind of contracts between the integrating parties. Mieghem [10] shows that, coordinating production and investment decisions in outsourcing is possible by price contracts. Price contracts are also studied in this thesis with an example problem in order to examine if the companies can satisfy their individual rationality constraints when they collaborate.

The contracts in energy production have also been studied in the literature. Xing and Wu [11] develop a mathematical model that is solved by two-level optimization, in order to examine the contracts for energy production system investments. Russo [12] analyzes the independent power production in America and shows that collective action by power exchange between independent power producers improved profits between 1978 and 1990. The power exchange between companies can be in terms of electricity as well as steam when the systems are cogeneration facilities. Electricity production in cogeneration facilities is known to be the most efficient thermal energy producing systems. The systems modeling of cogeneration facilities have been studied in the operations research literature by Kwun and Baughman [13]. They analyze the potential benefit of integrating supply planning of cogeneration facilities into that of utility facilities. They formulate mathematical models for the analysis of cogeneration facilities. The units are not modeled in detail like the model in this thesis, but in aggregate constraints and variables. The sectors with and without cogeneration are compared. It is suggested that utility companies and cogeneration facilities should have joint long-term planning framework.

The performance of an energy facility depends on the behavior of its structural units. Therefore, the detailed analysis for the structural analysis of energy facilities has also been studied in the literature. Boilers attracted most of the attention because they are the main factors in both the two performance criteria: economic –by cost of fuel- and environmental –by emissions from fuel-. Minimizing these two criteria on a boiler has been studied by Kuprianov [14]. He uses nonlinear boiler models in his examinations. Krüger et. al. [15] also use nonlinear boiler models in their study of optimization of boiler start-up costs. They use control techniques on the nonlinear model. Linear modeling on optimization of a boiler, in a non-periodic setting has been studied by Dragićević and Bojić [16], using parameters like temperature, enthalpy etc. An important characteristic of a boiler is the performance decay it experiences by time and usage intensity. Jain and Grossman [17] model the scheduling of parallel units with decaying performance with constant demand for the planning periods. Bizet et. al. [18] develops a scheduling of a process with decaying catalyst, by putting in use several disjunctions involving continuous variables. In this thesis, a model for boilers with linear capacity decrease is developed by a Generalized Disjunctive Programming methodology similar to [18].

Generalized Disjunctive Programming [19], [20] is used to model the discrete - continuous nature of the optimization problem under study. The discrete decisions are modeled with Boolean variables and the logical relationships among the discrete decisions are expressed using propositional logic[20], [21], [22]. This modeling approach constructs subspace information of each dynamic part and represents their interconnections by using suitable Boolean variables.

Another advanced modeling approach that is used in this thesis is multi objective optimization. The multi objective optimization is a decision support tool under the existence of more than one objective. Collette [23] explains its principles on sample cases. In the energy sector, environment and economy are two conflicting objectives that create a wide application and research area for multi objective optimization. It has been used in power systems design [24], diesel engine optimization [25], assessment of new and renewable power plants [26], energy systems design [27], [28] and regional sustainable energy planning models [29], [30], [31]. Pohekar and Ramachandran [32] give complete review of application of multi-criteria decision making to sustainable energy planning. In this thesis, the energy production systems, which face the conflict of emission reduction and cost minimization, are modeled with multi objective optimization techniques as a decision support tool in the $CO_2$ trading markets. By constructing efficient frontiers of the companies using realistic models, the $CO_2$ monetary value can be assessed. To our knowledge, that kind of a study incorporating detailed process models is new in the literature.

Environmentally Conscious Supply Chain Management (ECSCM) is a branch of supply chain management that takes environmental issues into account. ECSCM addresses the whole network of the product life cycle from raw materials to end customers and is an integrated method for environmental management. There has been extensive study in ESCM. Stuart [33] develops a mixed integer programming model to product and process selection problem by incorporating environmental considerations in the product life cycle. Nagurney [34] develops a framework for the modeling and analysis of supply chain networks with multiple criteria, including environmental ones. The optimality conditions for the manufacturers, retailers, and consumers are derived. However, the features of environmentally conscious supply chain like recycling, reusing or remanufacturing are not applicable to the electricity production, since electricity cannot be recycled or even stored. Therefore, other than studying the inventory relations between companies, in energy supply chain, the transactions and exchanges between the companies are studied.

Energy production is the major source of the environmentally harmful emissions. Therefore, the emission reduction technologies have been studied within the context of energy systems interactions. Barreto and Kypreos [35] model the $CO_2$ emissions trading in an energy systems model in a world-wide basis. They include technology learning in their model that affects the technology choice and emissions of regions. Hanson and Laitner [36] analyze the policies in order to select the most appropriate advanced energy- efficient low-carbon technology. They perform their analysis in the basis of sector inputs and outputs of U.S. economy. The study of McFarland et. al. [37] is a methodology for modeling low-carbon emitting technologies within the world economy. Investments for Carbon Capture and Sequestration (CCS) technologies in electric power sector are investigated. CCS technologies are found to be possibly competitive in the very long-run, where many uncertainties exist. Transition to new technologies requires irreversible investments in energy sector. This is modeled by Madlener et.al. [38] under uncertainty of Turkish electricity supply industry. This study determines the required capacity expansions and investment with the considerations of environmental sustainability and energy requirements.

In this thesis a model is developed to plan the transition to new technologies. In this model, as in [35], the $CO_2$ trading is incorporated to an energy systems model. Unlike this study, in the thesis the units are modeled with their detailed process behaviors and parameters. Moreover, the model shows a route for selecting the most appropriate advanced energy- efficient low-carbon technology as in [36], and the Carbon Capture and Sequestration (CCS) technologies in electric power sector are investigated as in [37]. The difference of the study from the mentioned papers is that, it does not model the systems in a regional or world- wide basis but in a company-wide basis. The investments for transition to new technologies are also modeled as in [38] without incorporating uncertainties in data.

# Chapter 3

# SYNERGY ANALYSIS OF COLLABORATION

## 3.1 Introduction

In this chapter, analysis of synergy that can be established by collaboration of energy production systems is conducted. The objective of this chapter is to identify the factors that create synergy among these systems. The analyses are performed for collaboration between two companies.

## 3.2 Analytic Solution

Conventional energy generation systems use fossil fuels to produce steam at high pressure in boilers and extract the energy of high pressure steam in turbines to generate electricity. In the simplest case, a fuel-based energy production system has one boiler and one turbine, as shown in Figure 3.1. For the sake of simplicity in the model the consumptions other than fuel, i.e. electricity, water, etc. are assumed to have fixed cost.

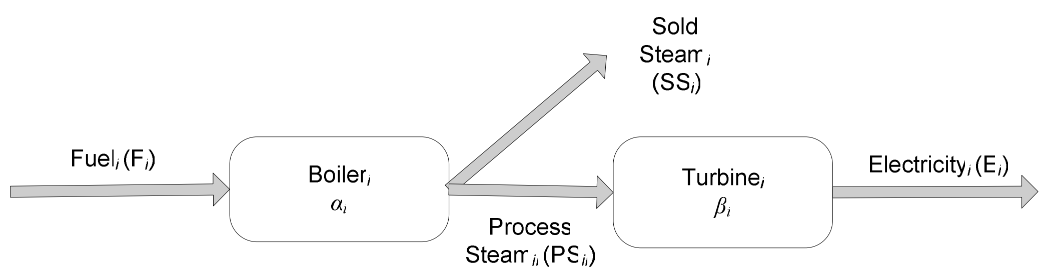



Figure 3.1 Process Flow in a Typical Energy Generation System

The boilers produce steam by burning fuel; then some part of produced steam is used in turbine for electricity generation and the steam demand is met with the rest of the steam. The performance parameter in boiler $i$ is $\alpha_i$ indicating units of steam generated per units of fuel consumed. Similarly, $\beta_i$ indicates the units of steam required per unit of electricity generated in the turbine. The set of equalities, Eq. (3.1), is written for the non-collaborated model with two companies, by ignoring the non-negativity of the variables.

$$\begin{gathered}
F_1 \times \alpha_1 = SS_1 + PS_{11} \\
F_2 \times \alpha_2 = SS_2 + PS_{22} \\
E_1 = \beta_1 \times PS_{11} \\
E_2 = \beta_2 \times PS_{22} \\
SS_1 = ds_1 \\
SS_2 = ds_2 \\
E_1 = de_1 \\
E_2 = de_2 \\
F_1 \times \alpha_1 + IB_1 = bc_1 \\
F_2 \times \alpha_2 + IB_2 = bc_2 \\
PS_{11} + IT_1 = tc_1 \\
PS_{22} + IT_2 = tc_2
\end{gathered} \tag{3.1}$$

These equations state that, the total steam output is equal to the sum of sold and consumed steam and all of the steam and electricity demands must be fulfilled. The variables are amount of fuel consumption ($F_i$), amount of steam that is produced by company $i$ and sold ($SS_i$), used in company $i$'s turbines ($PS_{ii}$), amount of electricity produced ($E_i$) and idle boiler ($IB_i$) and turbine capacities ($IT_i$). The parameters are: capacity of company $i$'s boiler ($bc_i$), performance parameter of company $i$'s boiler ($\alpha_i$), capacity of company $i$'s turbine ($tc_i$), performance parameter of company $i$'s turbine ($\beta_i$), steam demand of company $i$ ($ds_i$), electricity demand of company $i$ ($de_i$). When the equations are solved simultaneously, the system of equations, Eq. (3.2) is obtained.

$$
\begin{aligned}
F_1 &= \frac{de_1 + ds_1 \times \beta_1}{\alpha_1 \times \beta_1} \\
F_2 &= \frac{de_2 + ds_2 \times \beta_2}{\alpha_2 \times \beta_2} \\
SS_1 &= ds_1 \\
SS_2 &= ds_2 \\
PS_{11} &= \frac{de_1}{\beta_1} \\
PS_{22} &= \frac{de_2}{\beta_2} \\
E_1 &= de_1 \\
E_2 &= de_2 \\
IB_1 &= bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \\
IB_2 &= bc_2 - \frac{de_2 + ds_2 \times \beta_2}{\beta_2} \\
IT_1 &= tc_1 - \frac{de_1}{\beta_1} \\
IT_2 &= tc_2 - \frac{de_2}{\beta_2}
\end{aligned}
\tag{3.2}
$$

Collaboration between these two companies can be established by exchanging some of the steam with each other. They burn the fuel they individually purchase and still satisfy their own electricity and steam demands. Figure 3.2 illustrates the exchange mechanism between companies.

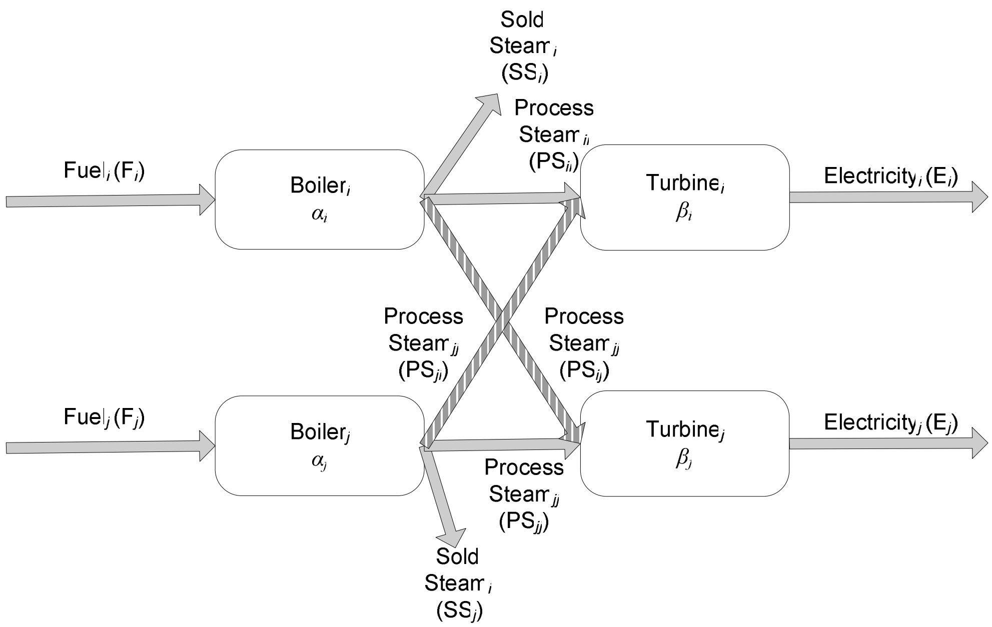



Figure 3.2 Process Flow in the Collaborated Energy Generation Systems

The system of equations, Eq. (3.3), models the collaborated case of two distinct energy generation systems. Note that, the steam can be exchanged as well as being sold or consumed in the turbines.

$$\begin{aligned}
F_1 \times \alpha_1 &= SS_1 + PS_{11} + PS_{12} \\
F_2 \times \alpha_2 &= SS_2 + PS_{21} + PS_{22} \\
E_1 &= \beta_1 \times (PS_{11} + PS_{21}) \\
E_2 &= \beta_2 \times (PS_{12} + PS_{22}) \\
SS_1 &= ds_1 \\
SS_2 &= ds_2 \\
E_1 &= de_1 \\
E_2 &= de_2 \\
F_1 \times \alpha_1 + IB_1 &= bc_1 \\
F_2 \times \alpha_2 + IB_2 &= bc_2
\end{aligned} \tag{3.3}$$

$$PS_{11} + PS_{21} + IT_1 = tc_1$$
$$PS_{12} + PS_{22} + IT_2 = tc_2$$

When the equations are solved simultaneously, the system of equations, Eq.(3.4), is obtained. It can be seen that the values of some variables depend on the idle capacity of the boilers, $IB_i$.

$$
\begin{aligned}
F_1 &= \frac{bc_1 - IB_1}{\alpha_1} \\
F_2 &= \frac{bc_2 - IB_2}{\alpha_2} \\
SS_1 &= ds_1 \\
SS_2 &= ds_2 \\
PS_{11} &= \frac{de_1 + \left(bc_1 - bc_2 - ds_1 + ds_2 - IB_1 + IB_2\right)\beta_1}{2\beta_1} \\
PS_{12} &= -\frac{de_1 + \left(-bc_1 - bc_2 + ds_1 + ds_2 + IB_1 + IB_2\right)\beta_1}{2\beta_1} \\
PS_{21} &= \frac{de_1 + \left(-bc_1 + bc_2 + ds_1 - ds_2 + IB_1 - IB_2\right)\beta_1}{2\beta_1} \\
PS_{22} &= \frac{2de_2\beta_1 + \left(de_1 + \left(-bc_1 - bc_2 + ds_1 + ds_2 + IB_1 + IB_2\right)\beta_1\right)\beta_2}{2\beta_1\beta_2} \\
E_1 &= de_1 \\
E_2 &= de_2 \\
IT_1 &= tc_1 - \frac{de_1}{\beta_1} \\
IT_2 &= tc_2 - \frac{de_2}{\beta_2}
\end{aligned}
\tag{3.4}
$$

The profit of the companies consists of revenue from steam and electricity sales minus the cost of consumed fuel. When $ps$, price of unit steam sold, $pe$, price of unit electricity sold, $cf$, the unit fuel cost, are included, the total profit of the companies in both cases becomes as in Eq.(3.5):

$$\text{Profit} = ps\left(SS_1 + SS_2\right) + pe\left(E_1 + E_2\right) - cf\left(F_1 + F_2\right) \tag{3.5}$$

It is clear that there is no change in total revenue since the sales are directly correlated with demand, when the nonnegativity of decision variables is ignored. Therefore, we can observe the potential benefits in terms of changes in fuel consumption. Fuel consumption of companies also depends on the idle capacities of the boilers. The total steam production has to be the same as the non-collaborated case since the steam demands are identical and each company produces its own electricity. This means that the sum of idle capacities of the boilers in terms of steam does not change with collaboration. Collaboration allows deciding on the variables $IB_1$ and $IB_2$ freely, while holding their sum constant. By a simple look, we can see that, if the parameters of the different companies are the same, the sum of fuel consumption in collaborated case is as in the equation set Eq. (3.6)

$$\begin{gathered} F_1 = \frac{bc_1 - IB_1}{\alpha_1} \\ F_2 = \frac{bc_2 - IB_2}{\alpha_2} \\ \alpha_1 = \alpha_2 = \alpha,\ bc_1 = bc_2 = bc \\ F_1 + F_2 = \frac{2bc - \left(IB_1 + IB_2\right)}{\alpha} \end{gathered} \tag{3.6}$$

It can be seen that, when characteristics of both systems are identical, no allocation of variables $IB_1$ and $IB_2$ can create any decrease in the fuel consumptions. This is because their sum is constant. This shows that, when the systems are totally identical, no synergy is created by collaboration.

### 3.2.1 The Difference in Boiler Performance Parameters

The non-collaborated and the collaborated cases will be examined, when all characteristics of companies except the boiler performance parameters are the same. It will be shown that when there is a difference between boiler performance parameters of the companies, they can benefit from collaboration under the existence of idle boiler capacities. When there is no collaboration, having $\Delta$ as the difference between $\alpha_1$ and $\alpha_2$, the total fuel consumption and the sum of idle boiler capacities are as in equation set Eq. (3.7).

$$\begin{gathered} \alpha_2 = \alpha_1 + \Delta,\ bc_1 = bc_2,\ de_1 = de_2,\ ds_1 = ds_2,\ \beta_1 = \beta_2 \\ F_1 + F_2 = \frac{de_1 + ds_1 \times \beta_1}{\alpha_1 \times \beta_1} + \frac{de_1 + ds_1 \times \beta_1}{(\alpha_1 + \Delta)\,\beta_1} \\ IB_1 + IB_2 = 2 \times \left( bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \right) \end{gathered} \tag{3.7}$$

Since the sum of the idle boiler capacities does not change, the sum is allocated into two companies. The allocation can be performed by introducing a sharing ratio, $k$, representing the ratio of total idle boiler capacity allocated to the boiler of company 1. The sharing ratio, $k$ should be in the range [0,1], in order to model the proportion of the sum of idle boiler capacity. The idle capacity in the boilers as a function of sharing ratio can be expressed as follows:

$$IB_1 = k \times 2 \times \left( bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \right),\ IB_2 = (1-k) \times 2 \times \left( bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \right) \tag{3.8}$$

Then the total fuel consumption in the collaborated case will be:

$$F_1 + F_2 = \frac{bc_1 - IB_1}{\alpha_1} + \frac{bc_2 - IB_2}{\alpha_2} = \frac{bc_1 - k \times 2 \times \left( bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \right)}{\alpha_1} + \frac{bc_1 - (1-k) \times 2 \times \left( bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \right)}{\alpha_1 + \Delta} \tag{3.9}$$

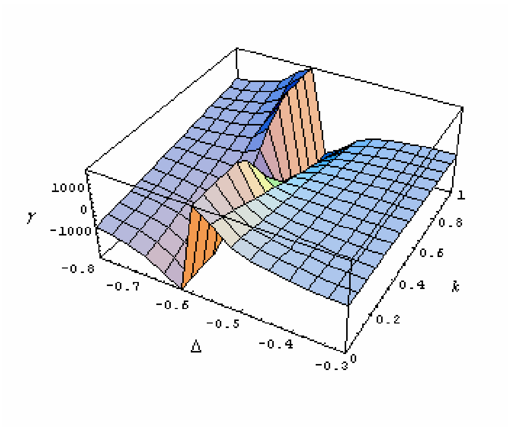
The collaboration benefit is defined in terms of the total decrease in fuel consumption, i.e. negative of the sum of the individual changes in fuel consumptions. It is possible to define it in financial values, but since the cost of fuel, *cf*, is constant, definition in terms of fuel consumption will result in a similar analysis. Then, the collaboration benefit ($\gamma$) becomes:

$$\gamma = \frac{de_1 + ds_1 \times \beta_1}{\alpha_1 \times \beta_1} + \frac{de_1 + ds_1 \times \beta_1}{(\alpha_1 + \Delta)\,\beta_1} - \frac{bc_1 - k \times 2 \times \left( bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \right)}{\alpha_1} - \frac{bc_1 - (1-k) \times 2 \times \left( bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1} \right)}{\alpha_1 + \Delta}$$

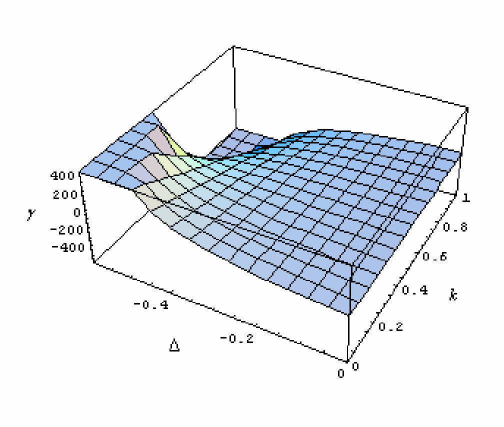
$$\gamma = -\frac{\Delta(-1+2k)\left(de_1 + (-bc_1 + ds_1)\beta_1\right)}{\alpha_1(\alpha_1+\Delta)\beta_1} \quad (3.10)$$

For the following parameter values, in Figure 3.3, collaboration benefit function is plotted versus the sharing ratio, $k$ in [0,1] and difference value, $\Delta$ in [-0.8,-.3], (-0.6,0] and [0,5].

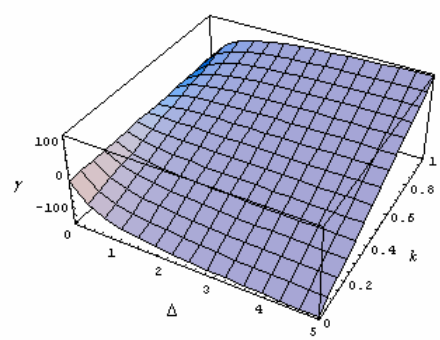
$$\alpha_2 = \alpha_1 + \Delta,\ \alpha_1 = 0.6,\ bc_1 = bc_2 = 250,\ de_1 = de_2 = 70,\ ds_1 = ds_2 = 50,\ \beta_1 = \beta_2 = 0.6$$




**a)**



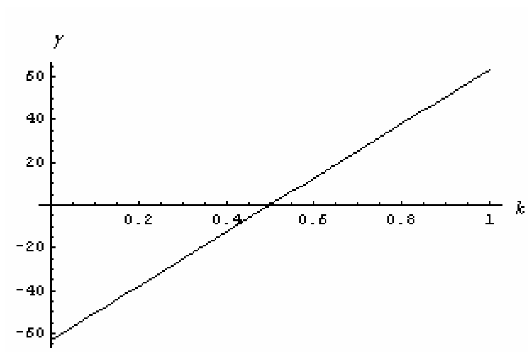

**b)**



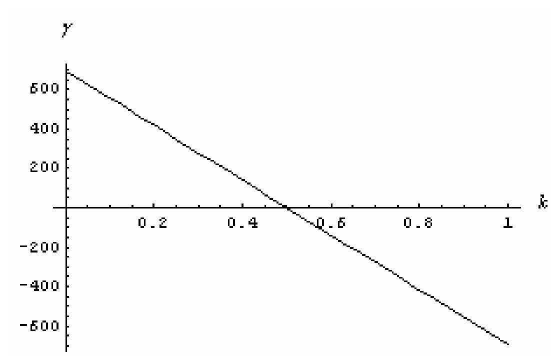

**c)**

Figure 3.3 Collaboration Benefit Function versus Difference Value in Boiler Parameter and Sharing Ratio ($\Delta$ in **a)** [-0.8,-0.3], **b)** (-0.6, 0] and **c)** [0, 5], respectively, $k$ in [0, 1] for all cases)

The difference between boiler performance parameters can be in a very large range. But when the difference, $\Delta = -\alpha_1 = -0.6$ then $\alpha_2$ becomes zero, and the benefit function becomes undefined. The part of the function left to $\Delta = -0.6$ is meaningless since $\alpha_2 < 0$ doesn't exist. While $\Delta$ is in (-0.6, 0), the benefit is decreasing in sharing ratio, *k*. When $\Delta$ is zero, the collaboration benefit is zero regardless of the sharing ratio. This coincides with our previous recognition that if the boiler parameters are identical, no allocation of idle boiler capacities can create synergy, since their sum will be constant. While $\Delta$ is greater than zero, the benefit is increasing in sharing ratio. If the allocation of the idle boiler capacities is performed in a way that all idle boiler capacity is allocated to the efficient boiler, i.e. less efficient boiler is used more extensively, then negative collaboration benefit can occur. The question is to select the collaboration ratio, *k* as the maximizer of the benefit. It is obvious that there are different *k* values that maximize the benefit for different $\Delta$ values. For the parameters fixed as above, Figure 3.4 demonstrates the behavior of the benefit function for $\Delta = 0.5$ and $\Delta = -0.5$. Adding up with previous discussion, the graph illustrates that, as soon as $-0.6 < \Delta < 0$, $k = 0$ is the maximizer of the benefit, and if $\Delta > 0$, $k = 1$ is the maximizer of the benefit. Both suggest allocating all idle capacity to the boiler with smaller performance parameter and using the more efficient one with full capacity.




**a)**




**b)**

Figure 3.4 Collaboration Benefit Function versus Sharing Ratio with Difference Value in Boiler Parameter

**a)** $\Delta = 0.5$ and **b)** $\Delta = -0.5$.

It is shown that when Δ > 0, it is optimal to choose $k = 1$ in order to allocate all idle boiler capacity to inefficient boiler. When $k$ is fixed to 1, this will result in an allocation as in Eq.(3.11).

$$IB_1 = 2\times\left(bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1}\right),\ IB_2 = 0$$

$$F_1 + F_2 = \frac{bc_1 - 2\times\left(bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1}\right)}{\alpha_1} + \frac{bc_1}{\alpha_1 + \Delta} \tag{3.11}$$

The difference between the fuel consumptions in non-collaborated and collaborated cases will be as in Eq. (3.12).

$$\gamma = \frac{de_1 + ds_1 \times \beta_1}{\alpha_1 \times \beta_1} + \frac{de_1 + ds_1 \times \beta_1}{(\alpha_1 + \Delta)\beta_1} - \frac{bc_1 - 2\times\left(bc_1 - \frac{de_1 + ds_1 \times \beta_1}{\beta_1}\right)}{\alpha_1} - \frac{bc_1}{\alpha_1 + \Delta} = -\frac{\Delta\left(de_1 + (-bc_1 + ds_1)\beta_1\right)}{\alpha_1(\alpha_1 + \Delta)\beta_1} \tag{3.12}$$

Since the parameters are logically nonnegative, the collaboration benefit in terms of total decrease in fuel consumption (γ) is positive if the inequality $-\left[de_1 + (-bc_1 + ds_1)\beta_1\right] > 0$ holds, which requires the inequality in Eq. (3.13) to be valid.

$$\frac{de_1}{\beta_1} + ds_1 < bc_1 \tag{3.13}$$

This inequality requires that there be idle capacity at the boiler, which is the main factor for collaboration to be successful. When the derivative of γ with respect to Δ, is checked, as in Eq.(3.14), it is realized that the same condition lets the derivative of the difference function to be greater than zero, which means that the collaboration benefit is increasing with increasing difference (Δ).

$$\frac{\partial\gamma}{\partial\Delta} = -\frac{de_1 + (-bc_1 + ds_1)\beta_1}{(\alpha_1 + \Delta)^2\beta_1} > 0 \tag{3.14}$$

When the second derivative is checked, as in Eq.(3.15) it is seen that the collaboration benefit function is increasing in a decreasing rate in Δ.

$$\frac{\partial^2 \gamma}{\partial \Delta^2} = \frac{de_1 + \left(-bc_1 + ds_1\right)\beta_1}{\left(\alpha_1 + \Delta\right)^3 \beta_1} < 0 \qquad (3.15)$$

The collaboration benefit function is plotted versus difference value Δ in [0,1] for the parameters $\alpha_2 = \alpha_1 + \Delta,\ \alpha_1 = 0.6,\ bc_1 = bc_2 = 250,\ de_1 = de_2 = 70,\ ds_1 = ds_2 = 50,\ \beta_1 = \beta_2 = 0.6$ in Figure 3.5.

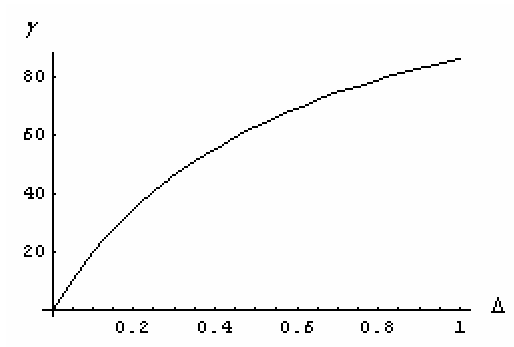
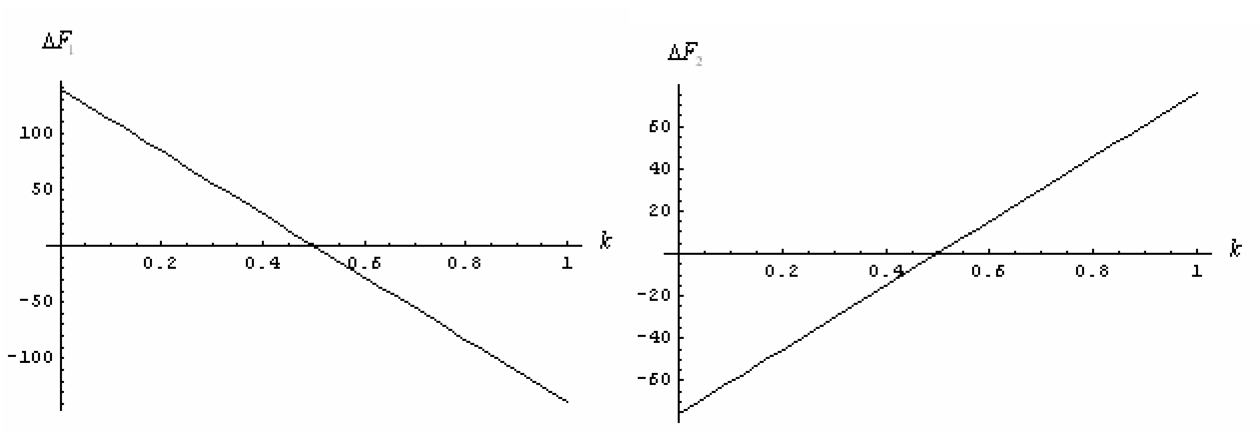



Figure 3.5 Collaboration Benefit Function versus Difference Value in Boiler Parameter

### 3.2.2 Rationality of Collaboration

If *k* is selected in a right way, the collaboration benefit is created by allocating idle boiler capacities to less efficient party. This results in an increase in one party's fuel consumption and a decrease in others. In fact, the change in fuel consumptions of individual parties is a function of sharing ratio, *k*. The Figure 3.6 illustrates the changes in fuel consumptions of individual companies versus sharing ratio at Δ= 0.5. $\Delta F_1$ is the company 1's fuel consumption difference between collaborated and non- collaborated settings, $\Delta F_2$, symmetrically. As it is shown before, for Δ= 0.5, *k*=1 is the maximizer of the benefit. At that point, $\Delta F_1$, the difference of company 1's fuel consumption is negative, i.e. company 1 spends less fuel with collaboration. And, $\Delta F_2$, is positive, i.e. company 2 spends more fuel with collaboration. The absolute value of decrease in fuel consumption of company 1 is greater than increase in fuel consumption of company 2. In total there is a decrease in total fuel consumption, i.e. increase in collaboration benefit as shown in Figure 3.4.a.




**a)** **b)**

Figure 3.6 The Changes in Fuel Consumptions of Individual Companies **a)** $\Delta F_1$ **b)** $\Delta F_2$ with $\Delta = 0.5$

The collaboration benefit ($\gamma$) was defined in terms of negative of the changes in fuel consumptions. i.e. $\gamma = -(\Delta F_1 + \Delta F_2)$. It is shown that when the difference between boiler performance parameters is positive, $\Delta > 0$, the companies select $k$ as 1 in order to maximize collaboration benefit. It has also been shown that, decrease in the fuel consumption of one company results in an increase in fuel consumption of the other one. When $k = 1$, $\Delta F_1 < 0$ and $\Delta F_2 > 0$. In order to obtain $\gamma = -(\Delta F_1 + \Delta F_2) > 0$, the inequality $|\Delta F_1| > |\Delta F_2|$ must hold. Then there exists a real number $a > 0$ such that the inequalities $\Delta F_1 + a < 0$ and $\Delta F_2 - a < 0$ hold, and both companies can gain from collaboration. This results in that, as soon as the company that burns less fuel gives the other one the money of its extra fuel, the collaboration can be rational for both companies. And if the collaboration results in a benefit, there is always a real positive number "*a*" that enables both of the companies gain from collaboration.

### 3.2.3 The Difference in Turbine Performance Parameters

The other major equipment in the fuel-fired energy generation systems is the turbine. Therefore, it is worthwhile to analyze the difference of turbine performance parameters on collaboration. If there is a difference between turbine performance parameters while all other parameters of the companies are the same, the allocation of idle boiler capacities are as in Eq.(3.16) with sharing ratio, $k$ in [0,1].

$$IB_1 = k\left(bc_1 - \frac{de_1 + ds_1\beta_1}{\beta_1} + bc_2 - \frac{de_2 + ds_2(\beta_1 + \Delta)}{(\beta_1 + \Delta)}\right) = k\left(2bc_1 - \frac{de_1 + ds_1\beta_1}{\beta_1} - \frac{de_1 + ds_1(\beta_1 + \Delta)}{(\beta_1 + \Delta)}\right)$$

$$IB_2 = (1-k)\left(2bc_1 - \frac{de_1 + ds_1\beta_1}{\beta_1} - \frac{de_1 + ds_1(\beta_1 + \Delta)}{(\beta_1 + \Delta)}\right) \qquad (3.16)$$

The total fuel consumption in the case that companies do not collaborate will be as in Eq.(3.17).

$$F_1 + F_2 = \frac{de_1 + ds_1\beta_1}{\alpha_1\beta_1} + \frac{de_1 + ds_1(\beta_1 + \Delta)}{\alpha_1(\beta_1 + \Delta)} = \frac{2\beta_1(de_1 + ds_1\beta_1) + \Delta(de_1 + 2ds_1\beta_1)}{\alpha_1\beta_1(\beta_1 + \Delta)} \qquad (3.17)$$

The total fuel consumption in collaborated case will be as in Eq.(3.18).

$$\begin{aligned} F_1 + F_2 &= \frac{bc_1 - IB_1}{\alpha_1} + \frac{bc_1 - IB_2}{\alpha_1} \\ &= \frac{bc_1 - k\left(2bc_1 - \frac{de_1 + ds_1\beta_1}{\beta_1} - \frac{de_1 + ds_1(\beta_1 + \Delta)}{(\beta_1 + \Delta)}\right)}{\alpha_1} + \frac{bc_1 - (1-k)\left(2bc_1 - \frac{de_1 + ds_1\beta_1}{\beta_1} - \frac{de_1 + ds_1(\beta_1 + \Delta)}{(\beta_1 + \Delta)}\right)}{\alpha_1} \\ &= \frac{2\beta_1(de_1 + ds_1\beta_1) + \Delta(de_1 + 2ds_1\beta_1)}{\alpha_1\beta_1(\beta_1 + \Delta)} \end{aligned} \qquad (3.18)$$

Regardless of the value of *k* the collaboration benefit, i.e. decrease in fuel consumption will be:

$$\gamma = \frac{2\beta_1(de_1 + ds_1\beta_1) + \Delta(de_1 + 2ds_1\beta_1)}{\alpha_1\beta_1(\beta_1 + \Delta)} - \frac{2\beta_1(de_1 + ds_1\beta_1) + \Delta(de_1 + 2ds_1\beta_1)}{\alpha_1\beta_1(\beta_1 + \Delta)} = 0 \qquad (3.19)$$

All other parameters being identical, it is shown that if there is a difference between turbine performance parameters, no synergy is created with collaboration.

The analyses were performed in a setting that, the variables could have negative values. Of course, other than difference variables, it is not logical in the real life. Therefore, experiments in a very similar setting were performed in order to examine the effects of nonnegativity assumption. The explanations of the experiments are given in Appendix A. The differences in the parameters that have no effect on the amount of steam produced or sold, like turbine efficiencies, electricity prices are found to create no benefit by collaboration, from the experiments.

### 3.3 Conclusion

Simplified examples of fuel-based cogeneration facilities have been modeled in order to examine the synergy achieved by collaboration that is formed by exchange of steam produced. It has been shown that if companies are completely identical, collaboration does not create any synergy at all. There must be some differences between the parameters of the companies. Idle boiler capacities are shown to be the driving factor underlying the synergy by collaboration. Energy production companies are known to have idle capacities in order to satisfy peak demands, so using these capacities effectively is the main source of synergy by collaboration. The differences in the parameters that have no effect on the amount of steam produced or sold are found to create no benefit by collaboration. On the other hand, the differences in the parameters those have effect on the amount of steam produced or sold are found to create benefit under some conditions which verify the existence of idle boiler capacities. Moreover, it has been shown that, as soon as a collaboration benefit exists, it is always possible for companies to share the benefit in a way that, both gain from collaboration.

As a last word, the analyses of this chapter are performed for financial synergy. However, if the objective is to minimize the total environmental effects of the companies and the performances are in terms of environmental effects, the analyses can be extended to show that environmental benefits can be achieved by collaboration. The major debate is between these two performance criteria, which will be discussed throughout the thesis.

# Chapter 4

# SYNERGY ANALYSIS IN ENERGY PRODUCTION SYSTEMS

## 4.1 Introduction

In this chapter, models for the energy production systems are presented with the aim of assessing the synergy analysis that is conducted in the previous chapter with systems that resemble real systems. A typical energy production system consists of storage tanks to inventory raw materials, boilers that convert fuel into steam at high pressures, turbines that expand higher pressure steam to lower pressure steam and convert the mechanical energy released during this expansion in the electricity and mixing equipment for mixing compatible materials originating from different sources in the system. Energy systems utilize fuel, air and other materials to generate electricity and steam. Companies can collaborate by exchanging High Pressure (HP), Medium Pressure (MP) and Low Pressure (LP) steam. There is an investment cost for such inter-company material exchanges, i.e. pipeline construction. The energy production systems that collaborate in order to improve their financial and environmental performance can exchange steam while satisfying the demand for HP, LP, MP steam and electricity. If an energy production system produces excess electricity, it can sell this to utility company that serves the region. When enough electricity cannot be produced or if it is profitable, electricity can be purchased from the utility company.

## 4.2 Problem Formulation

The modeling of energy systems has been addressed in the literature [2], [3]. In this work, the model is extended to cover advanced modeling techniques in order to make the existing model to cover more details of real life systems. After an overview of features, the model is explained in its final form.

The first extension on the existing model is the introduction of exchange equipments with discrete sizes and costs. Afterwards, environmental constraints are revised and limits for Green House Gases (GHG) have been added. It is essential to include the possibility of using renewable energy technologies in the energy production systems in order to improve environmental performance. For that purpose, a new renewable energy source, biodiesel is introduced to the model with its own limitations and constraints. The cost structures of the companies are remodeled and the costs of utility company are left out of the model. In addition to that startup and operating costs are modeled for boilers and turbines. The final form of the model consists of MILP models for boilers, turbines, fuel tanks, mixers, exchange structures and environmental constraints with an objective function of minimizing cost.

**4.2.1 Boiler Models**

The generation of HP steam is accomplished in the boilers by burning fuel, which results in emission of harmful substances such as GHG or $SO_x$. The boilers can be supplied with different fuels as raw material with minimal adjustments in the operating conditions. This requires the selection of economically and/or environmentally attractive fuel among the available alternatives. The alternatives may be sulfurless oil, heavy oil, etc. which differ in calorie content, harmful emissions and cost. When environmental constraints appear, companies try to find new alternatives for producing energy with minimum emissions. Biodiesel is a nontoxic alternative fuel made from renewable fats and vegetable oils with a performance a little lower than the petroleum-based diesel. Free of sulfur and aromatics, it can be used in engines and systems with few or no modifications. A biodiesel blend is pure biodiesel blended with petrodiesel. Blends up to 20 % biodiesel are compatible with all known oil tanks and systems. The compatibility of higher biodiesel blends depends on the properties of the materials of the tanks, pumps and fuel lines. The purchasing cost of biodiesel is a little higher than petrodiesel and holding cost is higher because of its material properties [39]. The biodiesel can be mixed to only one type of the fuel and the other fuels cannot be mixed to each other. The boiler models consist of the following equations.

$$X_{ijk_{fuel}l_{con}t}\frac{cc_k}{\eta_{ij}} = XHF_{ijk_{fuel}t} \tag{4.1}$$

$$X_{ijk_{HP}l_{gen}t} = \sum_{k\in \text{Fuel}} XHF_{ijkt} \tag{4.2}$$

$$\sum_{k\in \text{BioFuel}} X_{ijkl_{con}t} \le 0.2 \sum_{k\in \text{Fuel}} X_{ijkl_{con}t} \tag{4.3}$$

$$XHF_{ijkt} \le M \times YFU_{ijkt} \tag{4.4}$$

$$\sum_{\substack{k\in \text{Fuel} \\ k\notin \text{BioFuel}}} YFU_{ijkt} \leq 1 \tag{4.5}$$

$$X_{ijk_{MP}l_{con}t} = a_{ijk_{MP}} X_{ijk_{HP}l_{gen}t} \tag{4.6}$$

$$X_{ijk_{EL}l_{con}t} = a_{ijk_{EL}} X_{ijk_{HP}l_{gen}t} \tag{4.7}$$

$$X_{ijk_{SO_x}l_{gen}t} = \sum_{k\in fuel} s_{SO_x k_{fuel}} X_{ijk_{fuel}l_{con}t} \tag{4.8}$$

$$X_{ijk_{GHG}l_{gen}t} = \sum_{k\in fuel} s_{GHG,k_{fuel}} X_{ijk_{fuel}l_{con}t} \tag{4.9}$$

$$X^{L}_{jk_{HP}l_{gen}} i \times Y_{ijt} \leq X_{ijk_{HP}l_{gen}t} \leq X^{U}_{ijk_{HP}l_{gen}} \times Y_{ijt} \tag{4.10}$$

The variable representing the HP steam production in a boiler ( $X_{ijk_{HP}l_{gen}t}$ ) is disaggregated into variables ($XHF_{ijkt}$) for the fuel type it has been produced. Eq. (4.1) states that the HP steam production from a fuel is proportional to calorific value of fuel, $cc_k$, and the boiler efficiency, ($1/\eta_{ij}$). Eq. (4.2) models that the amount of HP steam produced in a boiler is equal to the sum of HP produced from different fuels in that boiler. Eq. (4.3) restricts the amount of biodiesel usage to maximum 20% of the blend used in that period. According to Eq. (4.4), if a fuel type is used in a boiler in that period $YFU_{ijkt}$ becomes 1 where $M$ is large number. Eq. (4.5) states that only one type of fuel can be used and mixed to biodiesel in a period. Eqs. (4.6) and (4.7) model the electricity and MP steam consumption in the boiler as a function of the HP steam generation. Eqs. (4.8) and (4.9) model the $SO_x$ and GHG generations which are proportional to the composition of the fuel and the amount of fuel consumption in the boilers. Eq. (4.10) determines the upper and lower bounds on the amount of HP steam generation in the boilers, if the boiler is operating.

### 4.2.2 Turbine Models

Turbines generate electricity by expanding steam from higher pressures to lower pressures. They receive HP steam and produce electricity as well as MP and LP steams. Electricity generation in a turbine is a function of HP steam input and MP and LP steam generation as shown in Eq. (4.11). The material balance around turbines is expressed in Eq. (4.12). Eq. (4.13) determines the upper and lower bounds on the amount of MP, LP and electricity generation in turbines, if the turbine is working. The parameters, $e_{ijk}$ and $g_{ijk}$ can be obtained from either design specifications of the turbine or the operating data of existing turbines.

$$X_{ijk_{EL}l_{gen}t} = e_{ijk_{HP}} X_{ijk_{HP}l_{in}t} - \sum_{k=MP,LP} g_{ijk} X_{ijkl_{gen}t} \quad (4.11)$$

$$X_{ijk_{HP}l_{in}t} = X_{ijk_{MP}l_{gen}t} + X_{ijk_{LP}l_{gen}t} \quad (4.12)$$

$$X^{L}_{ijkl_{gen}} \times Y_{ijt} \le X_{ijkl_{gen}t} \le X^{U}_{ijkl_{gen}} \times Y_{ijt} \quad (4.13)$$

**4.2.3 Fuel Tank Models**

Different types of fuel are stored in the fuel tanks with certain storage capacities and initial inventory, $I_{ijk0}$. Eq. (4.14) models the balance between a tank and the boilers that use the fuel. Material balance around a fuel tank is modeled by Eq. (4.15) such that the rate of flow out of tanks times length of period $t$ plus inventory at time $t$ is equal to incoming fuel plus fuel remaining from the previous period. Eq. (4.16) is equivalent of Eq. (4.15) for the first time period. Eq. (4.17) enforces the inventory at any period to be between the total storage capacity of the fuel tank and the safety stock level. Binary variable $YP_{ijkt}$ is equal to 1 if fuel $k$ is purchased for tank $j$ of company $i$ in period $t$. There is an upper and a lower limit for the fuel purchase amount as shown in Eq. (4.18). The cost of purchased fuel is modeled in Eq.(4.19). Eq. (4.20) models the fixed cost of purchase in terms of the fixed cost of purchase $v_{ijk}$ and the binary variable $YP_{ijkt}$. Finally, Eq. (4.21) models the holding cost of fuel inventory, $HC_t$, in terms of unit holding cost, $h_{ijk}$ and inventory level, $I_{ijkt}$.

$$X_{ijk_{fuel}l_{out}t} = \sum_{j \in \text{Boiler}} X_{ijk_{fuel}l_{in}t} \quad (4.14)$$

$$I_{ijk(t-1)} + X_{ijk_{fuel}l_{in}t} - I_{ijkt} - n_t \times \sum_{j' \in \text{Boiler}} X_{ijk_{fuel}l_{in}t} = 0 \qquad t > 1 \quad (4.15)$$

$$I_{ijk0} + X_{ijk_{fuel}l_{in}t} - I_{ijkt} - n_t \times \sum_{j' \in \text{Boiler}} X_{ijk_{fuel}l_{in}t} = 0 \qquad t = 1 \quad (4.16)$$

$$I^{U}_{ijk}\delta \le I_{ijkt} \le I^{U}_{ijk} \quad (4.17)$$

$$p^{L}_{ijk_{fuel}} \times YP_{ijk_{fuel}t} \le X_{ijk_{fuel}l_{in}t} \le p^{U}_{ijk_{fuel}} \times YP_{ijk_{fuel}t} \quad (4.18)$$

$$C_i = \sum_{j}\sum_{t}\sum_{k \in fuel} c_{fuel} X_{ijkl_{in}t} \quad (4.19)$$

$$CP_i = \sum_j \sum_{k \in \text{fuel}} \sum_t v_{ijk} YP_{ijkt} \tag{4.20}$$

$$HC_i = \sum_j \sum_{k \in \text{fuel}} \sum_t h_{ijk} I_{ijkt} \tag{4.21}$$

### 4.2.4 Mixer Models

Mixers receive and send one type of material from and to different units. There is a mixer for each type of material in the system. Eq. (4.22) represents the material balances around mixers. In a steam mixer, the total amount of steam that flows into the mixer from boilers, from other mixers and from other companies is equal to the total amount of steam that flows from the mixer to the turbines, to the boilers, to other mixers, to other companies and the demand.

$$\sum_j X_{ijkl_{out}t} + \sum_j XE_{iji'j't} = \sum_j X_{ijkl_{in}t} + \sum_j XE_{i'j'ijt} + d_{i'j't} \tag{4.22}$$

### 4.2.5 Exchange Structure Models

Companies must construct exchange equipment such as pipeline, compressors, pumps, in order to establish inter-company material exchanges. The equipments can be constructed in discrete capacities. The discrete capacities of High (H), Medium (M) and Low (L) are considered having different maximum exchange capacities. The fixed investment for a type of capacitated material exchange is specific. The companies might select to construct more than one type of exchange structure at one period. No steam exchange is possible before the construction of exchange equipment. Eq. (4.23) states that, in each period, the exchange amount is less than or equal to maximum installed exchange capacity. The exchange equipments wear out due to excessive operating conditions, and need to be replaced. Each type of exchange equipment has a lifetime ($\tau_{km}$). The maximum exchange capacity in each period is equal to the total capacity of constructed pipelines as shown in Eq. (4.24). $\xi_{jj'm}$, is the discrete capacity of pipelines, where $m$ is the index for H, M, L capacity structures. The pipelines can be used bidirectional as given in Eq. (4.25), i.e. once a pipeline is constructed between any two companies, the exchange from one company to the other one is possible, and vice versa. Because of this property of exchange structure, it is not logical for one of the companies only to cover the cost of installing exchange equipment. Eq. (4.26) models that each company pays a proportion ($\omega_i$) of the total exchange cost, where $\varphi_{iji'j'm}$ is the cost of exchange equipment construction. Eq. (4.27) states that the sum of the proportions must be equal to one.

$$XE_{iji'j't} \leq XEC_{iji'j't} \tag{4.23}$$

$$XEC_{iji'j't} = \sum_{m}\sum_{t'} \xi_{jj'm} YEC_{iji'j'mt'} \qquad t' < t < t' + \tau_{km} \tag{4.24}$$

$$XEC_{iji'j't} = XEC_{i'j'ijt} \tag{4.25}$$

$$CE_i = \omega_i \sum_{i}\sum_{j}\sum_{i'}\sum_{j'}\sum_{t'}\left(\sum_{m} \varphi_{iji'j'm} YEC_{iji'j'mt'}\right) \tag{4.26}$$

$$\sum_{i} \omega_i = 1 \tag{4.27}$$

#### 4.2.6 Environmental Considerations

The boilers release Green House Gases (GHG) and $SO_x$ as waste products that results from burning fuels. A model on energy production systems should include environmental limits. Eqs. (4.28) and (4.29) state that the total releases of the companies should be less than sum of their limits. The $SO_x$ emission limits are not included in the Kyoto Protocol, but they are determined by local regulations. The total $SO_x$ and GHG emissions are calculated over all periods. Here, the emission is calculated by multiplying the emission rate by the length of period $t$, $n_t$. Eq. (4.30) models the penalty cost of $SO_x$ release. Although the companies must decrease the GHG emissions levels according to Kyoto Protocol, as soon as they are below the limits, they do not pay penalty for GHG emissions.

$$\sum_{i}\sum_{j}\sum_{t} X_{ijk_{GHG}l_{gen}t} \times n_t \leq \sum_{i} \mathrm{X}^{\mathrm{U}}_{ik_{\mathrm{GHG}}} \tag{4.28}$$

$$\sum_{i}\sum_{j}\sum_{t} X_{ijk_{SO_x}l_{gen}t} \times n_t \leq \sum_{i} \mathrm{X}^{\mathrm{U}}_{ik_{SO_x}} \tag{4.29}$$

$$CS_i = \sum_{t}\sum_{j} X_{ijk_{SO_x}l_{gen}t} \varsigma_{SO_x} \times n_t \tag{4.30}$$

When companies do not collaborate, Eqs. (4.28) and (4.29) take a different form such that they state that their individual releases should be less than their individual limits. This is modeled by removing the summation over the companies.

### 4.2.7 Material Balance

Eqs. (4.31) relates the states of materials to reflect the conservation of mass. In order to maintain consistency in the material balances, Eq. (4.32) fixes some of the states of materials to zero (for example, there is no HP steam input to the boilers, so these variables are fixed to zero).

$$X_{ijkl_{in}t} + X_{ijkl_{gen}t} = X_{ijkl_{out}t} + X_{ijkl_{con}t} \tag{4.31}$$

$$X_{ijkl't} = 0 \tag{4.32}$$

### 4.2.8 Electricity Purchase

The companies can buy electricity from the utility company and sell the excess electricity to the utility company. This trade is modeled as an exchange activity between the energy producing company and the utility company. The parameter $\varepsilon_{iji'j'}$ is positive for purchasing and negative for selling electricity. The electricity cost for each company is determined with Eq. (4.33).

$$CEL_i = \sum_j \sum_{i'} \sum_{j'} \sum_t \left( XE_{iji'j't} \varepsilon_{iji'j'} \right) \tag{4.33}$$

### 4.2.9 Operating and Start-up Costs

If a boiler or a turbine of a company is operating on period *t*, the company spends a fixed amount of money. The operating cost is modeled for boilers and turbines with Eq. (4.34). While a process unit does not work in a period and works in the next period, the company pays a fixed cost for the startup operation. The startup cost for boilers and turbines is modeled with Eq. (4.35). Eq. (4.36) models the timing of startup such that if a unit does not work in a period and works in the next period, the next period must be a startup period.

$$CW_i = \sum_j \sum_t Y_{ijt} \times o_{ij} \tag{4.34}$$

$$CSU_i = \sum_j \sum_t YS_{ijt} \times \sigma_{ij} \tag{4.35}$$

$$Y_{ij(t-1)} - Y_{ijt} + YS_{ijt} \geq 0 \qquad t > 1 \qquad (4.36)$$

**4.2.10 Objective Function**

Eq. (4.37) is the objective function of the problem which is the minimization of the total cost consisting of cost of fuel purchased, fixed cost of purchase, holding cost of fuel, cost of installing exchange equipment, penalty for $SO_x$ release and cost of electricity purchase.

$$\min z = \sum_i \left( C_i + CP_i + HC_i + CE_i + CS_i + CEL_i + CW_i + CSU_i \right) \qquad (4.37)$$

The complete model can be solved under collaboration and non-collaboration scenarios with minor modifications. First modification is at the previously stated differences in environmental constraints by Eqs. (4.28) and (4.29): the individual releases should be less than individual limits. The second and functional modification is fixing the steam exchange between companies to zero. Therefore, the set of constraints for each company can be completely separated from each other. Since the costs are nonnegative, minimization of their sum is equivalent to minimizing their costs individually. The separable behavior of the model gives us the opportunity of comparing the costs under collaboration and non-collaboration scenarios.

**4.3 An Example of Energy Systems**

In order to understand the model behavior accurately, the model is solved for two energy producing companies whose schematic flowsheet is given in Figure 4.1. As can be seen, both companies have three fuel tanks, two boilers, two turbines and one mixer for each pressure level of steam. The main structures of companies are similar but the capacities and the performances of the units are different. The data regarding to all parameters of the model is given in Table 4.1.

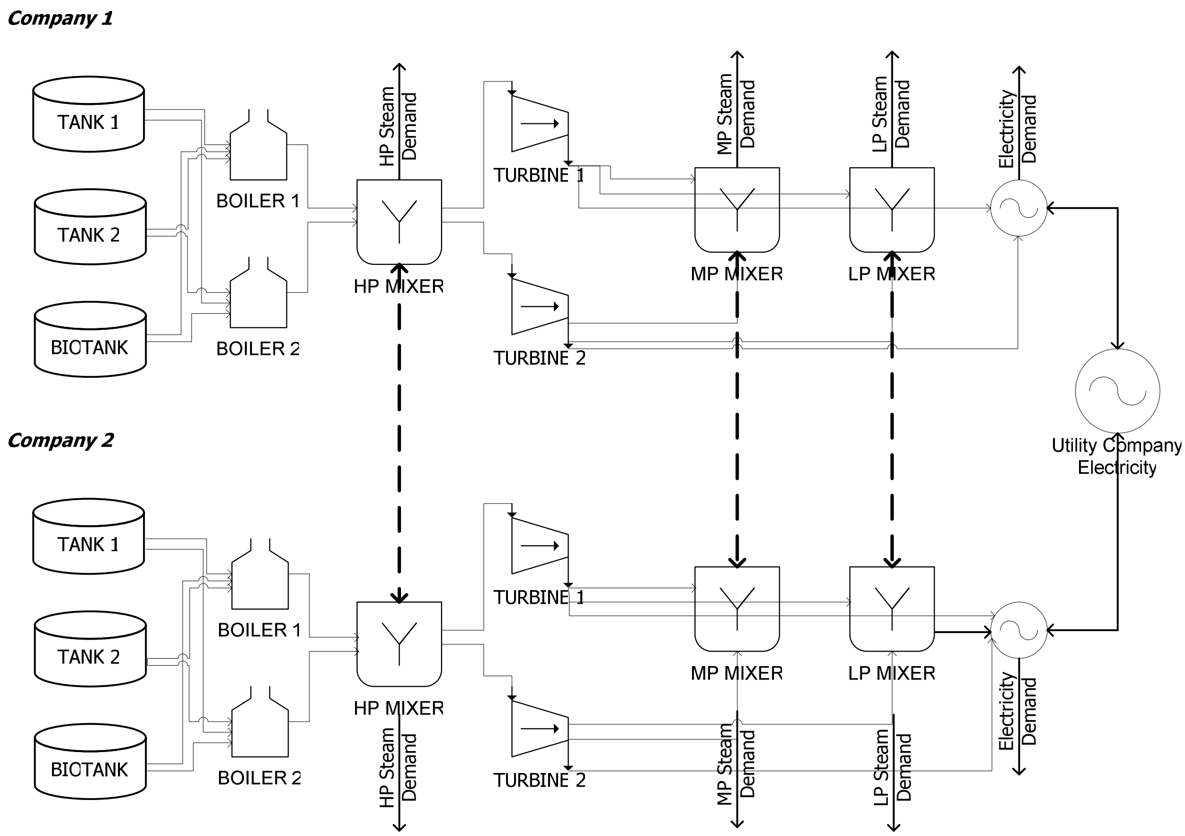



Figure 4.1 Schematic Flowsheet of Example with Two Companies

| **Fuel** | **Fuel 1** | **Fuel 2** | **Bio Diesel** |
|---|---|---|---|
| $cc$ | 42 | 38.6 | 36 |
| $s_{SOx}$ | 7.80 | 1.42 | 0.05 |
| $s_{GHG}$ | 17 | 5 | 2 |
| $c$ | 94 | 76 | 113 |

| $I_0$ / $I^U$ / $h$ | **Company 1** | **Company 2** |
|---|---|---|
| **Tank 1** | 15 / 120 / 1.0 | 5 / 130 / 1.0 |
| **Tank 2** | 10 / 100 / 1.5 | 10 / 140 / 1.5 |
| **Bio Tank** | 17 / 50 / 2.0 | 15 / 50 / 2.0 |

| $v$ / $p^L$ / $p^U$ | **Company 1** | **Company 2** |
|---|---|---|
| **Tank 1** | 100 / 10 / 25 | 100 /10 / 40 |
| **Tank 2** | 100 / 10 / 40 | 100 / 10 / 30 |
| **Bio Tank** | 150 / 10 / 30 | 150 / 10 / 30 |

| $(1/\eta)$ / $a_{EL}$ / $a_{MP}$ / $X_{HP,GEN}^L$ / $X_{HP,GEN}^U$ / $\sigma$ / $o$ | **Company 1** | **Company 2** |
|---|---|---|
| **Boiler 1** | 0.500 / 0.0020 / 0.1100 / 0 / 550 / 50 / 5 | 0.680 / 0.0025 / 0.1100 / 0 / 650 / 50 / 5 |
| **Boiler 2** | 0.510 / 0.0030 / 0.1200 / 0 / 530 / 50 / 5 | 0.690 / 0.0028 / 0.1200 / 0 / 680 / 50 / 5 |

| $e_{HP}$ / $g_{MP}$ / $g_{LP}$ / $\sigma$ / $o$ | **Company 1** | **Company 2** |
|---|---|---|
| **Turbine 1** | 0.150 / 0.070 / 0.009 / 10 / 5 | 0.160 / 0.070 / 0.012 / 10 / 5 |
| **Turbine 2** | 0.175 / 0.080 / 0.010 / 10 / 5 | 0.170 / 0.075 / 0.010 / 10 / 5 |

| $X_{MP,GEN}^L$ / $X_{MP,GEN}^U$ / $X_{LP,GEN}^L$ / $X_{LP,GEN}^U$ / $X_{EL,GEN}^L$ / $X_{EL,GEN}^U$ | **Company 1** | **Company 2** |
|---|---|---|
| **Turbine 1** | 0 / 300 / 0 / 300 / 0 / 70 | 0 / 400 / 0 / 300 / 0 / 90 |
| **Turbine 2** | 0 / 300 / 0 / 300 / 0 / 60 | 0 / 400 / 0 / 300 / 0 / 65 |

| **Company 1** | **t1** | **t2** | **t3** | **t4** | **t5** | **t6** | **t7** | **t8** | **t9** | **t10** | **t11** | **t12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $d_{HP}$ | 12 | 11 | 15 | 12 | 10 | 11 | 14 | 11 | 10 | 14 | 11 | 11 |
| $d_{MP}$ | 200 | 485 | 253 | 158 | 183 | 176 | 163 | 427 | 262 | 261 | 201 | 232 |
| $d_{LP}$ | 328 | 144 | 496 | 538 | 136 | 183 | 102 | 413 | 508 | 460 | 498 | 587 |
| $d_{EL}$ | 182 | 141 | 170 | 129 | 102 | 196 | 172 | 166 | 163 | 195 | 187 | 130 |
| **Company 2** | **t1** | **t2** | **t3** | **t4** | **t5** | **t6** | **t7** | **t8** | **t9** | **t10** | **t11** | **t12** |
| $d_{HP}$ | 14 | 12 | 13 | 13 | 11 | 14 | 12 | 12 | 13 | 12 | 13 | 12 |
| $d_{MP}$ | 186 | 259 | 276 | 380 | 138 | 434 | 139 | 260 | 479 | 498 | 188 | 188 |
| $d_{LP}$ | 376 | 162 | 501 | 112 | 114 | 146 | 157 | 177 | 373 | 193 | 311 | 107 |
| $d_{EL}$ | 184 | 185 | 197 | 146 | 149 | 118 | 149 | 174 | 138 | 168 | 188 | 143 |
| $t$ | **t1** | **t2** | **t3** | **t4** | **t5** | **t6** | **t7** | **t8** | **t9** | **t10** | **t11** | **t12** |
| $n_t$ | 744 | 672 | 744 | 720 | 744 | 720 | 744 | 744 | 720 | 744 | 720 | 744 |

| $\xi$ / $\tau$ / ( $\varphi_{Comp1,Comp2} = \varphi_{Comp2,Comp1}$ ) | **HP** | **MP** | **LP** |
|---|---|---|---|
| **High** | 20 / 5 / 100 | 100 / 5 / 150 | 100 / 5 / 150 |
| **Medium** | 15 / 6 / 75 | 70 / 6 / 125 | 70 / 6 / 125 |
| **Low** | 5 / 7 / 50 | 40 / 7 / 75 | 40 / 7 / 75 |

| $\varepsilon$ | **Company 1** | **Company 2** |
|---|---|---|
| **From Utility Company to Company *i*** | 2 | 2 |
| **From Company *i* to Utility Company** | 1.5 | 1.5 |

| | **Company 1** | **Company 2** |
|---|---|---|
| $X^U_{SOx}$ | 380000 | 380000 |
| $X^U_{GHG}$ | 1500000 | 1500000 |

| | |
|---|---|
| $\varsigma_{SOx}$ | 0.00646 |
| $\delta$ | 0.1 |
| $\omega$ | 0.5 |

Table 4.1 Data for Example Problem

The example energy production companies are modeled firstly for non-collaborated scenario. The following table shows that solving the non-collaborated model for minimizing the summation of two objectives gives the minimum cost values for both companies, since the costs are separated in non-collaborated case. First the total cost that includes the costs of company 1 and company 2 is minimized, that is shown in the first row of the Table 4.2. Then the problem is solved for minimizing the costs of company 1 while the constraints on company 1 and company 2 are satisfied simultaneously. In the last row, the results obtained by minimizing the costs of company 2 while satisfying the constraints on company 1 and company 2 are given. It can be seen in Table 4.2 that the costs are separable and can be used for comparison of financial performance of companies under different scenarios.

| | Total Cost | Cost of Company 1 | Cost of Company 2 |
|---|---|---|---|
| Solution for Minimization of Total Costs | 70,449.9 | 42,570.29 | 27,879.61 |
| Solution for Minimization of Company 1's Costs | 74,853.69 | 42,570.29 | 32,283.4 |
| Solution for Minimization of Company 2's Costs | 74,443.52 | 46,563.91 | 27,879.61 |

Table 4.2 Separable Behavior of Objective Function

The problem with the given data in Table 4.1 is solved under non-collaborated and collaborated scenarios. The models are coded in GAMS [40] and solved with CPLEX solver [41]. Table 4.3 gives model statistics for two cases. Non-collaborated case is easier to solve than collaborated case since in non-collaborated case the variables regarding to the exchange of steam between companies are fixed to zero and no investment decision for exchange structure construction is necessary.

| | Non-Collaborated Case | Collaborated Case |
|---|---|---|
| Optimal Objective Function Value | 70,449.90 | 66,122.55 |
| Single Equations | 3,150 | 3,080 |
| Single Variables | 10,558 | 10,562 |
| Discrete Variables | 2,027 | 2,027 |
| Iterations | 4,325 | 328,733 |
| Nodes | 874 | 23,972 |
| CPU Time (Sec) | 1.828 | 70.250 |

Table 4.3 Model Statistics for the Example

| | Non-collaborated Case | Collaborated Case [1] | Collaborated Case [2] |
|---|---|---|---|
| Total Cost | 70,449.9 | 66,122.55 | 66,728.23 |
| Total $SO_x$ Release | 658,672.5 | 703,195.9 | 658,672.5 |
| Total GHG Release | 2,420,271 | 2,465,647 | 2,353,268 |

Table 4.4 Cumulative Results for the Example

By solving the example for non-collaborated and collaborated cases the following cumulative results in Table 4.4 are obtained. When the first and second columns are compared, it is seen that there is a decrease in the total costs of the companies when they collaborate. However, since the limits are for the sum of the releases, the companies are freer to release harmful emissions in collaborated case. The releases in collaborated case are still under limits but they are higher than the non-collaborated case. In order to examine this situation, the total releases under non-collaborated case are set as total limits of collaborated case, and the "Collaborated Case [2]" column is obtained. The results in "Collaborated Case [2]" column are very promising. It is seen that, companies are improving their financial and environmental performances simultaneously by collaboration. This result is very useful in making collaboration decisions, especially when decreases in both costs and emissions are desired. On the other hand, this result does not show a symmetric situation, since new constraints on emissions are inserted. In order to be able to make symmetric examinations about collaboration dynamics, the results of first and second solutions will be examined.

When the objective function is examined in detail, it is known to consist of mainly costs of fuel (purchasing, ordering and holding), electricity, $SO_x$ penalty, unit operating, unit startup and construction of exchange structure. The following graph shows the changes in the costs with collaboration.

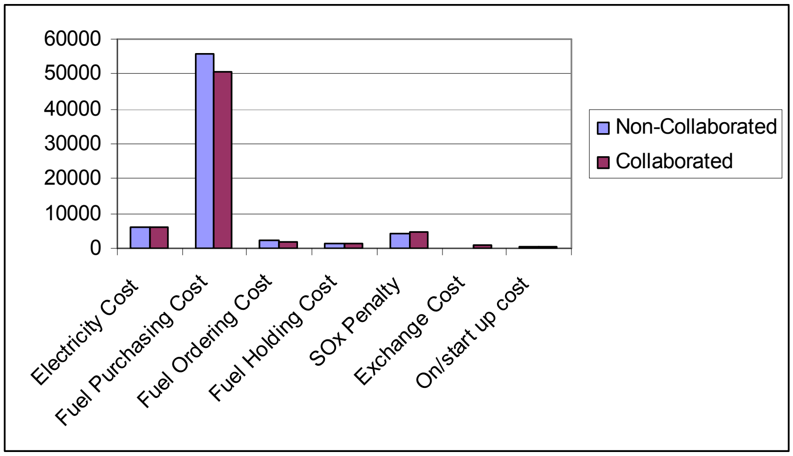



Figure 4.2 Changes in the Portions of Total Cost

It is seen that total cost companies decreases with collaboration. The main contribution for this decrease comes from the fuel purchasing cost. Companies save from fuel cost when they collaborate, although they spend for construction of exchange structure. The solution gives a timetable for companies regarding to their exchange structure construction. The timetable is given in Table 4.5.

| Company | Company | Unit | Mode | Period |
|---|---|---|---|---|
| Company1 | Company2 | MP | H | t1 |
| Company1 | Company2 | MP | L | t1 |
| Company1 | Company2 | MP | L | t5 |
| Company1 | Company2 | MP | L | t6 |
| Company1 | Company2 | LP | M | t1 |
| Company1 | Company2 | LP | L | t5 |

Table 4.5 Timetable for Exchange Structure Construction

It is beneficial for companies to construct more than one exchange unit at the first period as seen in Table 4.5. When some units are no longer usable after some time, new ones are constructed. For example, after five time periods, the high capacity MP steam exchange is no longer available, and the companies construct low capacity MP steam exchange at sixth time period. Table 4.6 gives the available exchange capacities between companies and the exchange amounts realized. Although the exchange units are bidirectional it is interesting that they are used only one way. This shows that one company's capacity is used by both companies.

| From Company | To Company | Unit | Period | Exchange Capacity | Exchange Amount | From Company | To Company | Unit | Period | Exchange Capacity | Exchange Amount |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Company1 | Company2 | MP | t2 | 140 | 0 | Company2 | Company1 | MP | t2 | 140 | 140 |
| Company1 | Company2 | MP | t3 | 140 | 0 | Company2 | Company1 | MP | t3 | 140 | 140 |
| Company1 | Company2 | MP | t4 | 140 | 0 | Company2 | Company1 | MP | t4 | 140 | 140 |
| Company1 | Company2 | MP | t5 | 140 | 0 | Company2 | Company1 | MP | t5 | 140 | 140 |
| Company1 | Company2 | MP | t6 | 180 | 0 | Company2 | Company1 | MP | t6 | 180 | 180 |
| Company1 | Company2 | MP | t7 | 120 | 0 | Company2 | Company1 | MP | t7 | 120 | 120 |
| Company1 | Company2 | MP | t8 | 120 | 0 | Company2 | Company1 | MP | t8 | 120 | 120 |
| Company1 | Company2 | MP | t9 | 80 | 0 | Company2 | Company1 | MP | t9 | 80 | 80 |
| Company1 | Company2 | MP | t10 | 80 | 0 | Company2 | Company1 | MP | t10 | 80 | 44.35 |
| Company1 | Company2 | MP | t11 | 80 | 0 | Company2 | Company1 | MP | t11 | 80 | 80 |
| Company1 | Company2 | MP | t12 | 80 | 0 | Company2 | Company1 | MP | t12 | 80 | 80 |
| Company1 | Company2 | LP | t2 | 70 | 0 | Company2 | Company1 | LP | t2 | 70 | 70 |
| Company1 | Company2 | LP | t3 | 70 | 0 | Company2 | Company1 | LP | t3 | 70 | 70 |
| Company1 | Company2 | LP | t4 | 70 | 0 | Company2 | Company1 | LP | t4 | 70 | 70 |
| Company1 | Company2 | LP | t5 | 70 | 0 | Company2 | Company1 | LP | t5 | 70 | 70 |
| Company1 | Company2 | LP | t6 | 110 | 0 | Company2 | Company1 | LP | t6 | 110 | 110 |
| Company1 | Company2 | LP | t7 | 110 | 0 | Company2 | Company1 | LP | t7 | 110 | 102 |
| Company1 | Company2 | LP | t8 | 40 | 0 | Company2 | Company1 | LP | t8 | 40 | 40 |
| Company1 | Company2 | LP | t9 | 40 | 0 | Company2 | Company1 | LP | t9 | 40 | 40 |
| Company1 | Company2 | LP | t10 | 40 | 0 | Company2 | Company1 | LP | t10 | 40 | 40 |
| Company1 | Company2 | LP | t11 | 40 | 0 | Company2 | Company1 | LP | t11 | 40 | 40 |
| Company1 | Company2 | LP | t12 | 40 | 0 | Company2 | Company1 | LP | t12 | 40 | 40 |

Table 4.6 Exchange Capacities and Amounts Realized

Another important characteristic to examine is the usage of biodiesel. According to, Table 4.7 in non-collaborated setting, because of tight limits on individual emission limits, the companies buy and use biodiesel more than collaborated setting. This is because the emissions from biodiesel are lower than other fuels. The usage is higher than purchase since the companies use the biodiesel in the inventory.

| | Non-collaborated Setting | Collaborated Setting |
|---|---|---|
| Total Biodiesel Purchase | 65.28 | 0 |
| Total Biodiesel Usage | 87.28 | 22 |

Table 4.7 Biodiesel Usage and Purchase with the Objective of Minimization of Total Costs

An important feature to examine is the average loads of the boilers. In previous chapter, it was seen that allocating idle boiler capacities differently was the main motivation in making benefits from collaboration. To examine if it holds for the example energy system, the following table indicating the boiler usage statistics has been constructed. Having in mind that the company 2's boilers are more efficient, it is seen in Table 4.8 that the idle capacity at more efficient boilers are shifted to less efficient ones and, the average load of more efficient boilers increased with collaboration.

| | | Non-Collaborated | | | Collaborated | | |
|---|---|---|---|---|---|---|---|
| | | Average Load | Average Idle Capacity | Number of Periods Used | Average Load | Average Idle Capacity | Number of Periods Used |
| Company 1 | Boiler 1 | 0.54 | 255.32 | 9 | 0.32 | 375.22 | 8 |
| | Boiler 2 | 0.92 | 39.89 | 12 | 0.77 | 121.86 | 12 |
| Company 2 | Boiler 1 | 0.27 | 477.63 | 4 | 0.36 | 415.04 | 8 |
| | Boiler 2 | 0.79 | 141.05 | 12 | 0.94 | 41.88 | 12 |

Table 4.8 Boiler Usage Statistics

Companies make some operational changes in their schedules and usage characteristics in order to benefit from collaboration. Therefore, they can gain more than they spent for constructing exchange structures. Making changes in operational characteristics requires some flexibility. We have seen in previous chapters that for the simple examples this flexibility came from the differences between the companies and available idle capacities of the units.

### 4.4 Synergy Analysis in Energy Systems

In this section, the findings of the Chapter 3 will be examined on the energy model that models the energy producing companies in more detail. This examination is performed on a setting that the companies are completely identical, i.e. second company's parameters are the same as that of first one. The results of the model with identical companies under different cases is given in Table 4.9.

| | Non-collaborated Case | Collaborated Case [1] | Collaborated Case [2] |
|---|---|---|---|
| Total Cost | 85140.58 | 85099.35 | 85140.58 |
| $SO_x$ Release | 760000 | 760000 | 760000 |
| GHG Release | 2882042 | 2882042 | 2882042 |
| Electricity Cost | 5498.98 | 5498.98 | 5498.98 |
| Fuel Purchasing Cost | 70096.38 | 70092.96 | 70096.38 |
| Fuel Ordering Cost | 2900 | 2750 | 2900 |
| Fuel Holding Cost | 1311.64 | 1423.81 | 1311.64 |
| SOx Penalty | 4909.6 | 4909.6 | 4909.6 |
| Exchange Cost | 0 | 0 | 0 |
| On/Start up Cost | 423.98 | 424 | 423.98 |

Table 4.9 The Comparison of Collaborated and Non-Collaborated Identical Companies

When the first and second columns of Table 4.9 are compared, we see that there is a decrease in the total costs of the companies. Since the limits are for the sum of the releases, the companies are freer to release harmful emissions in collaborated case. Therefore, this little decrease is because of the ability of choosing cheaper but more harmful fuel. In this case, no exchange structure is constructed, and it is not logical to compare the performance of the companies under total limits. Then, the case with possible collaboration, identical parameters, and individual emission limits is solved. The results are shown in the third column. It is seen that, the companies do not choose to collaborate and all decisions are the same as the non-collaborated case. Therefore, under the case companies are totally identical, there is no potential benefit of collaboration.

In order to examine if this is true for more than two companies, the model is enlarged to cover three, four, five and six companies. As soon as the companies are identical, there is no benefit in collaboration regardless the number of the companies, as can be seen in Figure 4.3.

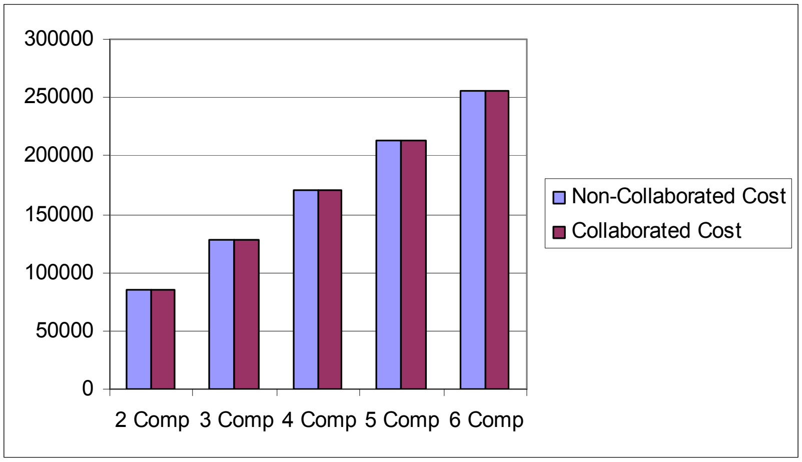



Figure 4.3 Comparison of Collaboration among Identical Companies

The finding of previous chapter that, "when companies are identical, collaboration creates no synergy" is verified with the examination of companies whose parameter values as well as structures are identical. The synergy occurs when there are some differences between parameters. It is important to understand why the synergy occurs and experiments are performed in order to explore the differences that create synergy. The changes are made from the model with identical companies in order to examine the effects of changes in parameters one by one with the assumption that changes in one parameter do not affect other parameters. The detailed figures and explanations according to these examinations can be found in Appendix B. It is observed in the experiments that the findings of Chapter 3 are supported in an energy system which is much more complicatedly modeled. According to the examinations, the differences that have effect on the amount of steam produced or sold are found to create synergy in the existence of idle capacities.

### 4.5 Rationality Analysis of Collaboration

Up to this point, it has been shown that, if companies have some differences, collaboration creates synergy and total cost decreases under certain conditions. In this section, the individual costs and releases of the companies will be studied to examine the rationality of collaboration.

The example with data given in Table 4.1 is used in examining rationality of collaboration. When the example is solved in collaborated and non-collaborated cases, the individual costs and releases of the companies are found as in Table 4.10.

| | Non-collaborated Case | Collaborated Case | Percent Change |
|---|---|---|---|
| Total Cost | 70,449.9 | 66,122.55 | -6.14% |
| Company 1's Cost | 42,570.29 | 31,196.27 | -26.72% |
| Company 1's $SO_x$ Release | 380,000 | 337,784.5 | -11.11% |
| Company 1's GHG Release | 1,441,021 | 1,181,648 | -18.00% |
| Company 2's Cost | 27,879.61 | 34,926.28 | 25.28% |
| Company 1's $SO_x$ Release | 278,672.5 | 365,411.3 | 31.13% |
| Company 1's GHG Release | 979,250.2 | 1,283,999 | 31.12% |

Table 4.10 Comparison of Individual Solutions of Collaborated and Non-collaborated Settings

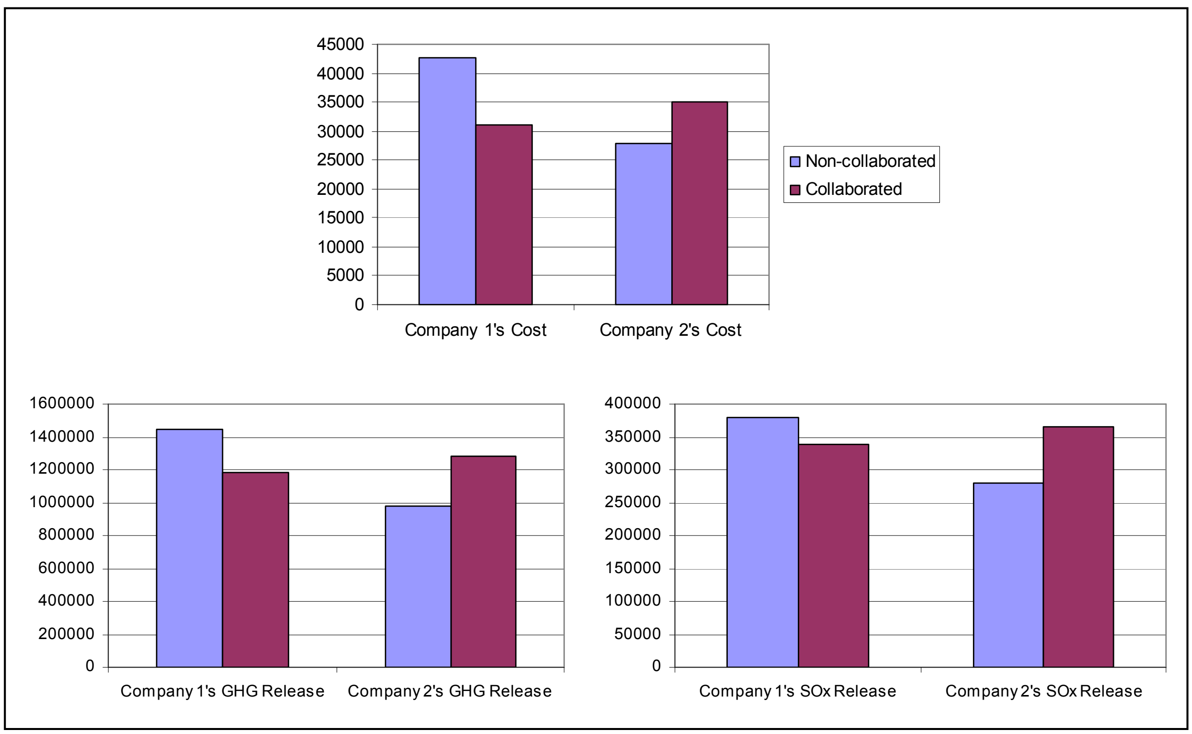



Figure 4.4 Comparison of Individual Solutions of Collaborated and Non-Collaborated Settings

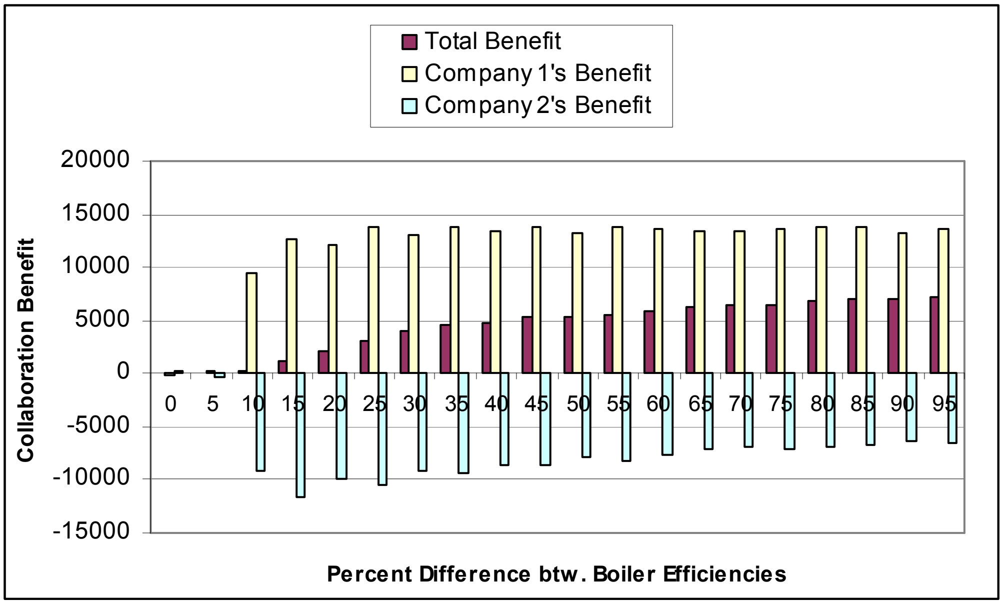



Figure 4.5 Comparison of Individual Costs of Collaborated and Non-collaborated Settings under the Existence of Differences in Boiler Efficiencies

Figure 4.4 shows that while one company gains with collaboration, the other one loses in all of the three performance parameters, i.e. cost, GHG and $SO_x$ emissions. Figure 4.5 verifies it for the case with boiler efficiency differences. But, since each company wants to minimize its own costs, collaboration is not logical for the losing party. In order to make a decision to work together with another company, the company must be sure that its new costs will be smaller than its previous costs. This is called *individual rationality*. When the individual rationality constraints are added to the model, optimization model becomes, minimizing collaborated total costs subject to operational constraints and individual rationality constraints.

In order to satisfy individual rationality constraints, the model is solved for non-collaborated case first and the individual costs of companies are called $TC_i^u$. Then, by adding the following constraint, the model is solved under collaborated scenario.

$$TC_i \leq TC_i^u \quad (4.38)$$

This model can only be successful if individual costs in collaborated case are smaller than in non-collaborated case. Adding this constraint to the model and solving it, suggests not constructing any exchange structure. However, the solution with smaller total cost –not as small as the collaborated case- is possible, because the looser environmental limits give the companies the flexibility of burning cheaper fuel. Therefore, if it is possible, companies can still benefit by only making coordination on environmental limits on their emissions. However, this is not the case for the setting tested; if companies do not collaborate their emissions are limited by individual limits. Then, the collaborated case is solved with individual emission limits. In this case, the addition of individual rationality constraints alone resulted in non-collaborated solution. In order to benefit from collaboration, some type of contract between the companies should be formed satisfying all constraints. Two types of contracts will be studied here.

### 4.5.1 Unit Exchange Cost

Companies can make a contract by exchanging money for unit of steam exchange. Different price schemes for steam at different pressures can be decided by contracts. In the model in order to test if the contract can be coordinating, one price is used for all three types of steam pressures. Unit exchange cost can be formed by defining the cost of exchange with the following constraint and adding this cost to the objective function.

$$CEC_i = \sum_j \sum_{i'} \sum_{j'} \sum_t \rho \times XEC_{i'j'ijt} - \sum_j \sum_{i'} \sum_{j'} \sum_t \rho \times XEC_{iji'j't} \qquad (4.39)$$

Eq.(4.39) states that if one company is receiving steam from the other one, the receiving company pays to the sender company in proportion to the amount of steam. This constraint is added to the model and the example problem is solved by increasing the unit exchange cost by increments of 0.5 starting from 0. Figure 4.6 is obtained for different values of unit exchange costs.

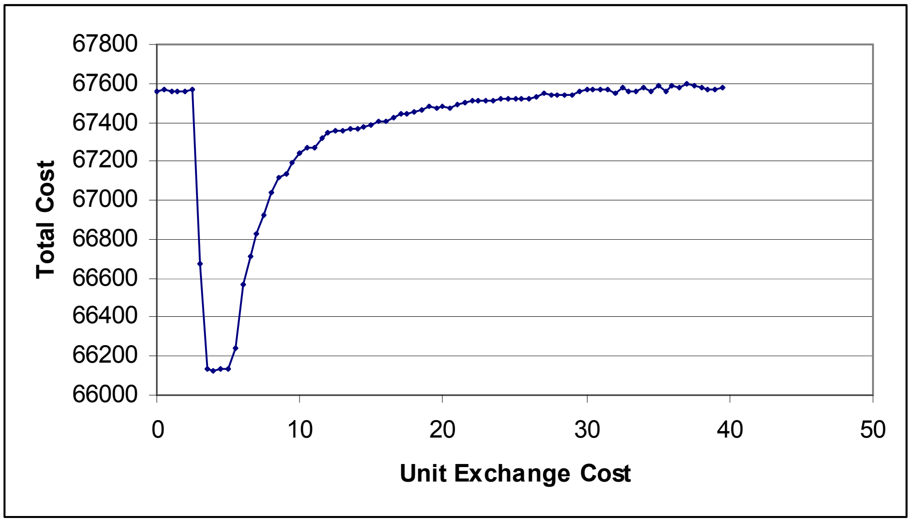



Figure 4.6 Total Cost vs. Unit Exchange Cost

When the figure is examined, it can be seen that at the minimum value of coordinated cost curve, the total cost and exchange investment are as follows:

| ρ | Total Cost | Exchange Investment |
|---|---|---|
| 4 | 66124.63 | 1250 |

Table 4.11 Benefit Analyses at the Best Point of Unit Sharing Cost

Note that the value of total cost is very near to the optimum value of collaborated case. This shows us that it is possible to get the benefits of collaboration by paying money for unit of steam exchange. In order to examine the steam exchange for different levels of unit exchange cost, the exchange investment is plotted vs. unit exchange cost in Figure 4.7. Exchange investment is a good indicator of steam exchange since the exchange structures are capacitated. According to Figure 4.7, for different values of unit exchange cost, exchange investment changes and for very small and very large values of unit exchange cost, companies select not to make any investment for steam exchange.

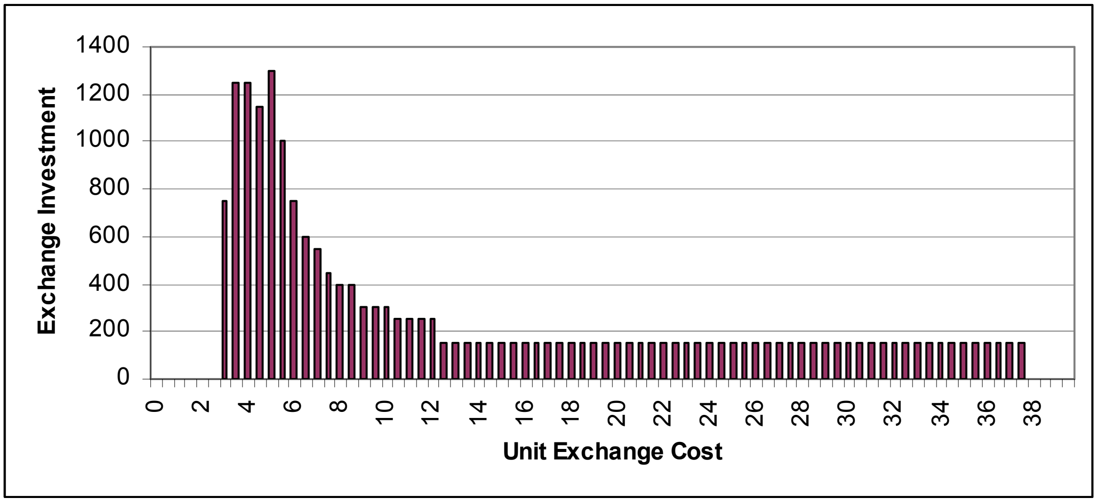



Figure 4.7 Exchange Investment vs. Unit Exchange Cost

The contract can be extended with various different approaches. First of all, the contract can be modified to support different prices for steam at different pressures. Moreover, as seen in the Figure 4.4, with collaboration the GHG release and the cost of a company increase at the same time. This is because one company's resources are used more extensively and the companies are more flexible to emit GHG as a result of the pooling effect on GHG emissions with collaboration. Unit exchange cost contract models the increase in costs in terms of steam exchange. The contract can be extended with modeling the change in GHG emissions as if the company is selling GHG release permits to the other one. However, since the main logic is the same and only the parameters change, the mentioned extensions will not be analyzed here.

### 4.5.2 Cost Sharing

Cost sharing contract is simple: in order to make the losing company gain from exchanging steam, the company with profit gives money to the losing one. This is added to the model by adding the following constraints to the model. The amount of money that company *i* pays to company *j* is modeled with variable $VS_{ij}$.

$$TC_i + \sum_j VS_{ij} \leq TC_i^u \qquad (4.40)$$

$$\sum_i \sum_j VS_{ij} = 0 \qquad (4.41)$$

Eq. (4.40) states that for company *i* the sum of its cost and the amount of money given to other companies must be less than its cost in non-collaborated case. According to Eq.(4.41), the total amount of money exchanged in the system must add to zero. The example is solved with the addition of the Eqs. (4.40) and (4.41) as constraints and fixing $VS_{12} = -VS_{21}$ to 3000+ 250$q$ for each loop $q$, such that $q \in \{0, 80\}$. Figure 4.8 is plotted for shared cost value vs. total cost of companies.

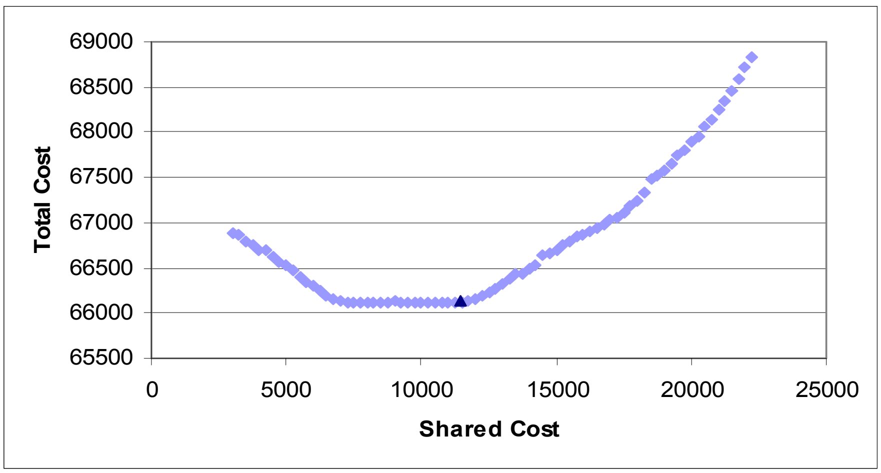



Figure 4.8 Cost in Coordinated Case vs. Shared Cost

When Figure 4.8 is examined, it is seen that, for the example problem, the optimal solution of total cost is convex with respect to shared cost. The shape of total cost function vs. shared cost reminds that there is a shared cost value that minimizes the total cost of collaborated companies. This coincides with the discussion of rationality analysis in Section 3.2.2. When the optimization problem is solved without fixing the shared cost to a value, but solving for it as a free variable, the point shown with dark triangle is obtained. This is the optimal value that is achieved by collaboration. There is more than one value giving the optimal objective function value. This is logical since, as soon as the individual rationality constraints are satisfied, the companies may decide to exchange any amount of money summing up to the collaboration benefit. Figure 4.8 is important to show that if the shared cost parameter is incorrectly decided, there might be deviations from the minimum total cost.

### 4.6 Collaboration for Environmental Synergy

Although it has already been shown that both environmental and financial improvement is possible with collaboration, there was a little increase in the emissions of the companies, since no extra limit was defined on emissions in order not to distract from the symmetry of the analysis. In this part, the question "can the companies benefit in terms of environmental performance, without worsening financial performance?" will be answered. First of all, the problem is solved in non-collaborated setting. The total costs of the companies in non-collaborated setting will be taken as limits on the total cost of the collaborated setting. This is logical since by a sharing costs contract, the companies can satisfy individual rationality constraints on their costs. The setting is solved by making the objective function minimization of the total GHG releases. The results are as at Table 4.12:

| | Non-collaborated Case | Collaborated Case | Percent Change |
|---|---|---|---|
| Total Cost | 70,449.9 | 70,280.18 | -0.24% |
| Total GHG Release | 2,420,271.2 | 2,100,144.3 | -13.23% |
| Company 1's Cost | 42,570.29 | 24,611.95 | -42.19% |
| $SO_x$ Release | 380,000 | 176,271 | -53.61% |
| GHG Release | 1,441,021 | 676,530.5 | -53.05% |
| Company 2's Cost | 27,879.61 | 45,668.23 | 63.81% |
| $SO_x$ Release | 278,672.5 | 370,786.7 | 33.05% |
| GHG Release | 979,250.2 | 1,423,614 | 45.38% |

Table 4.12 Benefit Analyses for Minimizing GHG

As can be seen from Table 4.12, by collaboration, it is possible for companies to benefit in environmental criteria without sacrificing from financial performance. The extensive synergy analysis will not be performed here, since the dynamics of the synergy will follow the same principles for environmental constraints, too. It is interesting to examine the biodiesel usage and its effects on environmental improvements. Table 4.13 gives the usage and purchase amounts of biodiesel in collaborated cases with different objectives. The companies spend more biodiesel than they purchase because of the initial inventory in their fuel tanks. According to the table, both usage and purchase of biodiesel increase when the objective is to minimize GHG emissions. This shows us that, as a quick action in emission reduction route, increasing the biodiesel usage is a possible alternative.

| | Collaborated Case with Minimizing Cost Objective | Collaborated Case with Minimizing GHG Emissions Objective |
|---|---|---|
| Total Biodiesel Purchase | 0 | 108.66 |
| Total Biodiesel Usage | 22 | 130.71 |

Table 4.13 Biodiesel Usage and Purchase with Minimizing Emissions Objective

**4.7 Conclusion**

The model for energy systems was enhanced in order to cover more features and to examine if collaboration still works with more characteristics. It is shown that, the basic feature of collaboration benefit holds: differences create synergy. When it is seen that collaboration is beneficial for the whole system, the benefits of individual companies have been examined. It is observed that it is possible to make the collaboration financially work with some contracts among the parties. It has also been shown that, it is possible for companies to benefit in environmental criteria without sacrificing from financial performance.

# Chapter 5

# ADVANCED MODELS IN ENERGY PRODUCTION SYSTEMS

## 5.1 Introduction

Advanced models for two different levels of decision are developed in this chapter. The first level of decisions involves the realistic modeling of performance maintenance of the boilers. The performance of boilers decreases with time due to operating conditions of boilers. The decaying performance can be represented as reduction in the maximum capacity. The second level of decisions is incorporated by modeling the multi-objective nature of the energy production systems. The decisions in this level aim to help the decision makers in their search for minimum emissions with minimum costs. The synergy created by collaboration is examined in both levels of decision and found to be successful in both of the modeling techniques.

## 5.2 Decreasing Capacity of Boilers

Performance monitoring of boilers is very important especially in energy production systems since a major part of the operating cost is determined by the fuel consumed in the boilers. As it is in the example in Chapter 4, cost of purchasing fuel constitutes the largest portion in the total cost. In addition to this, as it was shown in Chapter 3, idle boiler capacities of the boilers are important in obtaining collaboration benefit. Therefore, it is essential to study the complex nature of the boilers in order to see their effects on collaboration. In the energy systems model, boiler capacity is assumed to be constant. In fact, boiler capacity decreases with time. As fuels are not in their pure form, they tend to deposit scales in the main parts of the boiler. A steady loss in the evaporating capacity is experienced due to accumulation of scales, [42], [43]. The performance of the boiler is increased to its design levels after a cleanup. Hence performance monitoring of the boiler is essential to decide at what point of time the boiler needs to be taken out of service for cleaning and other maintenance jobs.

In this study two main approaches are for the performance maintenance modeling. In the first one, the boilers age with the number of periods they work since the last cleanup and the boiler capacity decreases with increasing ages. In the second approach, the boilers are worn out with the amount of steam that has been produced since the last cleanup. In both approaches, optimization model decides the number, and the schedule of the cleanups, as well as the states of the boilers.

### 5.2.1 Capacity Decrease with the Number of Periods a Boiler Used

The boiler capacity decreases with the number of periods that the boiler is used to produce steam. It is assumed that, there is a linear decrease in the boilers capacity in proportion to the number of periods it has been used. This is a linear approximation of boiler capacity decrease with age. In reality, the boiler capacity decrease depends on more than one parameter's changes and there are various models including nonlinear and linear ones in the literature. This approximation is a generalization of all of the parameters assuming that if a boiler is used in a period the decrease in the capacity of the boiler is constant. This approximation was used in order not to give up the mixed-integer linearity of the energy systems model. New variables and sets are required to model the changing states of the boilers, maintenance schedules and capacities.

In order to model the boiler performance maintenance, a new set of devices is defined. As seen in Figure 5.1, this set consists of available boiler devices that are used when the changeover is necessary. When maintenance is performed, the model behaves like a new device is assembled to the boiler. The device set stands for the first, second… maintenances. In reality, there are no device changes during the cleanups. The device set is as an auxiliary set for modeling of maintenances. Each of the maintenances is modeled as a device change. When a boiler undergoes a cleanup, i.e., device change, then it can not be used for production during the cleanup period. The maintenance costs will be modeled as the same as the changeover costs.

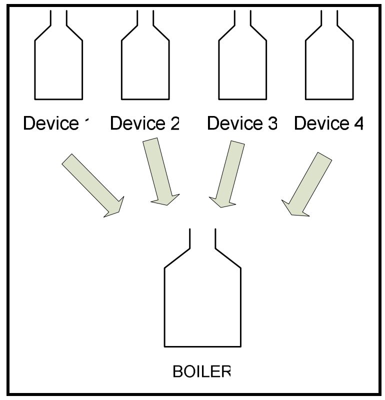



Figure 5.1 An Example of Available Devices for a Boiler

The model has the flexibility of selecting maintenance numbers and periods. In order to give the model the freedom to decide the number of changeovers, a large number of devices can be defined. The state of any device is modeled with binary variables. If a device is at a state, the corresponding binary variable gets a value of 1, 0 otherwise. A device in period *t* can be in four distinct states:

$YO_{ijbt}$ = 1, if the device *b* is on boiler *j* of company *i* at period *t* (On-State)

$YN_{ijbt}$ = 1, if the device *b* for boiler *j* of company *i* is not used yet at period *t* (New-State)

$YX_{ijbt}$ = 1, if the device *b* for boiler *j* of company *i* has been taken off and is old at period *t* (X-State)

$YC_{ijbt}$ = 1, if the device *b* for boiler *j* of company *i* is at set up at period *t* (Change-State)

There is also an additional state ($YW_{ijbt}$) that models the "Working-State" of a device. A device that is 'on' a boiler, can either be working in a period or not, i.e. "Working-State" is a subset of "On-State". The required changeovers -maintenances- can be modeled by using the relationships between these variables. In order to introduce maintenance equations into the energy systems model in Chapter 4, the equations in boiler models need to be reconstructed. For that reason, the Eq. (4.1) is removed and the following set of equations is inserted to the model.

$$FD_{ijk_{fuel}l_{con}bt} \frac{cc_k}{\eta_{ij}} = XHFD_{ijk_{fuel}bt} \tag{5.1}$$

$$XHF_{ijkt} = \sum_b XHFD_{ijk_{fuel}bt} \tag{5.2}$$

$$X_{ijk_{fuel}l_{con}t} = \sum_b FD_{ijk_{fuel}bt} \tag{5.3}$$

$$A_{ijbt} = \sum_{q=1}^{t-1} YW_{ijbq} \tag{5.4}$$

$$XHFD_{ijk_{fuel}bt} \leq \lambda\left(\kappa - A_{ijbt}\right) + \Theta \tag{5.5}$$

The variable $XHF_{ijkt}$, stating the amount of HP steam produced from a specific fuel is disaggregated into variables ($XHFD_{ijkbt}$) according to the device that is on the boiler during the steam production. The variable for fuel consumption is also disaggregated into variables ($FD_{ijkbt}$) for each device. Eq. (5.1) models the production of HP steam in a boiler when a device is on it. Eq.(5.2) states that the sum of HP steam production in devices from a specific fuel is equal to the total HP steam production in a boiler from that fuel. According to Eq.(5.3) the sum of fuel consumption in devices is equal to the total fuel consumption in a boiler. Eq. (5.4) determines the age of a device to be the number of periods that a device is "used" since the last cleanup. Eq. (5.5) models that the HP production from a boiler when a device is 'on', is less than the minimum capacity plus the depreciation rate times the difference between the maximum age and the device's age. The following set of equations between variables model the states of the variables and their interrelationships.

$$YO_{ijbt} + YN_{ijbt} + YX_{ijbt} + YC_{ijbt} = 1 \tag{5.6}$$

$$FD_{ijk_{fuel}bt} \leq M \times YW_{ijbt} \tag{5.7}$$

$$FD_{ijk_{fuel}bt} \leq M \times \left(1 - YN_{ijbt}\right) \tag{5.8}$$

$$FD_{ijk_{fuel}bt} \leq M \times \left(1 - YC_{ijbt}\right) \tag{5.9}$$

$$FD_{ijk_{fuel}bt} \leq M \times \left(1 - YX_{ijbt}\right) \tag{5.10}$$

$$\sum_b \left(YO_{ijbt} + YC_{ijbt}\right) = 1 \tag{5.11}$$

$$XHFD_{ijk_{fuel}bt} \leq M \times YW_{ijbt} \tag{5.12}$$

$$XHFD_{ijk_{fuel}bt} \leq M \times \left(1 - YN_{ijbt}\right) \tag{5.13}$$

$$XHFD_{ijk_{fuel}bt} \leq M \times \left(1 - YC_{ijbt}\right) \tag{5.14}$$

$$XHFD_{ijk_{fuel}bt} \leq M \times \left(1 - YX_{ijbt}\right) \tag{5.15}$$

$$YW_{ijbt} \leq YO_{ijbt} \tag{5.16}$$

Eq. (5.6) requires a device be in one of the available states. Eqs. (5.7, 5.8, 5.9, 5.10) state that there is no fuel consumption if the device is not working, is not used yet, is at setup or has already taken out of a boiler, respectively. Eq.(5.11) states that a boiler should have a device 'on' or a setup of a device must be conducted on a period. Eqs. (5.12, 5.13, 5.14, 5.15) state that there is no HP production if device is not working, is not used yet, is at setup or has already taken out of a boiler, respectively. The following group of equations: Eqs. (5.12, 5.13, 5.14, 5.15) requires the group Eqs. (5.6, 5.7, 5.8, 5.9), and one of the pair can be taken out of the model without losing from accuracy. But they are included in the model for keeping consistency. Eq. (5.16) states that a device cannot work unless it is on a boiler. The following set of equations is included for modeling logical relationships between the states and the timing of the maintenances. In modeling these relationships the propositional logic methodology has been put in use.

Eq. (5.17) states that if the device is not on a boiler in period '*t*-1' and is on a boiler at period *t* then it must have been assembled at period '*t*-1'. Its derivation from the logical expressions is performed as follows:

$$\neg YO_{ijb(t-1)} \wedge YO_{ijbt} \Rightarrow YC_{ijb(t-1)} \qquad t > 1$$

$$\left(1 - YO_{ijb(t-1)}\right) \wedge \left(YO_{ijbt}\right) \Rightarrow YC_{ijb(t-1)} \qquad t > 1$$

$$\neg\left(\left(1 - YO_{ijb(t-1)}\right) \wedge \left(YO_{ijbt}\right)\right) \vee YC_{ijb(t-1)} \qquad t > 1$$

$$\neg\left(1 - YO_{ijb(t-1)}\right) \vee \neg\left(YO_{ijbt}\right) \vee YC_{ijb(t-1)} \qquad t > 1$$

$$YO_{ijb(t-1)} + \left(1 - YO_{ijbt}\right) + YC_{ijb(t-1)} \geq 1 \qquad t > 1$$

$$1 - YO_{ijbt} + YO_{ijb(t-1)} + YC_{ijb(t-1)} \geq 1 \qquad t > 1$$

$$YO_{ijb(t-1)} - YO_{ijbt} + YC_{ijb(t-1)} \geq 0 \qquad t > 1 \tag{5.17}$$

Eq. (5.18) states that if the device was new in period '*t*-1' and is not new in period *t*, then it is assembled to a boiler on period *t*.

$$\neg YN_{ijbt} \wedge YN_{ijb(t-1)} \Rightarrow YC_{ijbt} \qquad t > 1$$

$$YN_{ijbt} - YN_{ijb(t-1)} + YC_{ijbt} \geq 0 \qquad t > 1 \qquad (5.18)$$

Eq. (5.19) states that if the device is assembled to a boiler on period '*t*-1' then it must be 'on' that boiler in period *t*.

$$YC_{ijb(t-1)} \Rightarrow YO_{ijbt} \qquad t > 1$$

$$YO_{ijbt} - YC_{ijb(t-1)} \geq 0 \qquad t > 1 \qquad (5.19)$$

Eq. (5.20) states that if the device is on a boiler in period '*t*-1' and is not on it in period '*t*', then it must be in "X-state" on period *t*.

$$\neg YO_{ijbt} \wedge YO_{ijb(t-1)} \Rightarrow YX_{ijbt} \qquad t > 1$$

$$YO_{ijbt} - YO_{ijb(t-1)} + YX_{ijbt} \geq 0 \qquad t > 1 \qquad (5.20)$$

Eq. (5.21) states that if a device is in "X-state" on period '*t*-1', it must be in "X-state" in period '*t*'.

$$YX_{ijb(t-1)} \Rightarrow YX_{ijbt} \qquad t > 1$$

$$YX_{ijbt} - YX_{ijb(t-1)} \geq 0 \qquad t > 1 \qquad (5.21)$$

A device cannot be in "X-state" for all of the planning period. According to Eq. (5.22) it must be assembled to a boiler at least for one period before converted to "X-state".

$$YX_{ijbt} \leq \sum_{k=1}^{t} YO_{ijbk} \qquad (5.22)$$

Most of the equations above are for periods after the first period. It is possible to fix which device is on the boiler at the first period before running the model. However, it is not necessary and the optimization can select one. In addition to these constraints, the cost of changing a device, i.e. maintenance cost –modeled by Eq.(5.23) has been inserted to the objective function. The objective function then becomes as in Eq. (5.24).

$$CM_i = \sum_j \sum_b \sum_t \mu \times YC_{ijbt} \tag{5.23}$$

$$\min z = \sum_i \left( C_i + CP_i + HC_i + CE_i + CS_i + CEL_i + CW_i + CSU_i + CM_i \right) \tag{5.24}$$

In the model, the parameters for the devices are identical. If there are more than one type of maintenance with different cost and performance parameters, the model is capable of using specific parameters for maintenance types.

The equations for performance decrease have been inserted to the energy model explained with data from Table 4.1. The resulting optimization problem for collaborated and non-collaborated cases has been solved with parameters, $\lambda = 200$, $\kappa = 7$, $\Theta = 0$ and $\mu = 70$. As expected, there has been significant decrease in total costs with collaboration. Table 5.1 shows the results of performance criteria comparison of collaborated and non-collaborated cases. Note that the results are not the same as the previous results because of new features of the system.

| | Non-Collaborated Case | Collaborated Case | Percent Change |
|---|---|---|---|
| Total Cost | 70,589.05 | 66,311.3 | -6.06% |
| Total GHG Release | 2,404,232 | 2,459,750 | 2.31% |
| Total $SO_x$ Release | 56,005.09 | 50,527.96 | -9.78% |

Table 5.1 Comparison of Performance Criteria with Boiler Capacity Decrease with Age

The aim of this comparison is to see that when the model is very complicated, like including maintenance scheduling, collaboration is still beneficial for companies. To see the aging of a device and change, Figure 5.2 is drawn for company 1's boiler 2 in non-collaborated case. It starts with device 1, and after aging it is changed to device 4. The schedules of the maintenances of individual companies under collaborated and non-collaborated cases are as seen in the Figure 5.3. The companies start with device 1 installed on their boilers in both cases, this is because in order to reduce the solution time, the corresponding states are fixed to 1. Under non-collaborated case only company 1 makes a device change in boiler 2. However, the schedule changes with collaboration and in this case, both companies make device changes in their second boilers. It is seen that companies change their schedules as well as their performance maintenances in order to benefit from collaboration. Although the companies perform more maintenance operations in collaborated case, it is still more beneficial to collaborate because of the flexibility of using more efficient units, selecting cheaper fuels. Since the ages of the boilers cannot be seen but only their schedules can be seen in Figure 5.4 the ages are given in Appendix C.

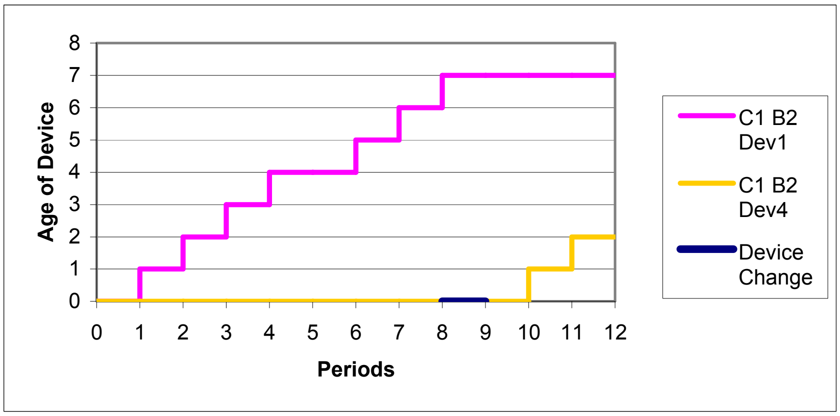



Figure 5.2 Aging of Devices on Company 1's Boiler 2 in Non-Collaborated Case

| Non- Collaborated Case | | | | | | Collaborated Case | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| C1 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | C1 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 1 | | | | | | 1 | | | | |
| 2 | | | | | | 2 | | | | |
| … | | | | | | … | | | | |
| 11 | | | | | | 11 | | | | |
| 12 | | | | | | 12 | | | | |
| C1 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | C1 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 1 | | | | | | 1 | | | | |
| 2 | | | | | | 2 | | | | |
| 3 | | | | | | 3 | | | | |
| 4 | | | | | | 4 | | | | |
| 5 | | | | | | 5 | | | | |
| 6 | | | | | | 6 | | | | |
| 7 | | | | | | 7 | | | | |
| 8 | | | | | | 8 | | | Change | |
| 9 | | | | Change | | 9 | | | | |
| 10 | | | | | | 10 | | | | |
| 11 | | | | | | 11 | | | | |
| 12 | | | | | | 12 | | | | |
| C2 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | C2 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 1 | | | | | | 1 | | | | |
| 2 | | | | | | 2 | | | | |
| … | | | | | | … | | | | |
| 11 | | | | | | 11 | | | | |
| 12 | | | | | | 12 | | | | |
| C2 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | C2 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 1 | | | | | | 1 | | | | |
| 2 | | | | | | 2 | | | | |
| 3 | | | | | | 3 | | | | |
| 4 | | | | | | 4 | | | | |
| 5 | | | | | | 5 | | | | |
| 6 | | | | | | 6 | | | | |
| 7 | | | | | | 7 | | Change | | |
| 8 | | | | | | 8 | | | | |
| 9 | | | | | | 9 | | | | |
| 10 | | | | | | 10 | | | | |
| 11 | | | | | | 11 | | | | |
| 12 | | | | | | 12 | | | | |

Figure 5.3 Performance Maintenance of Boilers with Boiler Capacity Decrease with Age

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| "On-State" | | "New-State" | | "X-State" | | "Change-State" | Change |

### 5.2.2 Capacity Decrease with the Amount of Steam Produced

In the second approach in modeling the capacity decrease, the capacity decreases with the total HP steam production since the last maintenance. This case is very similar to the case of capacity decrease with the number of periods a boiler is used. The equations for changeovers and states, i.e. Eqs (5.1-5.3, 5.6-5.24) are the same. The equations stating the age and the capacity decrease, i.e. Eqs. (5.4) and (5.5) are replaced by the Eqs. (5.25) and (5.26).

$$XSUM_{ijbt} = \sum_{k} \left( \sum_{q=1}^{t-1} XHFD_{ijk_{fuel}bq} + 0.5 \times XHFD_{ijk_{fuel}bt} \right) \quad (5.25)$$

$$XHFD_{ijk_{fuel}bt} \leq X^{U}_{ijk_{HP}l_{gen}} - XSUM_{ijbt} \times \ell \quad (5.26)$$

Eq. (5.25) states that the cumulative HP steam production in a device in period $t$ is equal to the HP steam production in that device until $t$ plus the half of HP steam production in period $t$. This type of averaging was obligatory because of the discrete periods used in the model. Eq.(5.26) models the capacity decrease with the cumulative HP steam production time depreciation rate, $\ell$ .

The same example with the capacity decrease has been solved with parameter $\ell = 0.01$, i.e. 1% capacity decrease for each unit of steam produced. The results of performance criteria are as in Table 5.2. Note that the results are not the same as the previous results because of new features of the system.

| | Non-Collaborated Case | Collaborated Case | Percent Change |
|---|---|---|---|
| Total Cost | 70,388.24 | 66,148.63 | -6.02% |
| Total $SO_x$ Release | 658,816.1 | 700,889.2 | 6.39% |
| Total GHG Release | 2,420,412 | 2,459,371 | 1.61% |

Table 5.2 Comparison of Performance Criteria with Boiler Capacity Decrease with Cumulative HP Steam Production

It is observed that collaboration is still beneficial in the existence of the performance scheduling of the boilers with cumulative HP steam production. An example for the cumulative HP productions of the devices on boiler 1 of company 2 is given in Figure 5.4. As can be seen, the model finds it better to change device 1 before it is used to the end of its full capacity, and suggests installing device 2. With this modeling approach, the schedules of the maintenances of individual companies under collaborated and non-collaborated cases are as seen in the Figure 5.5. According to figure, in both cases both companies start with device 1 installed on their boilers, since they are fixed. This time under non-collaborated case, each company makes one device change, under non collaborated case, the second company makes two device changes, since -as it is known from previous chapters- its boilers are used more intensely with collaboration. The details about the cumulative HP steam productions of boiler under collaborated and non- collaborated cases can be found in Appendix D.

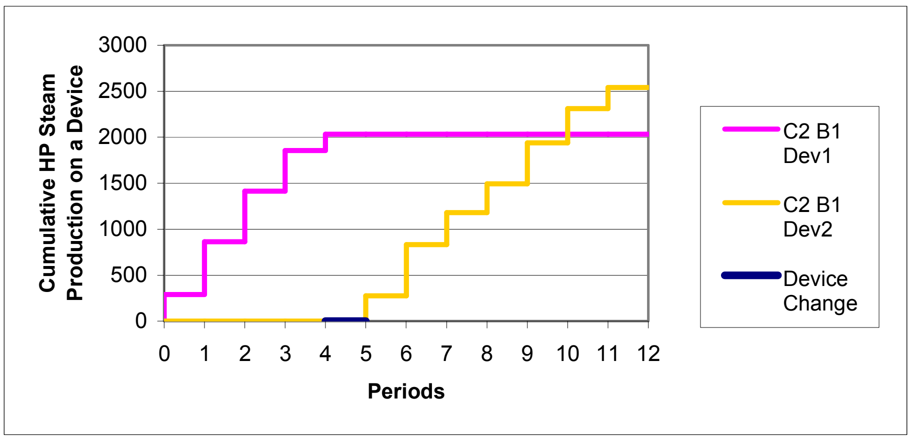



Figure 5.4 Cumulative HP Steam Production of Devices on Company 2's Boiler 1 in Collaborated Case

| Non-Collaborated Case | | | | | | Collaborated Case | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| C1 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | C1 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 1 | | | | | | 1 | | | | |
| 2 | | | | | | 2 | | | | |
| … | | | | | | … | | | | |
| 11 | | | | | | 11 | | | | |
| 12 | | | | | | 12 | | | | |
| C1 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | C1 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 1 | | | | | | 1 | | | | |
| 2 | | | | | | 2 | | | | |
| 3 | | | | | | … | | | | |
| 4 | | | | | | 11 | | | | |
| 5 | | | | | | 12 | | | | |
| 6 | | | | | | C2 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 7 | | | | Change | | 1 | | | | |
| 8 | | | | | | 2 | | | | |
| 9 | | | | | | 3 | | | | |
| 10 | | | | | | 4 | | | | |
| 11 | | | | | | 5 | | Change | | |
| 12 | | | | | | 6 | | | | |
| C2 B1 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | 7 | | | | |
| 1 | | | | | | 8 | | | | |
| 2 | | | | | | 9 | | | | |
| … | | | | | | 10 | | | | |
| 11 | | | | | | 11 | | | | |
| 12 | | | | | | 12 | | | | |
| C2 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 | | C2 B2 | Dev 1 | Dev 2 | Dev 3 | Dev 4 |
| 1 | | | | | | 1 | | | | |
| 2 | | | | | | 2 | | | | |
| 3 | | | | | | 3 | | | | |
| 4 | | | | | | 4 | | | | |
| 5 | | | | | | 5 | | | | |
| 6 | | | | | | 6 | | | | |
| 7 | | | | | | 7 | | Change | | |
| 8 | | | Change | | | 8 | | | | |
| 9 | | | | | | 9 | | | | |
| 10 | | | | | | 10 | | | | |
| 11 | | | | | | 11 | | | | |
| 12 | | | | | | 12 | | | | |

Figure 5.5 Performance Maintenance with Boiler Capacity Decrease with Cumulative HP steam Production

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| “On-State” | | “New-State” | | “X-State” | | “Change-State” | Change |

### 5.2.3 Concluding Remarks on Modeling Decreasing Capacity of Boilers

Modeling the capacity decrease in the boilers is a tedious approach, since the resetting the age of boilers or the cumulative HP steam production on a boiler to 0 after a changeover, is not straightforward. The idea of using new devices was derived from Bizet et al. [18] and this idea is extended to represent maintenance operations. Bizet et al. also use disjunctive variables for representing the changes and the states. But the states are defined much more different than our approach, i.e. no states are defined for new or old boilers, there is more than one type of time periods. In addition, the production function is nonlinear in time and the ages of units are estimated by the production. Therefore, the approach presented is developed for the boiler maintenance problem. The aim of this section was to model the complex nature of the energy production systems and test the success of collaboration with a model that contains details about the behavior of the units.

## 5.3 Multi Objective Modeling

In the previous parts of this thesis, a systematic approach is presented to model and analyze the synergy generated by collaboration in energy production systems. The energy production systems are modeled with their intrinsic complexities to show that collaboration results in performance improvements in financial terms. The objective in the analysis has been to minimize cost while satisfying energy requirements with given environmental and operational constraints. When environmental constraints are considered, it is usually very hard to quantify the harmful releases in monetary terms. The reduction of emissions is becoming an objective with the demanding environmental problems rather than simple limits on production constraints. Therefore, the system has two competing objectives: minimizing cost and environmental releases. It is worth to note that, the boiler capacity decrease constraints are not included in the following models since they increase the computational complexity without adding any value to the analysis of the effect of multiple objectives: environment - economy modeling other than schedule changes.

### 5.3.1 Constructing the Efficient Frontier

The problem is posed as a multi objective optimization problem by treating the limits on GHG as another objective rather than a constraint. The new objective function is defined as the minimization of the sum of Green House Gas emissions. The multi objective model has two conflicting objectives, with infinitely many efficient solutions. A feasible solution to a multi objective optimization model is an efficient point if no other feasible solution scores at least as well in all objective functions and strictly better in one. The efficient frontier of a multi objective optimization problem is the collection of efficient points for the model. The set of points on the efficient frontier can be constructed by repeated optimization. There are many alternative ways of constructing the efficient frontier. In our system, the algorithm [45] used for constructing the efficient frontier is as follows:

- Solve the system with objective 'minimize total GHG emissions'
    - $GHG_{min}$ = value of GHG objective function
    - Solve the system with objective 'minimize total cost' such that total GHG emissions = $GHG_{min}$
    - $Cost_{max}$ = value of cost function
- Solve the system with objective 'minimize total cost'
    - $Cost_{min}$ = value of cost function
    - Solve the system with objective 'minimize total GHG emissions' such that total cost of the system = $Cost_{min}$
    - $GHG_{max}$ = value of GHG objective function
- Set the number of subproblems that will be used to construct the efficient frontier as $q$=1, 2,...,$Q$ For subproblem $q$, solve the system with objective 'minimize total GHG emissions' with addition of the constraint $\text{Cost} \leq \frac{(\text{Costmax-Costmin})}{Q} \times q + \text{Costmin}$ until all $Q$ solutions are obtained.
- Plot the two objectives, GHG and Cost for each $q$

In order to guarantee the points ($GHG_{min}$, $Cost_{max}$) and ($GHG_{max}$, $Cost_{min}$) are truly efficient, the second solution steps of the systems are included to the algorithm. With the algorithm a sample from the efficient set is generated. The level of detail can be adjusted by changing the $Q$ value. Utopia point is the point which takes the minimum value for both of the objective functions, i.e. it is the point ($GHG_{min}$, $Cost_{min}$). The collaborated system is solved for $Q$ = 20 and the efficient frontier and the utopia point are plotted in Figure 5.6.

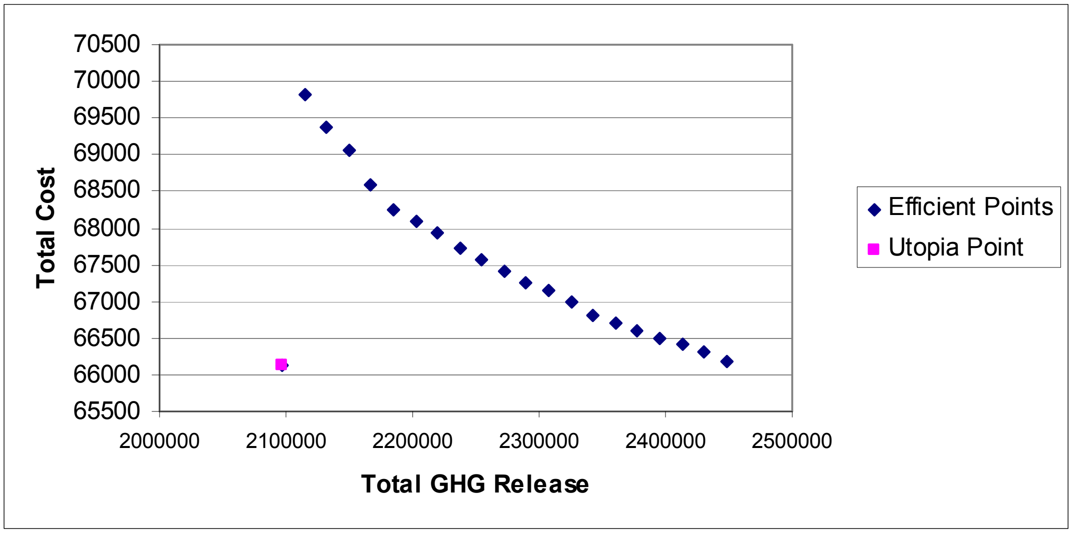



Figure 5.6 Efficient Frontier and Utopia Point for the Multi Objective System

### 5.3.2 Decision Support Suggestions

When the decision maker does not want to degrade from any of the objectives, the ideal compromising solution search method provides a guideline for the selection process. The goal of the ideal solution search method is to find the solution which is closest to the utopia point [44]. The distance should be designed to equally deal with all objective values, so they should be normalized between 0 and 1. The following normalization can be applied to all points on the efficient frontier.

$$\tilde{f}_i = \frac{f_i - f_{\min}}{f_{\max} - f_{\min}} \tag{5.28}$$

The distance ($\delta_p$) between the utopia point and the efficient points is defined with Eq.(5.29) where $p$ is the order of the norm.:

$$\delta_p = \left[ \left( \tilde{f}_{GHG} - GHG_{\min} \right)^p + \left( \tilde{f}_{Cost} - Cost_{\min} \right)^p \right]^{\frac{1}{p}} \qquad 1 \le p \le \infty \tag{5.29}$$

The distance depends on the particular norm value, $p$. For example, for $p = 2$, the distance is Euclidean distance that can be formulated as in Eq. (5.30).

$$\begin{aligned} & p = 2 \\ & \min_{x} \left\{ \sqrt{\left(\tilde{f}_{\text{GHG}}\right)^2 + \left(\tilde{f}_{\text{Cost}}\right)^2} \right\} \\ & \text{s.t.} \quad x \in \text{Constraint Set} \end{aligned} \tag{5.30}$$

Using $p = 2$ makes the model nonlinear, because of the square and root functions of the normalized values. However, selecting the norms $p = 1$ and $p \to \infty$ will give the following deviations from the utopia point:

$$\begin{aligned} & p = 1 \\ & \min_{x} \left\{ \tilde{f}_{\text{GHG}} + \tilde{f}_{\text{Cost}} \right\} \\ & \text{s.t.} \quad x \in \text{Constraint Set} \end{aligned} \tag{5.31}$$

$$\begin{aligned} & p \to \infty \\ & \min_{x} \max \left\{ \tilde{f}_{\text{GHG}} + \tilde{f}_{\text{Cost}} \right\} \\ & \text{s.t.} \quad x \in \text{Constraint Set} \end{aligned} \tag{5.32}$$

Eq. (5.31) suggests using rectilinear distances and Eq. (5.32) suggests using minimax distances. Eq. (5.32) can be formulated as Eq.(5.33).

$$\begin{aligned} & p \to \infty \\ & \min_{x} \chi \\ & \text{s.t.} \quad \chi \geq \tilde{f}_{\text{GHG}} \\ & \qquad \chi \geq \tilde{f}_{\text{Cost}} \\ & \qquad x \in \text{Constraint Set} \end{aligned} \tag{5.33}$$

By selecting the norms $p = 1$ and $p \to \infty$, the formulations do not disturb the mixed-integer linearity of the model, since Eqs. (5.31) and (5.33) are linear. The optimum solutions for $p = 1$ and $p = \infty$, provide lower and upper bounds respectively for the sum of fractional deviations from the utopia point [44]. If there is no other specific criterion for selection of an efficient point, the decision maker can use $p$=1 if she wants the minimum of the total of displacements from the minimum values for environmental and economic objectives. And she can use $p \rightarrow \infty$ if she wants to minimize the maximum displacements of the objective functions from the utopia point.

The two values are calculated for the example problem by solving the model after making the required changes, i.e. Eq. (5.31) for $p$=1 and Eq. (5.33) for $p \rightarrow \infty$. The two best compromise points according to the selection of $p$ are plotted with normalized efficient points in the Figure 5.7. The points lie within the efficient points. Table 5.3 gives the values of GHG and cost objectives for the two norm values.

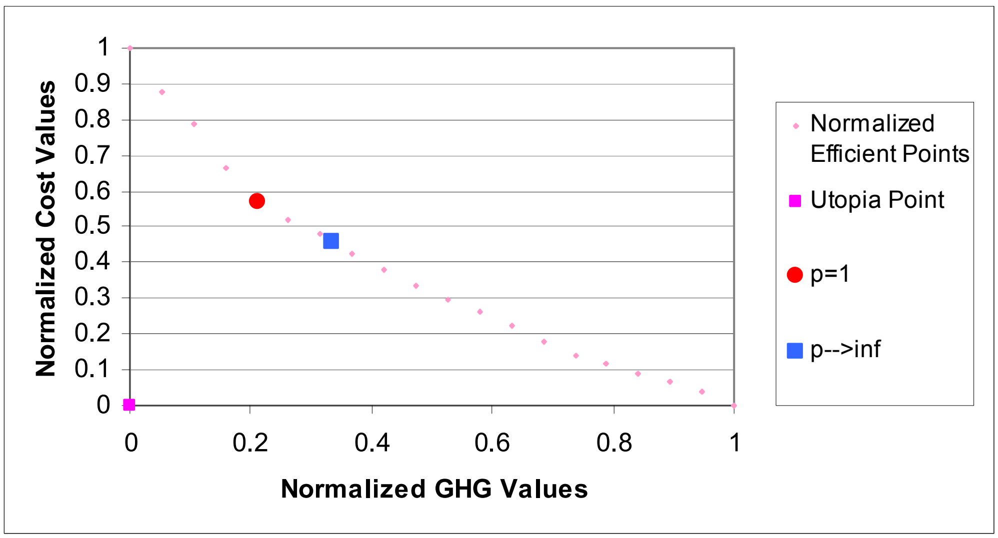



Figure 5.7 Normalized Efficient Frontier and Best Compromise values for Norms $p$=1 and $p \rightarrow \infty$

| | Total GHG Value | Total Cost Value |
|---|---|---|
| $p = 1$ | 2,180,162 | 68,310.73 |
| $p \rightarrow \infty$ | 2,226,584 | 67,840.65 |

Table 5.3 The Values of GHG and Cost Objectives for the Two Norm Values

In order to give the decision maker the flexibility of selecting a desired combination on efficient set, finding a sample of efficient set and making the decisions from this set is preferred to best compromise method. As seen in Figure 5.7, the efficient set includes the best compromise points already. Therefore, the efficient set is generated for non-collaborated case in addition to collaborated case. Points calculated with well known weighted sum method are also included in the efficient sets, which were previously calculated. Figure 5.8 shows the efficient frontiers of the companies in collaborated and non-collaborated cases. The frontier above is the one for non-collaborated case. In non-collaborated case, companies operate at the dark diamond minimizing total costs. Since the solution for non-collaborated is at the rightmost point of the efficient frontier, it is seen that they are already operating under their limits of GHG emissions. In collaborated case, companies operate at the dark square minimizing total costs. It is shown that the example companies operate under GHG limits, since this point is also the rightmost point of the efficient frontier. The graph explicitly shows the benefits of collaboration both in terms of financial and environmental criteria. In addition to that, if the companies are willing to decrease their GHG emissions, in order to perform the same amount of decrease, they should spend more in non-collaborated case. This is because the efficient frontier of the non-collaborated case is steeper than that of the collaborated case.

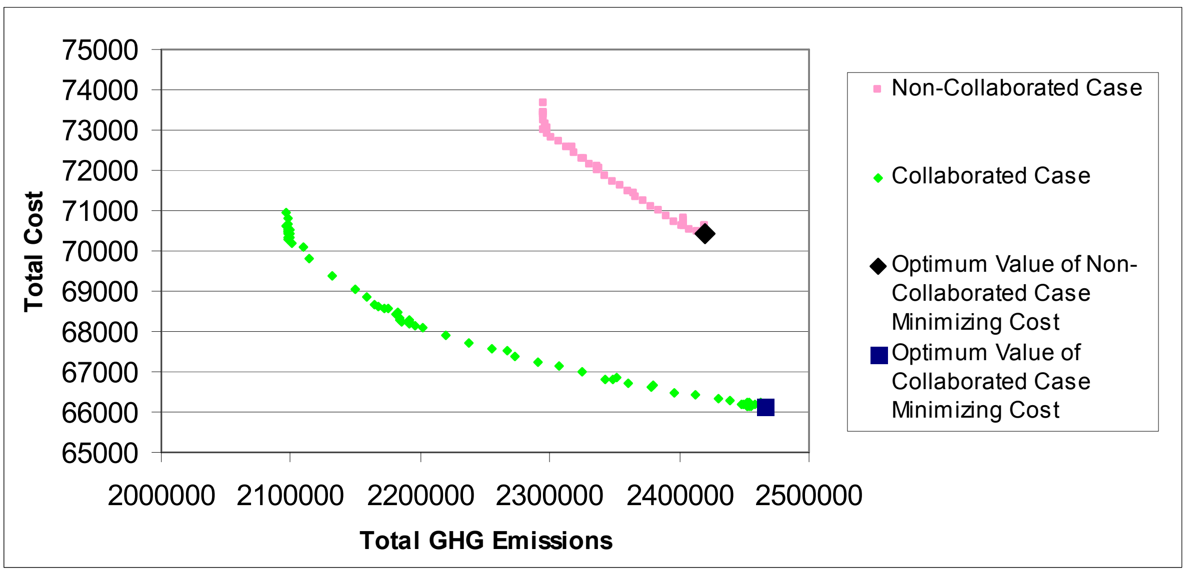



Figure 5.8 Efficient Sets for Collaborated and Non-Collaborated Cases

### 5.3.3 The Efficient Frontier and Strategies for $CO_2$ Trading Market

It is shown in the previous sections that, by collaboration, the companies can benefit in environmental performance without sacrificing from financial performance and vice versa. The multiobjective optimization is used when it is not possible to quantify one objective in terms of the other one. In the real world, there is a market that the two objectives are related to each other: in $CO_2$ trading markets companies can exchange their $CO_2$ release permits. Although, the market is not mature now; the prices are negotiated before transactions. Therefore, it is worthwhile for the companies to see what they can gain or lose by reducing emissions.

After performing collaboration analysis, the multi-objective optimization techniques can be used in determination of a policy for companies in $CO_2$ emissions trade. At the beginning of the planning period, the decision maker knows the approximate demand and the operating conditions of their own facilities. The GHG permits are probably less than the previous period. She must decide one of the two options: either to select performing diminishments by increasing costs or buying more permits from another company who is successful in reaching their limits. Efficient frontier is helpful in the sense that, the decision maker can see the financial effect of reduction in GHG limits. By using efficient frontier, it is possible to assess $CO_2$ monetary value, i.e. cost of unit reduction in GHG emissions.

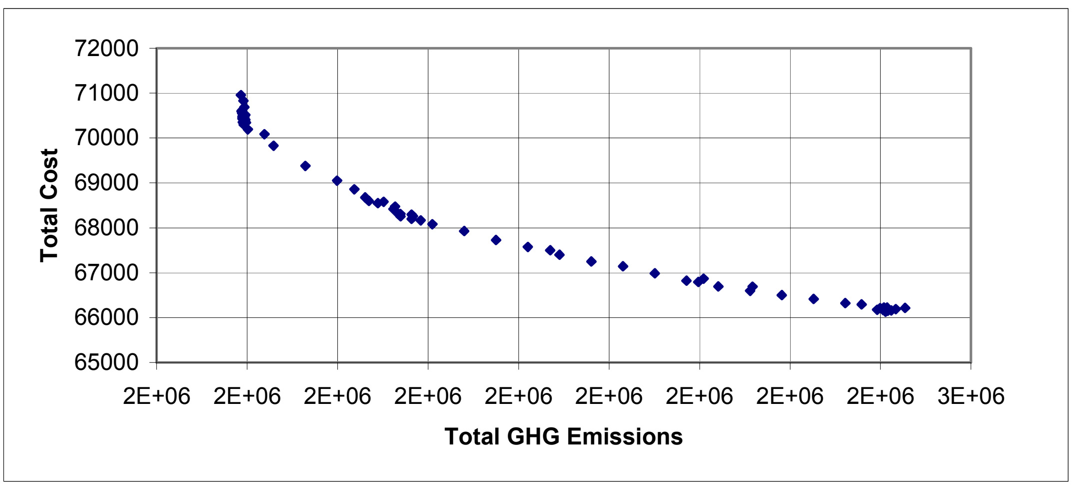



Figure 5.9 The Efficient Frontier of the Companies Operating under Collaborated Case

The efficient frontier of the companies operating under collaborated case is as in Figure 5.9. Notice that it becomes more expensive to attain the same amount of reduction as the emission limits decreases. The cost of reducing the emissions from 22 $Mm^3$ to 21 $Mm^3$ is approximately twice of the cost of reduction from 24 $Mm^3$ to 23 $Mm^3$. This agrees with the Energy Information Administration (EIA)'s Report [5], which states that the carbon prices are projected to rise with higher emission reductions. The incentive of companies paying more prices increases by increasing reductions. The decision makers can utilize this figure in negotiations in $CO_2$ market.

### 5.3.4 Concluding Remarks on Multi Objective Modeling

In studying the multi- objective optimization, the techniques explained in [44] and [45] are used interchangeably and the efficient frontiers for the energy production systems are obtained for collaborated and non-collaborated cases. The best compromise solutions on the efficient frontier are calculated for different norm values that can be used as suggestions for decision makers. The synergy of collaboration is verified by comparison of efficient frontiers. This synergy is reflected both on economical and financial criteria. As shown in Fig 5.8, all of the points on the efficient frontier to the collaborated solution are always better than the respective solutions for the non-collaborated case. As a last discussion, the effective use of efficient frontier in $CO_2$ trading is proposed. To our knowledge, solution of the energy production systems by multi-objective optimization and suggestion of using the results as a decision tool in $CO_2$ trading markets is not studied in the literature.

## 5.4 Conclusion

By developing advanced models for two different levels of decision, it is shown that, regardless of the complexity of the models and the level of decision, collaboration between companies creates synergy. Boiler performance maintenance is reflected as schedule changes to the collaboration dynamics. Multi objective modeling is used for examination of economy-environment debate and for developing decision support tools for energy production companies.

# Chapter 6

# TRANSITION TO NEW TECHNOLOGIES IN ENERGY PRODUCTION SYSTEMS

## 6.1 Introduction

A detailed analysis for the improvement of financial and environmental performance of energy production systems is conducted in the previous parts of this thesis. It is shown that inter-company collaboration provides improvements in both performance criteria. However, the environmental regulations are expected to become stricter in the future in the presence of public awareness. Meantime, new technologies are emerging for cleaner energy production. A short review of new energy technologies has been given in the introduction of this thesis. Most of the suggested solutions are either in very small scale, i.e. home appliances like photovoltaics or in a very large scale that needs to be planned nation wide, like hydro centrals. The US Electric Power Sector and Climate Change Mitigation[46], suggests that in the far future, the world's energy requirements will be supplied by solutions like fusion or space power. However, they require extensive research, while the companies need to reduce emissions in the transition period. Biodiesel blending into fuels is modeled in this thesis as an urgent action that can be performed for decreasing environmentally harmful gas emissions. Other transition solutions for the fossil fuel based energy companies are switching the boilers to natural gas and Carbon Capture and Sequestration (CCS).

Switching the boilers to natural gas requires some capital investment. The natural gas technology is energetically more efficient and emits less harmful materials than fuel oil. However, its increasing demand results in increase of natural gas prices. The other technology, CCS, involves capturing carbon emissions from the boilers of fossil fuel based boilers and then injecting it underground. There are three basic design systems: post- combustion, oxygen-combustion and pre-combustion [46]. Post combustion capture has an important role in making fossil fuel based energy production systems environmentally friendly in the transition period, since it can capture from the exhaust released from the plant. Therefore, this technology is considered as an alternative to further reduce emissions in the model. Benson [47] states that it has an "energy penalty" that it uses up to 30% of the electricity produced. She adds that, the separated carbon can be sequestrated in depleted oil and gas reservoirs, coal-bed reservoirs and salt water filled formations. Burrus [48] estimates that only depleted oil and gas reservoirs have a capacity for 40-50 years injection. CCS is a very complicated and costly investment, in addition to its energy penalty. However, as technology matures its investment costs are expected to decrease.

**6.2 The Model**

The alternatives discussed in section 6.1 in emission management are incorporated into the optimization model given in Chapter 4. Firstly, the period structure of the model is reconstructed: New indices are introduced for covering the periods of investments and yearly reduction in emission limits. As a general rule, investments are planned every five years, so a new index *f* is introduced representing a five-year period. Index *y* is introduced for year, which is used in GHG and $SO_x$ limits as well as in calculating operational costs. In addition, the index for the period is updated to represent 3 months since energy shows a seasonal demand profile. New variables, sets and parameters are introduced for the changes in the model, which will be explained within the equations.

The companies can purchase new boilers that burn natural gas. In order to model this, subsets of boiler set for new boilers and existing boilers are defined and a new fuel, natural gas, is added to the system. The Eqs.(6.1) and (6.2) are written for the new boiler set. Eq. (6.1) states that the new boilers cannot be used before they are purchased, *t'* is the period that the boiler *j* of company *i* is purchased. $YBN_{ijt'}$ is the binary variable that represents purchase of a new boiler. According to Eq. (6.2) a boiler can be purchased at most once. The new boilers can only burn natural gas. This condition is specified in the model by fixing other fuel input to these boilers to zero in the material balance equation, Eq. (4.32). Therefore, the biodiesel mixing to natural gas is also avoided. A modification is also conducted in Eq.(4.17) regarding to the safety stock requirement for the fuels. The set of equations written for inventory management is modified to exclude natural gas since the companies do not hold any natural gas but they procure it from the pipelines that are found in any industrial area.

$$X_{ijk_{HP}l_{gen}t} \leq X^{U}_{ijk_{HP}l_{gen}} \times \sum_{t'=1}^{t-1} YBN_{ijt'} \qquad (6.1)$$

$$\sum_{t'} YBN_{ijt'} \leq 1 \qquad (6.2)$$

The companies can also purchase new turbines if the existing ones are not successful in meeting the increasing electricity demand anymore. The models for purchasing new turbines are developed similar to that of the boilers. Eq. (6.3) states that the new turbines cannot be used before purchased, *t'* is the period that the boiler *j* of company *i* is purchased. $YTN_{ijt'}$ is the purchasing binary variable of a new turbine. According to Eq. (6.4) a turbine can be purchased once or may not be purchased.

$$X_{ijkl_{gen}t} \leq X^{U}_{ijkl_{gen}} \times \sum_{t'=1}^{t-1} YTN_{ijt'} \tag{6.3}$$

$$\sum_{t'} YTN_{ijt'} \leq 1 \tag{6.4}$$

The existing boilers can be modified to burn natural gas. Once they are modified, they cannot burn other fuel anymore. The sets are interrelated as existing boilers can burn both fuel (different types of fuel and biodiesel) and natural gas. Eq.(6.5) states that the existing boilers cannot burn natural gas until the switch to natural gas is conducted, represented by binary variable, $YNG_{ijt'}$. Eq.(6.6) eliminates the possibility of using other types of fuel once the boilers are switched to natural gas. The equation also forces the production in particular boiler to be zero in the period that natural gas switching is performed. Eq.(6.7) specifies that an existing boiler can be switched to natural gas at most once.

$$XHF_{ijk_{\text{NatGas}}t} \leq \sum_{t'=1}^{t-1} YNG_{ijt'} \times M \tag{6.5}$$

$$XHF_{ijk_{\text{Diesel}}t} \leq \left(1 - \sum_{t'=1}^{t} YNG_{ijt'}\right) \times M \tag{6.6}$$

$$\sum_{t'} YNG_{ijt'} \leq 1 \tag{6.7}$$

CCS system can be constructed by the companies as a low-carbon technology. The CCS system is not modeled as a new unit in the system, its existence is modeled by the interactions between disjunctions and binary variables. CCS system can capture the $CO_2$ equivalent materials emitted by the boilers at different percentages of fuel from different types of fuels. The capture ratio from natural is about twice of the capture ratio from diesel. Since the type of fuel used and the existence of CCS system have to be distinguished, a new variable representing the type of fuel used in the boiler under the existence or not existence of CCS system is defined, $F_{ijkct}$. The disjunction index $c$ represents the existence of CCS or not, with "CCS" and "NoCCS", respectively. Moreover, since the GHG emissions to the atmosphere depend on the existence of CCS, a new variable is introduced for the emitted GHG, disaggregated on index $c$, represented by $G_{ijkct}$. Eq. (4.9) is replaced by the following set of constraints.

$$X_{ijk_{\mathrm{GHG}}l_{gen}t} = \sum_k \sum_c G_{ijk_{\mathrm{fuel}}ct} \tag{6.8}$$

$$X_{ijk_{\mathrm{fuel}}l_{con}t} = \sum_c F_{ijk_{\mathrm{fuel}}ct} \tag{6.9}$$

$$G_{ijkct} = s_{\mathrm{GHG},kc} \times F_{ijkct} \tag{6.10}$$

$$G_{ijkc_{\mathrm{CCS}}t} \le CCE_{it} \times M \tag{6.11}$$

$$G_{ijkc_{\mathrm{NoCCS}}t} \le \left(1 - CCE_{it}\right) \times M \tag{6.12}$$

$$CCE_{it} \le \sum_{t'=1}^{t-1} CC_{it'} \tag{6.13}$$

$$\sum_{t'} CC_{it'} \le 1 \tag{6.14}$$

Eq.(6.8) states that the total of disaggregated GHG variables sum to total GHG emissions and Eq.(6.9) states that the total of disaggregated fuel consumption variables sum to total fuel consumption. Eq. (6.10) sets the value of GHG emissions with and without CCS system with the updated GHG emission parameters. Eqs. (6.11) and (6.12) regulate the GHG emissions according to whether CCS system exists for a company $i$, denoted by $CCE_{it}$. Eq. (6.14) ensures the existence of CCS at period $t$ if it has been constructed before $t$. And Eq. (6.14) limits the CCS construction for a company $i$ with 1.

Existence of CCS in an energy production system creates energy inefficiency since it uses some of the produced electricity. In order to incorporate this into the model, the production from turbines was also disaggregated according to existence of CCS. In order to express this in the optimization model, Eq.(4.11) is replaced by the following set of constraints.

$$XC_{ijk_{EL}l_{gen}ct} = e_{ijck_{HP}} XC_{ijk_{HP}l_{in}ct} - \sum_{k=MP,LP} g_{ijck} XC_{ijkl_{gen}ct} \qquad (6.15)$$

$$X_{ijklct} = \sum_{c} XC_{ijklct} \qquad (6.16)$$

$$XC_{ijklc_{\mathrm{CCS}}t} \le CCE_{it} \times M \qquad (6.17)$$

$$XC_{ijklc_{\mathrm{NoCCS}}t} \le (1 - CCE_{it}) \times M \qquad (6.18)$$

Eq.(6.15) models the disaggregated variables of turbine with updated parameters according to existence of CCS. Eq. (6.16) states that, the total of disaggregated variables of turbine sum to total variables of HP, LP, MP steams and electricity. Eqs. (6.17) and (6.18) regulate the variables according to whether CCS system exists for a company *i*.

The companies can buy $CO_2$ emission permits from outside also and the limits of GHG emissions are updated with year. In order to incorporate emission emits purchasing of $CO_2$ emission permits, the Eq. (4.28) replaced by Eq.(6.19). It states that, in a year *y*, the total GHG releases of companies should be less than the sum of their individual limits plus individual emission right purchases. When companies do not collaborate, Eq.(6.19) takes a different form such that it states that their individual releases should be less than their individual limits plus individual emission right purchases. This is modeled by removing the summation over the companies. The emission rights that a company can purchase are also limited by regulations in a year in order to keep the companies from reducing production. This is modeled by Eq. (6.20)

$$\sum_{i}\sum_{j}\sum_{t} X_{ijk_{GHG}l_{gen}t} \times n_t \le \sum_{i}\left( \mathrm{X}^{\mathrm{U}}_{ik_{\mathrm{GHG}}y} + GP_{iy} \right) \quad t \in y \qquad (6.19)$$

$$GP_{iy} \le GP^{U}_{iy} \qquad (6.19)$$

The cost of each energy production system is modified to include the alternative actions to reduce emissions. The constructions of CCS, new turbine, new boiler, boiler switching to natural gas are new investments, as well as the building of exchange equipment for collaboration. Therefore, these costs are collected in a group of investment costs, ($IC_{if}$). As a general rule, the decisions for investments are given for five years, as well their costs change for five years period, and there is a limit on them. Eq. (6.20) determines the investment costs in terms of new boiler, new turbine, boiler switching, CCS construction and exchange structure construction. Eq. (6.21) determines the upper bound of investments in a five year period *f*. Constructing a CCS facility is beneficial for both companies, since their GHG limits are calculated as a sum of their individual limits. However, a CCS facility can only be used by one company because of the structure of the facility. The mutual benefit of construction of other equipment is rational, too. As it has been shown in the synergy analysis of individual companies, the companies can always guarantee individual rationality constraints by making contracts. Therefore, it is logically true that the cost planning of total of investments is covered by both companies in collaborated case. As expected, in non-collaborated case, the summation over the companies is removed from Eq.(6.21).

$$IC_{if} = \sum_{t'} \Big[ YBN_{ijt'} \times cbn_f + YTN_{ijt'} \times ctn_f + YNG_{ijt'} \times cng_f +$$

$$CC_{it'} \times ccc_f + \omega_i \sum_i \sum_j \sum_{i'} \sum_{j'} \Big( \sum_m \varphi_{iji'j'm} YEC_{iji'j'mt'} \Big) \Big] \quad t' \in f \tag{6.20}$$

$$\sum_i IC_{if} \leq \sum_i IC_{if}^U \tag{6.21}$$

The other costs such as fuel purchasing, fuel ordering, holding and GHG emission purchasing are grouped as operational costs of a company ($OC_{iy}$). Operational costs are calculated on a yearly basis. Although the prices of GHG emits are unstable right now, like all other parameters, the price of unit $CO_2$ emission permit purchasing is taken as a deterministic parameter, changing with years in the model. In order to model $OC_{iy}$, the summations over *t* have been removed from cost equations Eq. (4.19), (4.20), (4.21), (4.30), (4.33), (4.34) and (4.35). The operational cost of a company *i* in year *y* is calculated as in Eq. (6.22).

$$OC_{iy} = \sum_t \left( C_{it} + CP_{it} + HC_{it} + CS_{it} + CEL_{it} + CW_{it} + CSU_{it} \right) + GP_{iy} \times pg_y \quad t \in y \tag{6.22}$$

The objective function of the system Eq. (4.37) is changed to minimizing the summation of total investment and operational cost as in Eq.(6.23).

$$\min z = \sum_y \sum_i OC_{iy} + \sum_f \sum_i IC_{if} \tag{6.23}$$

The system including the unchanged and modified equations in Chapter 4 is modeled for collaborated case. It can be solved for non-collaborated case by performing the mentioned differences about investment and environmental limits and by fixing the steam exchange between companies to zero.

### 6.3 An Example for Transition Period of Energy Systems

The optimization model for the transition period of an example energy system which is under the quest of emission reduction is solved for a planning period of twenty years. The data given in Table 4.1 are modified for supporting the long run. For the ones that do not exist, like the cost of new technologies, price of $CO_2$, data from the literature [5] are modified. Fuel prices- other than biodiesel- electricity prices, GHG emission purchasing prices are expected to increase. However, with developing technology the construction costs of carbon reduction techniques as well as GHG emission limits are expected to decrease by time. The energy demands are anticipated to rise with increasing population and life standards. The problem is solved with data incorporated in these expected trends in collaborated case and non-collaborated case. The cumulative results of total costs and GHG emissions are given in Table 6.1.

| | Non-Collaborated Case | Collaborated Case |
|---|---|---|
| Total Cost | 1,755,443 | 847,290.7 |
| Total GHG Release | 23,250,608 | 31,028,456 |

Table 6.1 Comparison of Non-Collaborated and Collaborated Cases

In non-collaborated case, the solution of the problem suggests both companies construct CCS systems in order to achieve the target GHG emission reductions. Switching to natural gas is found to be useful for all four of the existing boilers, in addition to buying two new boilers for each company. Moreover, in order to satisfy the demand of electricity, new turbine construction for both companies is found to be necessary. Small amounts of GHG emission purchases are suggested for both of the companies.

In collaborated case, the construction of CCS is found to be necessary for only one company, company 2. In addition, only company 2 converts its boilers to natural gas. Company 1 buys one new boiler and company 2 buys two new boilers. In addition, only company 2 buys one new turbine. The construction of exchange structure is performed in different capacities for different pressures of steam. New ones are constructed when the existing ones get out of order. Small amounts of GHG emission purchases are suggested for both of the companies.

The big difference between the costs of collaborated and non-collaborated cases in Table 6.1 becomes clearer with the given information on the future investments. When companies collaborate, they can make planned investments. For example, only one CCS construction is enough in the collaborated case. Since the companies do not operate at their individual limits of GHG, but under total limits, they are free to release more emissions. That is the reason of increase in total GHG emissions in Table 6.1.

Collaboration benefit is observed in future planning. However, from the construction of CCS system, it is understood that collaboration is not enough for satisfying future reductions in GHG emissions. New investments such as CCS, switching to natural gas boilers are necessary for reduction in GHG emissions. Moreover, the $CO_2$ emissions trading is found have a role in future planning of energy production companies.

### 6.4 Conclusion

The optimization model is capable of planning the investments, emissions, production and consumption values for energy production systems in their route to reduce emissions. It gives the timings of necessary investments and the amounts of GHG emit purchases, etc. However, the most difficult part of planning for the future is using accurate data. The data used in the example are not provided here, because they are rough estimates of expected values. The model is run with different data sets for several times. Although the scheduling and the amount of investment changes with changing data sets, the main idea of the necessity of future investments does not change. In all cases, it is observed that, in order to achieve reductions, new technology investments are necessary. This coincides with the projections in EIA's report [5].

The model is found to be useful in strategy planning for the future. It can be run under different scenarios with different projections of data and it can be enlarged to incorporate the stochastic nature of future demands, prices etc. Biodiesel, switching to natural gas and CCS techniques are the three techniques suggested for transition of cogeneration fuels to low-carbon emissions. The model can be enlarged to cover new technologies like different types of CCS techniques.

# Chapter 7

# CONCLUSION

In this thesis, detailed models and suggestions are developed for energy production systems within emission reduction and cost minimization objectives by using different analysis and modeling techniques. A systematic approach is conducted to examine the synergy created by collaboration among the energy systems. In all different cases examined, the benefits of synergy have been observed.

In Chapter 3, the synergy created by collaboration among energy companies is examined analytically. It is shown that, differences between companies are the main source of the synergy. However, only the differences that effect the amount of produced or sold steam are found to be effective on creating collaboration benefit. Moreover, the allocation of idle capacities in boilers is found to be main driving force in collaboration benefit.

The findings on synergy are tested on an energy production systems model with is the enhanced version of an existing model [2], [3]. The findings on collaboration benefit are verified and examinations are conducted for the environmental criteria. The biodiesel usage is suggested when emission reductions aimed. In addition to that, the one-way profit nature of the collaboration benefit is examined and two simple contracts are suggested to make both companies gain from collaboration. It is shown that, in the existence of collaboration benefit, it is always possible to satisfy individual rationality constraints of the companies.

Since the major portion of the energy production costs are boiler related, boiler performance is very important in modeling energy production companies. An approach is developed for modeling the performance maintenance of boilers with decaying performance, using advanced modeling techniques. The applicability of the model could not be tested on real systems but it is found to be successful in scheduling of units in example problems. The synergy of collaboration is observed to be successful in the existence of maintenance schedule changes. The models can be enlarged to cover boiler efficiency decrease in addition to capacity decrease with time and usage. Also, modeling the reliability of the system would be a great contribution to performance maintenance models.

Another advanced modeling technique that is put in use in this thesis is the multi objective optimization modeling of the problem. The energy production systems face with two major issues: decreasing emissions and satisfying the demand with minimum cost. These two contradicting objectives are solved by multi objective techniques and efficient frontier that can be used as a tool by decision makers is obtained. The benefit of collaboration is justified by the comparison of efficient frontiers in collaborated and non-collaborated cases. Moreover, it is shown that it becomes more expensive to achieve the required emission reductions with the increasing targets on reductions.

A model is developed for future emission reduction targets of energy production companies. The model incorporates new technologies, as well as $CO_2$ trading features. On an example problem, it is shown that, in order to achieve the reductions proposed, the companies must make investments on low-carbon technologies. However, future planning requires studying of different scenarios and involving randomness to some degree. Conducting experiments on the model with different scenarios or solving it stochastically would be a great contribution to the model that could not be performed in this thesis.

To our knowledge, a future emission reduction planning model, incorporated with CCS and other transition technologies, covering this many details of energy production systems does not exist in the literature. The existing models for planning the energy-economy debate in the future are in the form of regional planning models that take the energy production either as nodes in the system or as a sector [31], [32]. The regional planning approach is useful in the sense that it can incorporate the global nature of the energy and environment relations in a major scale. Moreover, the transition to other low-carbon technologies, such as renewable energy sources like wind turbine can be modeled in a regional or global model. This kind of a study aiming to plan the transition to renewable energy sources in Turkey by using linear programming, has been developed by Soylu and Türkay, to be presented in Yenilenebilir Enerji Kaynakları Sempozyumu (YEKSEM), Mersin [49].

All of the analyses and models in the thesis have been performed with sample data modified from a real energy production company or forecasted ones. The thesis does not claim that the results of the analyses will be the same for all energy production systems. Each system has specific characteristics that should be examined individually. However, the results provide an insight for the future and the tools developed can be used as decision support tools in emission decreasing quest of energy production companies.

**BIBLIOGRAPHY**

[1] UNFCC, 2004. Climate Change Information Kit, retrieved from http://www.unfccc.int/resource/iuckit/cckit2001en.pdf., on April 15, 2005

[2] M. Türkay, C. Oruç, K. Fujita, T. Asakura, Multi-Company Collaborative Supply Chain Management with Economical and Environmental Considerations, *Computers and Chemical Engineering*, 28 (2004), 985–992.

[3] C. Oruç, Analysis of Multi-Company Collaborative Supply Chain Management Using MILP, M. Sc. Thesis, Koç University, (2003)

[4] J. Reinaud, Industrial Competitiveness Under the European Union Emissions Trading Scheme International Energy Agency, Iea Information Paper, December 2004

[5] What Does the Kyoto Protocol Mean to U.S. Energy Markets and the U.S Economy, Energy Information Administration, retrieved from www.eia.doe.gov on 02.19.2005

[6] E. S. Cassedy, *Prospects for Sustainable Energy: A Critical Assessment*, Cambridge University Press, 2000, Cambridge, UK

[7] A. Soylu, C. Oruç, M. Türkay, K. Fujita and T. Asakura, Synergy analysis of collaborative supply chain management in energy systems using multi-period MILP, *European Journal of Operational Research*, In Press, Corrected Proof, Available online 23 May 2005,

[8] Z. Fluck and A. W. Lynch, Why Do Firms Merge and Then Divest? A Theory of Financial Synergy, *The Journal of Business*, 72 (1999), 319-346

[9] H. Min and G. Zhou, Supply Chain Modeling: Past, Present and Future, *Computers & Industrial Engineering*, 43 (2002), 231-249

[10] J.A. Van Mieghem, Coordinating Investment, Production and Subcontracting, *Management Science*, 45 (1999), 954-971

[11] W. Xing and F.F. Wu, A game-theoretical model of private power production, *Electrical Power and Energy Systems*, 23 (2001), 213-218

[12] M. V. Russo, Institutions, Exchange Relations, and the Emergence of New Fields: Regulatory Policies and Independent Power Production in America, 1978-1992, *Administrative Science Quarterly*, 46 (2001), 57-86

[13] Y. H. Kwun and M.L Baughman, Joint Optimal Planning of Industrial Cogeneration and Conventional Electricity Systems, *Operations Research*, 39 (1991), 798-806

[14] V. I. Kuprianov, Applications of a Cost-Based Method of Excess Air Optimization for the Improvement of Thermal Efficiency and Environmental Performance of Steam Boilers, *Renewable and Sustainable Energy Reviews*, 9 (2005), 474-498

[15] K. Krüger, R. Franke and M. Rode, Optimization of Boiler Start-up Using a Nonlinear Boiler Model and Hard Constraints, *Energy*, 29 (2004), 2239-2251

[16] S. Dragićević and M. Bojić, Optimization of a Steam Boiler by Using Linear Programming Method, *Facta Universitatis Series: Mechanical Engineering*, 1 (2003), 1407-1414

[17] V. Jain and I. E. Grossmann, Cyclic Scheduling of Continuous Parallel- Process Units with Decaying Performance, *AIChE Journal*, 44 (1998), 1623-1636

[18] V. M. Bizet, I.E. Grossmann and N. M. Juhasz, Optimal Production and Scheduling of a Process with Decaying Catalyst, *AIChE Journal*, 51 (2005), 909-921

[19] R. Raman and I.E. Grossmann, Modeling and Computational Techniques for Logic Base Integer Programming, *Computers & Chemical Engineering*, 18 (1994), 563

[20] M. Türkay and I.E. Grossmann, Logic-based MINLP Algorithms for the Optimal Synthesis of Process Networks, *Computers & Chemical Engineering*, 20 (1996), 958-978

[21] R. Raman and I.E. Grossmann, Relation between MILP Modeling and Logic Inference for Chemical Process Synthesis, *Computers & Chemical Engineering*, 15 (1991), 73-84

[22] T.M. Cavalier, P.M. Pardalos and A.L. Soyster, Modeling and Integer Programming Techniques Applied to Propositional Calculus, *Computers & Operations Research*, 17 (1990), 561-570

[23] Y. Collette and P. Siarry, *Multiobjective Optimization: Principles and Case Studies*, Springer-Verlag, Heidelberg, Germany (2003)

[24] L. Shi and G. Xu, Self-Adaptive Evolutionary Programming and Its Application to Multi-Objective Optimal Operation of Power Systems, *Electric Power Systems Research*, 57 (2001), 181–187

[25] T. Hiroyasu, M. Miki, J. Kamiura, S. Watanabe and H. Hiroyasu, Multi-Objective Optimization of Diesel Engine Emissions and Fuel Economy using Genetic Algorithms and Phenomenological Model, *Society of Automotive Engineers*, 02FFL-183 (2002)

[26] N.H. Afgan and M.G. Carvalho, Multi-Criteria Assessment of New and Renewable Energy Power Plants, *Energy*, 27 (2002)

[27] C. Giannantonia, A. Lazzarettob, A. Macorb, A. Mirandolab, A. Stoppatob, S. Tononb and S. Ulgiatic, Multicriteria Approach for the Improvement of Energy Systems Design, *Energy* 30, (2005) 1989–2016

[28] A. Lazzaretto and A. Toffolo, Energy, Economy and Environment as Objectives in Multi-Criterion Optimization of Thermal Systems Design, *Energy*, 29 (2004), 1139–1157

[29] A. R. Borges and C. H. Antunes, A Fuzzy Multiple Objective Decision Support Model for Energy-Economy Planning, *European Journal of Operational Research*, 145 (2003), 304–316

[30] C. Oliveira and C. H. Antunes, A Multiple Objective Model to Deal with Economy–Energy–Environment Interactions, *European Journal of Operational Research*, 153 (2004), 370–385

[31] C. Cormio, M. Dicorato, A Minoia and M. Trovato, A Reginal Energy Planning Methodology Including Renewable Energy Sources and Environmental Constraints, *Renewable and Sustainable Energy Reviews*, 7 (2003), 99-130

[32] S.D. Pohekar and M. Ramachandran, Application of Multi-Criteria Decision Making to Sustainable Energy Planning—A Review, *Renewable and Sustainable Energy Reviews*, 8 (2004), 365–381

[33] J. A. Stuart, J.C. Ammons and L. J. Turbini, A Product and Process Selection Model with Multidisciplinary Environmental Considerations, *Operations Research*, 47 (1999), 221-234

[34] A. Nagurney, F. Toyasaki, Supply Chain Supernetworks and Environmental Criteria, *Transportation Research Part D*, 8 (2003), 185–213

[35] L. Barreto and S. Kypreos, Emissions Trading and Technology Deployment in an Energy-Systems "Bottom-Up" Model with Technology Learning, *European Journal of Operational Research*, 158 (2004), 243-261

[36] D. Hanson and J. A. S. Laitner, An Integrated Analysis of Policies that Increase Investments in Advanced Energy-Efficient / Low-Carbon Technologies, *Energy Economics*, 26 (2004), 739-755

[37] J. R. Mcfarland, J.M. Reilly and H.J Herzog, Representing Energy Technologies in Top-Down Economic Models Using Bottom-Up Information, *Energy Economics*, 26 (2004), 685-707

[38] R. Madlener, G. Kumbaroğlu, V. Ş. Ediger, Modeling Technology Adoption as an Irreversible Investment under Uncertainty: The Case of the Turkish Electricity Supply Industry, *Energy Economics*, 27 (2005), 139-163

[39] L.S Belyaev, O.V. Marchenko, S.P. Filippov, S.V. Solomin, T. B. Stepanova and A.L. Kokorin, *World Energy and Transition to Sustainable Development*, Kluwer Academic Publishers, Dordrecht, The Netherlands, (2002)

[40] GAMS IDE, 2.0.26.8 License date Jan 19, 2004. Build VIS 21.3 138.

[41] Ilog, 2003. ILOG CPLEX 9.0 User's Manual.

[42] G.G. Rajan, *Optimizing Energy Efficiencies in Industry*, McGraw-Hill , New York, The U.S., 2003

[43] B. G. Lipták, Optimization Industrial Unit Processes, CRC Press LLC, Florida, The U.S, 1999

[44] I.E. Grossmann, R. Drabbant and R.K. Jain, Incorporating Toxicology in the Synthesis of Industrial Complexes, *Chemical Engineering Communications*, 17 (1982), 151-170

[45] R. L. Rardin, *Optimization in Operations Research,* Prentice Hall, New Jersey, the U.S., 1998

[46] G. Morgan, J. Apt and L. Lave, The U.S. Electric Power Sector and Climate Change Mitigation, Carnegie Mellon University, 2005

[47] S. M. Benson, Carbon Dioxide Capture and Storage in Underground Geologic Formations, Pew Center / NCEP, the 10-50 Solution. Technologies and Policies for a Low-Carbon Future, Workshop (2004), Washington DC, the U.S.

[48] R.C. Burruss, Contributing Paper: Geologic Sequestration of Carbon Dioxide in the Next 10 to 50 Years: An Energy Resource Perspective, Pew Center / NCEP, the 10-50 Solution. Technologies and Policies for a Low-Carbon Future, Workshop (2004), Washington DC, the U.S.

[49] A. Soylu and M. Türkay, Yenilenebilir Enerji Kaynaklarına Geçiş Sürecinde Doğrusal En İyileme Tekniğinin Kullanılması, 3. *Yenilenebilir Enerji Kaynakları Sempozyumu*, Ekim 2005, Mersin

**Appendix A : Synergy Analysis in a Simple Example**

It is shown that, collaboration enables companies to plan and act more effectively. An insight into obtaining benefits with collaboration is also developed. Now, nonnegativity of decision variables is introduced and this simple case is solved as an optimization model. The model is identical to the model described in Section 3.2 with the following difference: Penalty for unsatisfied steam ($lsp_i$) and electricity demands ($lep_i$) is introduced in order to obtain feasible solutions. $LS_i$ and $LE_i$ are unsatisfied steam and electricity demands, respectively. The optimization model is as follows:

$$\max \sum_i \left( pe_i \times E_i + ps_i \times SS_i - cf_i \times F_i - lsp_i \times LS_i - lep_i \times LE_i \right)$$

subject to

$$\alpha_i \times F_i = \sum_j PS_{ij} + SS_i$$
$$\sum_i PS_{ij} \times \beta_j = E_j$$
$$\sum_j PS_{ij} + SS_i + IB_i = bc_i$$
$$\sum_i PS_{ij} + IT_j = tc_j$$
$$SS_i + LS_i = ds_i$$
$$E_j + LE_j = de_j$$
$$\text{all var.} \geq 0$$

**A.1 The Effect of the Difference in Boiler Performance Parameters**

If the companies have different boiler performance parameters, then collaboration creates synergy as can be seen in the following graph. It is worth to note that this graph is drawn for values. $\alpha_2 = \alpha_1 + \Delta,\ \alpha_1 = 0.6,\ bc_1 = bc_2 = 250,\ de_1 = de_2 = 70,\ ds_1 = ds_2 = 50,\ \beta_1 = \beta_2 = 0.6$. The difference in boiler performance parameters, $\Delta$, is increased by increments of 0.01 in each run for 100 runs. These values satisfy the following condition that is found before such that:

$$\frac{de_1}{\beta_1} + ds_1 < bc_1$$

$$\frac{70}{0.6} + 50 < 250$$
$$166.\bar{6} < 250$$

Figure A.1 shows the behavior of collaboration benefit vs. boiler performance parameter difference similar to what is found before, as shown in Fig. 3.5.

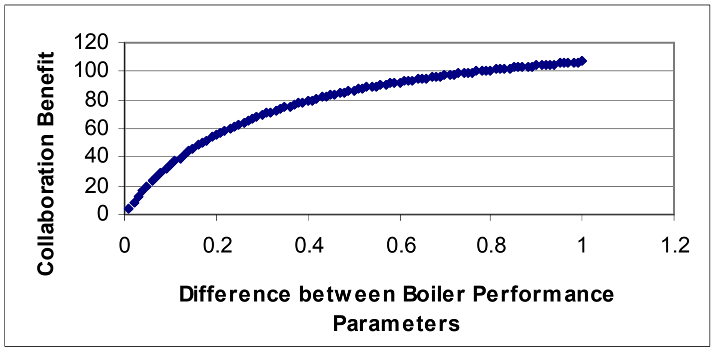



Figure A.1 Collaboration Benefit Function versus Difference Value in Boiler Performance Parameter

However, if the condition $\frac{de_1}{\beta_1} + ds_1 < bc_1$ does not hold, collaboration between the companies will not create any synergy regardless of differences in the boiler performance parameters. This finding supports the claim that the synergy is created with the allocation of idle boiler capacities. If there is no idle boiler capacity, then changes in boiler performances will not create any synergy.

### A.2 The Effect of the Difference in Fuel Prices

If the companies pay different prices for fuel, then collaboration can create synergy. It is worth to note that this graph is plotted in fuel price increases for both of the companies but with a higher rate for one of them. Figure A.2 shows the relationship between idle boiler capacities and difference between fuel costs. Up to some point, there is no synergy, since it is profitable for both companies to produce without collaboration. But when the cost of using fuel gets very high, in non-collaborated setting it is not profitable for one company to produce any more and the idle boiler capacities become greater than zero. In this case, the synergy increases with increasing difference in fuel costs. After a while, the second company also decides not to produce. After that point, the collaboration benefit doesn't change with increasing fuel costs any more.

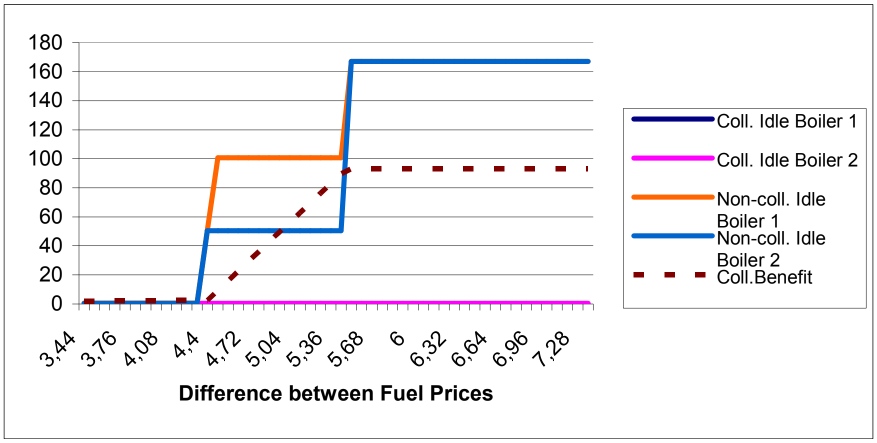



Figure A.2 Collaboration Benefit Function versus Difference between Fuel Costs

It is worthwhile to note that this graph can be drawn even if the condition $\frac{de_1}{\beta_1} + ds_1 < bc_1$ doesn't hold, because, with increasing fuel costs, it will be very costly for companies to produce at boilers and there will be idle boiler capacities in any case.

### A.3 The Difference in Steam Demands

When companies have different steam demands, this may also create synergy with collaboration. This is because, the steam demands affect the usage of boilers and any change in them may cause a reallocation of idle boiler capacities. Figure A.3 shows the relationship between steam demand difference, the collaboration benefit and the idle boiler capacities. The graph is plotted while both demands are increasing one with a higher ratio: The first company gets out of idle boiler capacity and later the other one gets out of idle boiler capacity in non-collaborated case. The synergy increases during only one is out of idle boiler capacity and starts decreasing when the other one also gets rid of idle boiler capacity. The benefit reaches zero when the collaborated setting has no idle boiler capacity left.

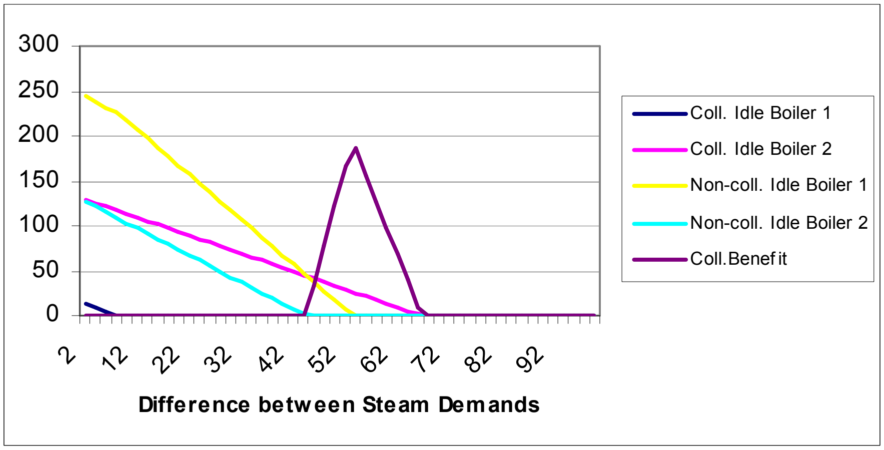



Figure A.3 Collaboration Benefit Function versus Difference between Steam Demands

### A.4 The Difference in Boiler Capacities

The effect of boiler capacity difference is important because it is the main factor affecting the idle boiler capacities. Figure A.4 indicates the effect of difference in boiler capacities. It is plotted for $bc_1$ =50 and increasing $bc_2$ by increments of 3 in each run. It can be seen in Figure A.4, the starting point of the first inclination, $bc_1$ = 50 and $bc_2$ = 119 and their difference is 69. This is the first point that the sum of boiler capacities is greater than 166.6. This is the previously calculated value for having idle boiler capacity.

$$\frac{de_1}{\beta_1} + ds_1 = \frac{70}{0.6} + 50 = 166.\bar{6}$$

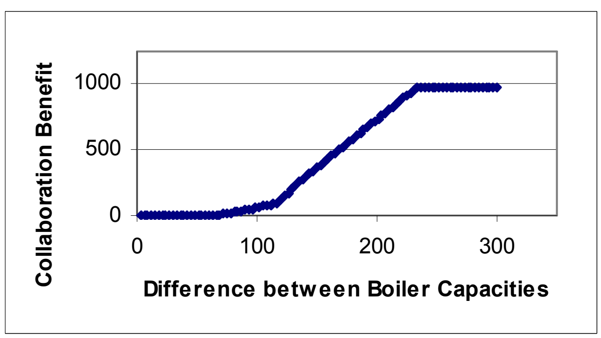



Figure A.4 Collaboration Benefit Function versus Difference between Boiler Capacities

Figure A.5 shows the relationship among boiler capacity difference, the collaboration synergy and the idle boiler capacities. The figure is plotted while both capacities are increasing one with a higher ratio. With increasing capacity, one company gains idle boiler capacity earlier than the other one. The synergy increases when only one has idle boiler capacity and decreases as far as the idle boiler capacity of the other one increases. It is equal to zero when both have idle boiler capacities in both cases. This is because nothing will be gained by allocating boiler efficiencies differently since the companies are totally identical.

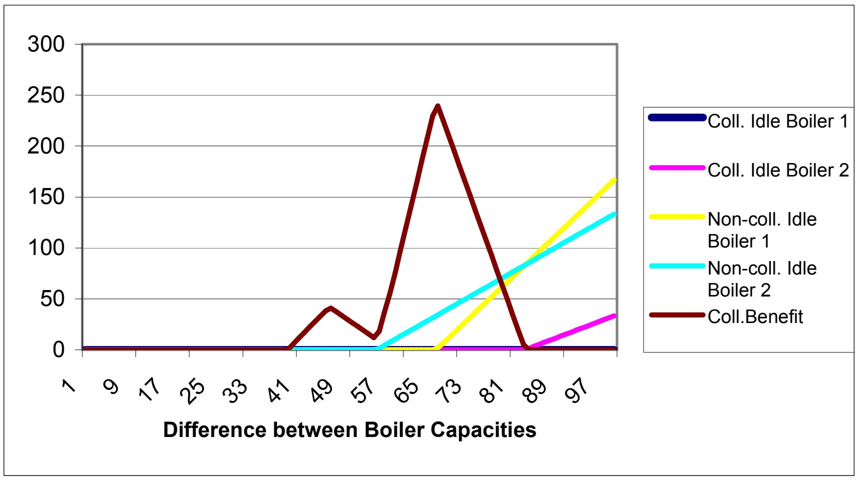



Figure A.5 Collaboration Benefit Function versus Difference between Boiler Capacities

### A.5 The Effect of the Differences in Various Parameters

It is essential to examine other parameters one by one, to understand whether differences between their values create benefit from collaboration. The experiments are performed as keeping other parameters identical and creating differences between the parameters examined. According to the experiments, if the companies pay different penalties for unsatisfied steam demand, pay different penalties for unsatisfied electricity demand, have different turbine performance parameters have different electricity demands charge different prices for electricity charge different prices for steam then collaboration does not create any synergy. To sum up, by the experiments, the differences in the parameters that have no effect on the amount of steam produced or sold are found to create no benefit by collaboration.

# Appendix B: Synergy Analysis in Energy Production Systems Model

## B.1 The Effect of the Differences in Boiler Efficiencies

Since it is found to have significant effect on collaboration benefit, the first parameter to examine is boiler performance parameter, i.e. boiler efficiency. In order to perform examination, one company's all parameters are kept constant while the other's boiler efficiency is increased by increments of 5 percent in each run. Figure B.1 summarizes the results as an increasing with a decreasing trend in collaboration benefit.

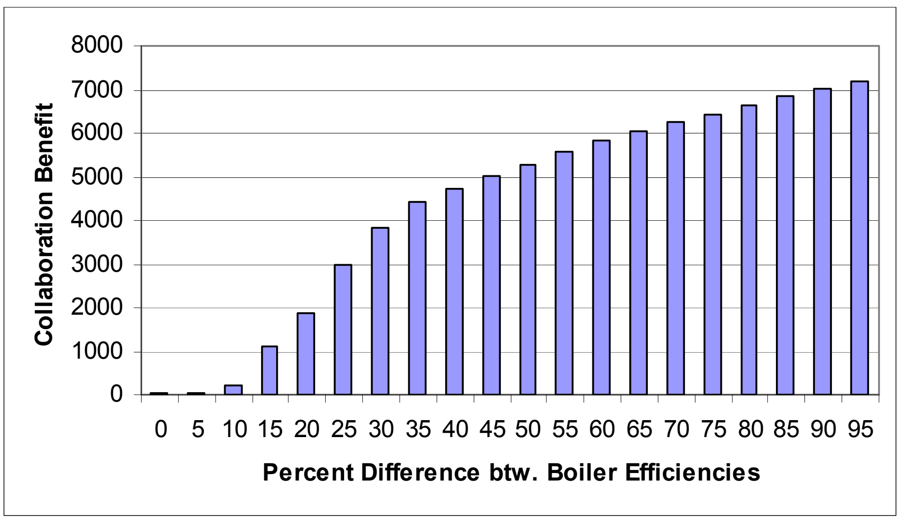



Figure B.1 Collaboration Benefit vs. Difference between Boiler Efficiencies

## B.2 The Effect of the Differences in Boiler Capacities

Boiler capacities are also found important to benefit in collaboration. The examination is performed by holding one company's parameters constant and increasing the boiler capacities of the other by 5% in each run. Figure B.2 shows that the differences between boiler capacities create benefit.

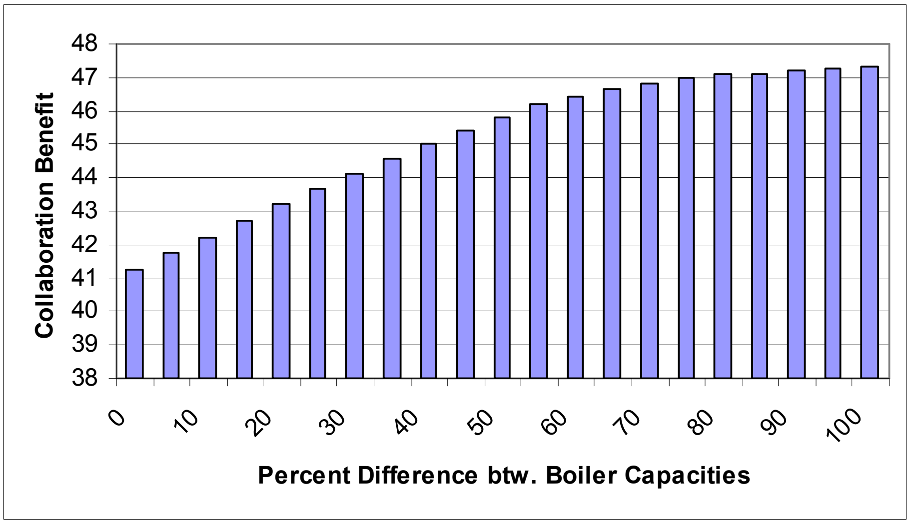



Figure B.2 Collaboration Benefit vs. Difference between Boiler Capacities

When the experiments were run as decreasing one company's parameters while holding the other constant, for a few runs, collaborated solution was feasible but non-collaborated was infeasible. Then, collaborated one became infeasible, too. This is also a benefit of collaboration: the demands can be satisfied even if one of the individual solutions is infeasible, in some cases.

### B.3 The Effect of the Differences in Steam Demands

The examination is performed by holding one company's parameters constant and decreasing the steam demands of the other by 5% in each run. Figure B.3 shows that increase in differences between steam demands show an increasing benefit up to some point, at which one company is able to satisfy all required HP steam. After that point, the effect of difference in steam demands on collaboration benefit stays constant.

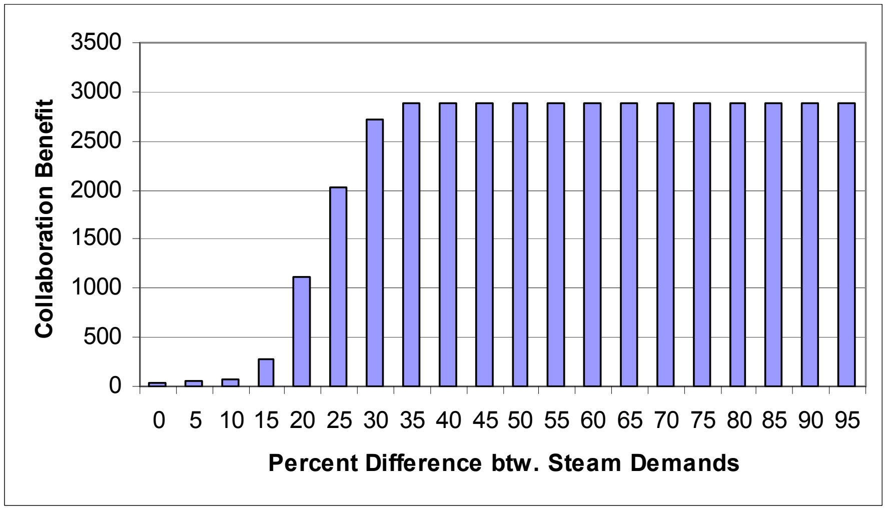



Figure B.3 Collaboration Benefit vs. Difference between Steam Demands

### B.4 The Effect of the Differences in Environmental Constraints

The effect of difference between the environmental constraints depends on the tightness of the constraint. If the companies operate at $SO_x$ limits a positive difference in one of theirs limit will create synergy on collaboration. For the example, the synergy becomes constant when the limit is no longer tight for one company, but still tight for the other one. This is the upper limit of synergy that can be gained by collaboration, in the existence of differences in $SO_x$ limits.

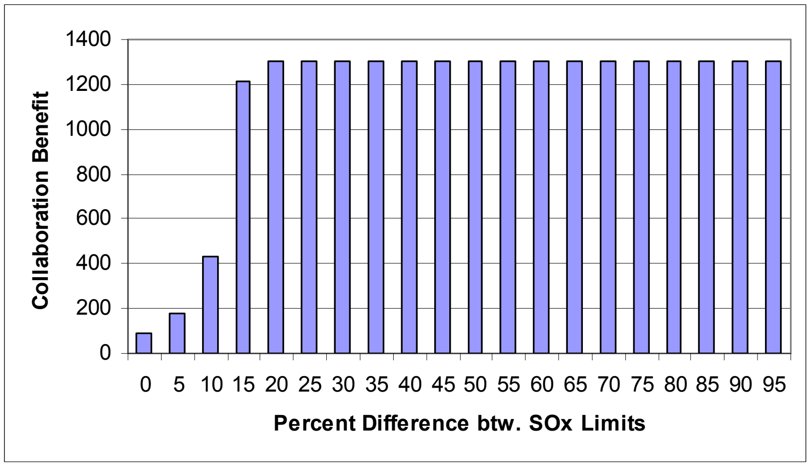



Figure B.4 Collaboration Benefit vs. Difference between $SO_x$ limits

Since GHG limits are not tight for any of the companies, creating difference by increasing one of them doesn't create any synergy. But decreasing one of them creates synergy for a few runs, after that the non-collaborated solution becomes infeasible. After a while, the collaborated solution becomes infeasible, too.

### B.5 The Effect of the Differences in Fuel Costs

If the companies pay different prices for fuel, collaboration creates synergy as can be seen in Figure B.5. Linear increase in differences between fuel costs creates a linear increase in collaboration benefit because, the difference between fuel costs directly effects the collaboration benefit coming from decrease in total fuel consumptions. This figure is different from Figure A.1.2 in the sense that, the companies have to satisfy the steam demand in this case. Therefore, they have to use the expensive fuel. However, in that case, the companies could give up production, when steam prices are too high to produce.

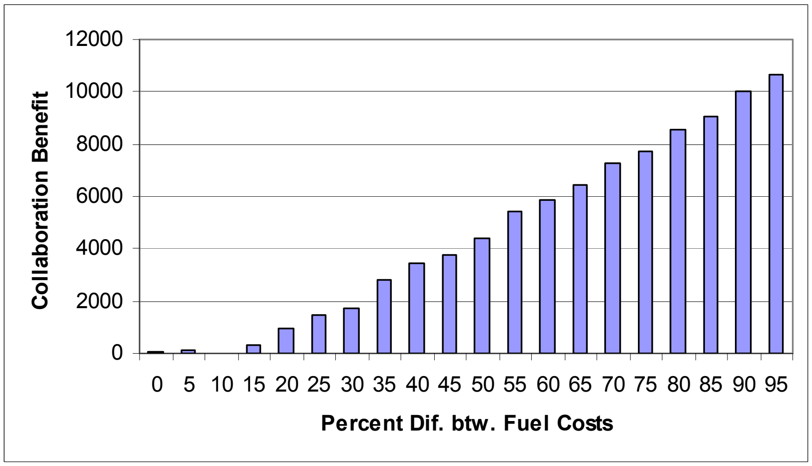



Figure B.5 Collaboration Benefit vs. Difference at Fuel Costs

### B.6 The Effect of the Differences in Turbine Capacities

The effects of differences in turbine capacities are to found have no effect on collaboration benefit in the analytic solution. When the effect of the differences in turbine capacities is examined in the model, they have found to have an effect on collaboration benefits, too. But this is the only effect coming from relaxing the tight limits on environmental constraints. That is why the benefit is constant. Then we can understand that the differences in turbine capacities do not have an effect on collaboration benefit.

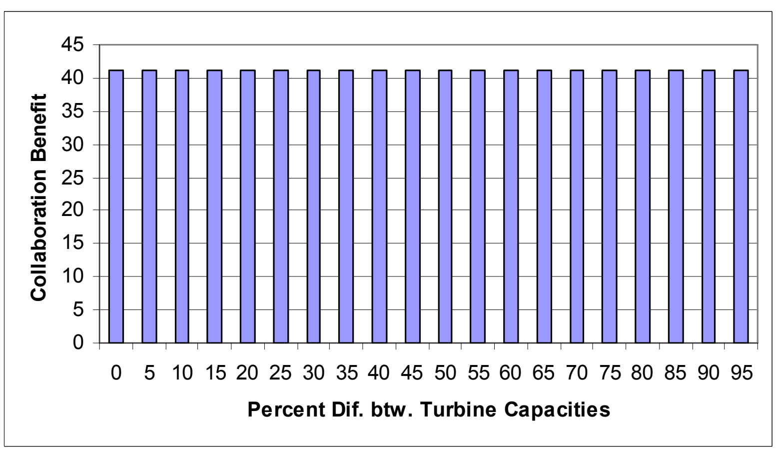



Figure B.6 Collaboration Benefit vs. Difference at Turbine Capacities

## Appendix C: Capacity Decrease with the Number of Periods a Boiler Used

### C.1 Aging of Devices in Non-collaborated Case

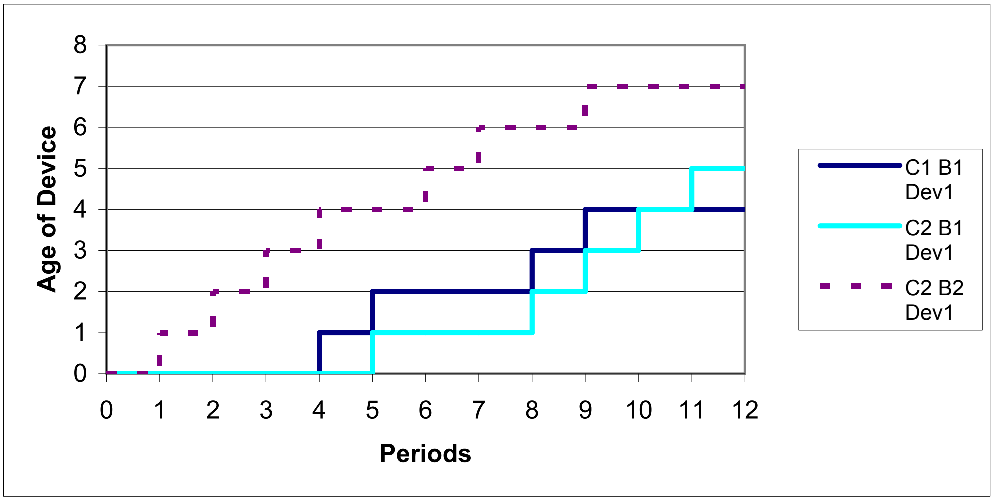



Figure C.1 Aging of Devices on Company 1's Boiler 1 and Company 2's Boilers in Non-Collaborated Case

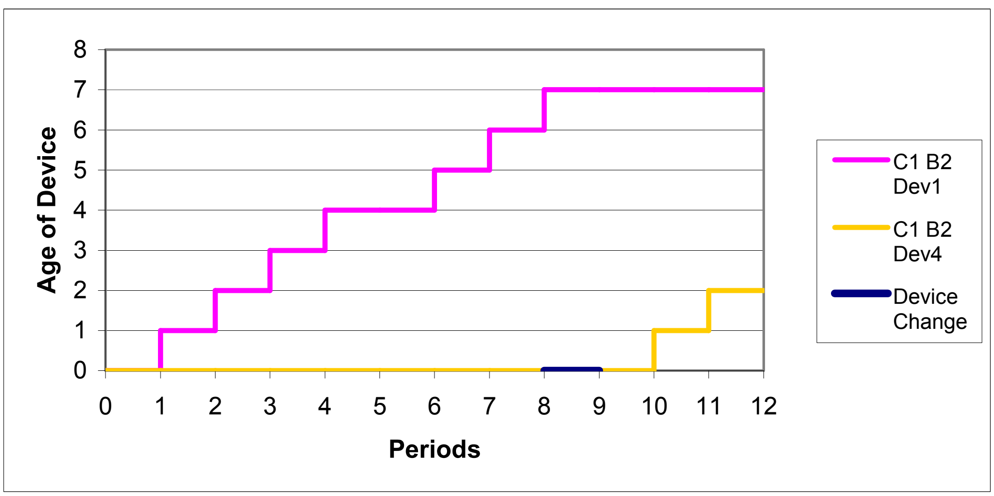



Figure C.2 Aging of Devices of Company 1's Boiler 2 in Non-Collaborated Case

### C.2 Aging of Devices in Collaborated Case

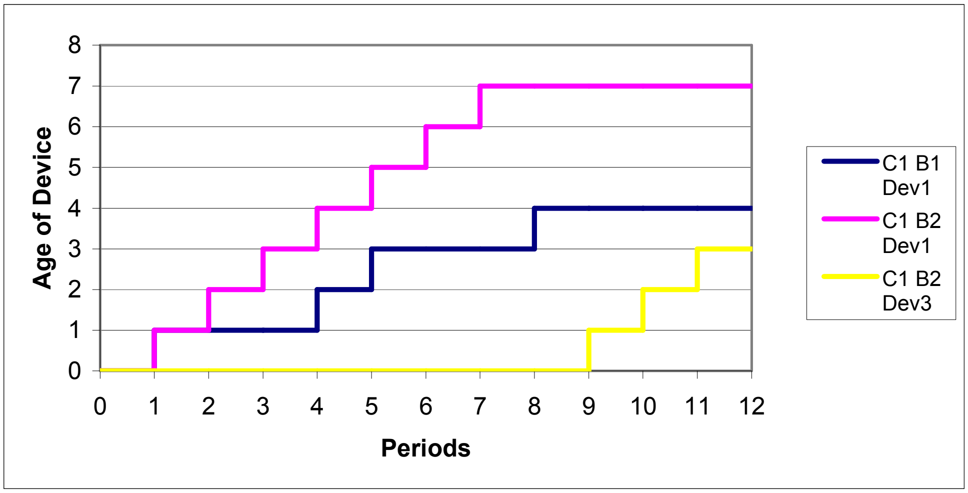



Figure C.3 Aging of Devices on Company 1's Boilers in Collaborated Case

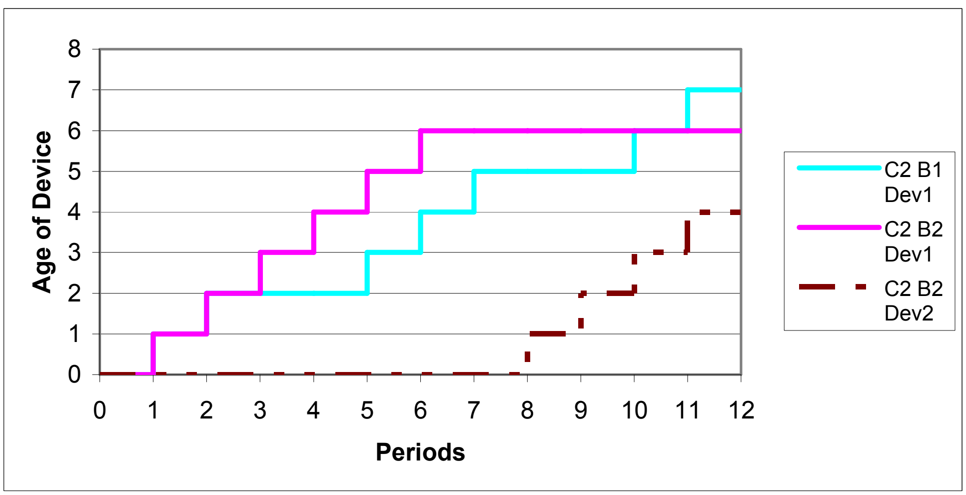



Figure C.4 Aging of Devices on Company 2's Boilers in Collaborated Case

## Appendix D : Capacity Decrease with the Amount of Steam Produced

### D.1 Cumulative HP Steam Production of Devices in Non-Collaborated Case

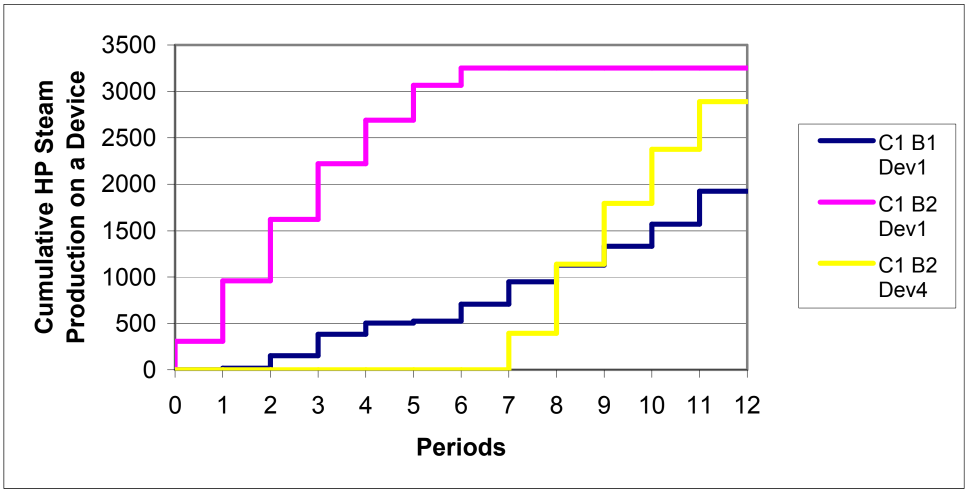



Figure D.1 Cumulative HP Steam Production of Devices on Company 1's Boilers in Non-Collaborated Case

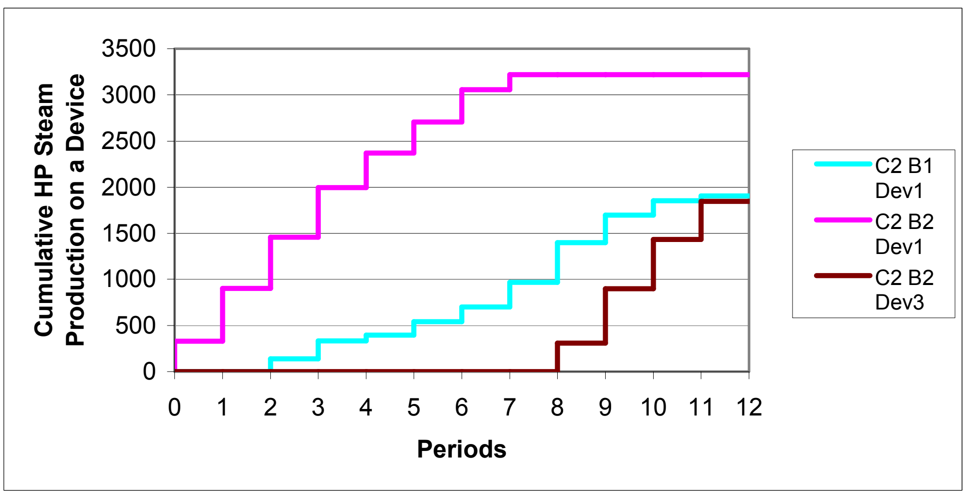



Figure D.2 Cumulative HP Steam Production of Devices on Company 2's Boilers in Non-Collaborated Case

### D.2 Cumulative HP Steam Production of Devices in Collaborated Case

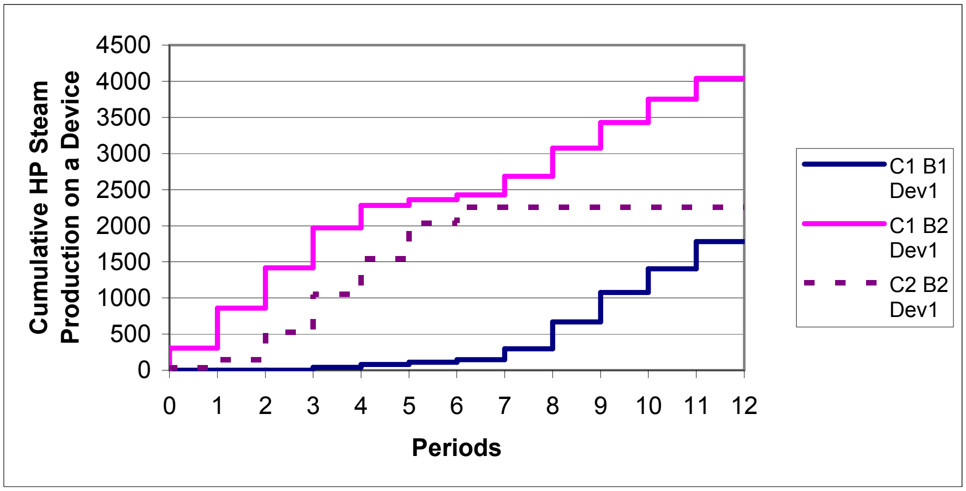



Figure D.3 Cumulative HP Steam Production of Devices on Company 1's Boilers in Collaborated Case

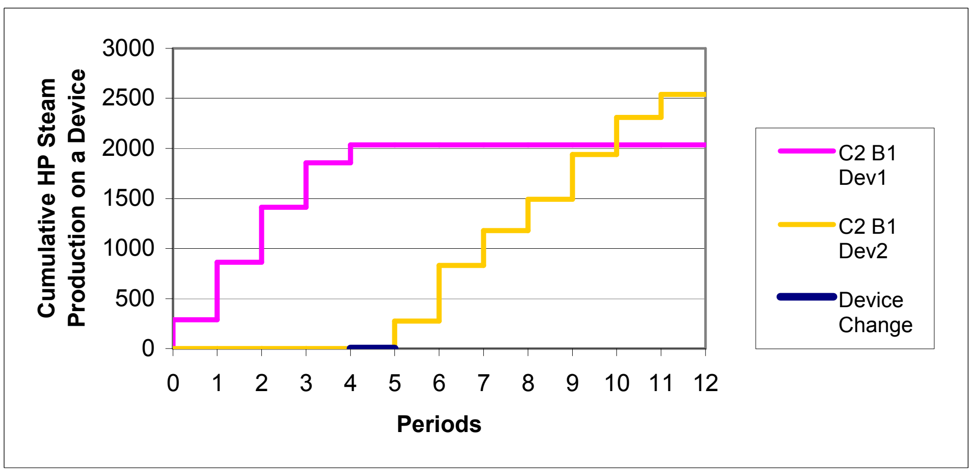



Figure D.4 Cumulative HP Steam Production of Devices on Company 2's Boiler 1 in Collaborated Case

# VITA

Ahu Soylu completed the high school in Eskişehir Anadolu Lisesi, Eskişehir, in 1999. She received her B. Sc. degree in Industrial Engineering from Bilkent University, Ankara, in 2003. Since 2003, she is in the M. Sc. program in Industrial Engineering of Koç University as a teaching/research assistant. For the completion of the program she has studied the thesis “Modeling and Analysis of Energy Production Systems for Environmentally Conscious Supply Chain Management”