MODELING ECO-EFFICIENCY CHANGES OF HETEROGENEOUS FIRMS WITH AN APPLICATION IN POWER PLANTS

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Abstract

The objective of power industry restructuring worldwide has been to enhance efficiency, hence providing an increased focus on efficiency measurement in power industries. Power generation which plays a key role in the power industry accounts for a noticeable share of emission generation amongst all power industry sectors. This would be costly not only for the sector itself, but also for the entire economy. Thus, the ecological impact of power generation should not be neglected in efficiency measurement. In addition, the non-homogeneous nature of power generation technologies has always been a barrier to drawing a complete picture of power generation industry efficiency or to compare the relative efficiency of different power plant technologies using methodologies such as Data Envelopment Analysis (DEA).

In view of the above, this research aims for introducing a more comprehensive DEA method to measure the ecological efficiency or eco-efficiency trend of heterogeneous power plants during an eight-year period of power industry restructuring in Iran using a popular measure known as the Malmquist-Luenberger index (MLI). Toward this aim, the study tackles a prevalent infeasibility problem which occurs when the traditional Directional Distance Function (DDF) or slack-based DEA models are adopted to measure MLI. This study introduces an algorithm accompanied by a slack-based model to tackle the infeasibility problem. In addition, to represent thermodynamic realities of mechanical systems more accurately, the study incorporates the Materials Balanced Principle (MBP) requirement in the measurement of efficiency by adopting a slack-based DEA model. As fuel rotation is an approach to generate the same amount of energy with less emission or cost, a fuel control constraint has been introduced to all MBP-enabled DEA models.

Furthermore, to measure the trend of ecological efficiency during the eight-year period of restructuring across the Iranian power industry, in addition to conventional technical efficiency measures, some DEA models are also introduced and adopted to identify efficient power plants based on a number of factors; namely, less fuel consumption, combustion of less polluting fuel types, and incorporating emission factors. In addition, to see the effects of restructuring on the efficiency measures, rather than on the factors conventionally used for eco-efficiency and cost efficiency measurement, values of inputs and outputs are calculated using a new set of rules and regulations affected by restructuring. Due to the non-homogenous nature of different power plant technologies, in the studies undertaken so far, efficiency and eco-efficiency measurements have been carried out within the homogenous power plant categories. However, in order to provide more comprehensive information for future planning and budgeting and to draw a complete picture of the performance delivered by heterogeneous power plants, this study introduces models which can handle heterogeneous firms and are deployed to measure cost and allocative efficiency in addition to the eco-efficiency of power plants.

Results reveal improvements in the eco-efficiency, cost efficiency and allocative efficiency of power plants during the restructuring period. It is also shown that although hydro power plants may look more eco-efficient, in Iran, the combined-cycle ones have been more allocatively efficient than those of other power generation technologies. Furthermore, results have exhibited that gas is the most cost-efficient, but less allocatively efficient technology in Iran.

Abstrak

Objektif utama penstrukturan semula industri kuasa elektrik merupakan peningkatan tahap kecekapan, yang menyebabkan fokus yang meningkat terhadap pengukuran kecekapan industri kuasa elektrik. Penjanaan kuasa elektrik, yang memainkan peranan penting di dalam industri kuasa elektrik, bertanggungjawab menghasilkan sebahagian besar emisi di antara semua sektor industri kuasa. Ini bukan sahaja meningkatkan kos sektor tersebut, malah juga ekonomi negara secara menyeluruh. Justeru itu, kesan ekologi penjanaan kuasa harus diambil kira dalam pengukuran kecekapan. Tambahan pula, sifat teknologi stesen janakuasa yang tidak homogen merupakan satu halangan untuk mendapat gambaran penuh tahap kecekapan industri janakuasa atau untuk melakukan perbandingan kecekapan relatif teknologi janakuasa yang berlainan menggunakan kaedah Data Envelopment Analysis (DEA).

Memandangkan itu, kajian ini bertujuan untuk memperkenalkan kaedah DEA yang lebih menyeluruh untuk mengukur trend kecekapan ekologi atau eko-kecekapan stesen janakuasa, yang bersifat heterogen, dalam tempoh lapan tahun penstrukturan semula industri janakuasa di Iran dengan menggunakan kaedah Malmquist-Luenberger Index (MLI). Untuk mencapai tujuan ini, kajian ini akan menyelesaikan masalah ketidaksauran yang berlaku apabila kaedah lazim yang dipanggil Directional Distance Function atau model DEA berasaskan slack, digunakan untuk mengukur MLI. Kajian ini memperkenalkan suatu algoritma beserta dengan model berasaskan slack bertujuan untuk mengatasi masalah ketidaksauran tersebut. Tambahan pula, untuk mewakili unsur-unsur termodinamik yang nyata dalam sistem mekanikal secara lebih tepat, kajian ini mengambilkira keperluan prinsip keseimbangan bahan (MBP) di dalam pengukuran kecekapan dengan mengunakan model DEA berasaskan slack. Memandangkan bahawa penukaran bahan bakar merupakan salah satu cara penghasilan jumlah tenaga yang sama sambil menghasilkan emisi dan kos yang berkurangan, suatu kekangan kawalan bahan bakar telah digunakan di dalam semua model DEA yang mengambilkira MBP.

Tambahan pula, untuk mengukur trend kecekapan ekologi sepanjang tempoh lapan tahun penstrukturan semula industri janakuasa di Iran, disamping mengambilkira ukuran kecekapan teknikal konvensional, beberapa model DEA juga diperkenalkan dan digunapakai untuk mengenalpasti stesen janakuasa yang cekap berdasarkan beberapa faktor; khususnya, pengurangan penggunaan bahan bakar, penggunaan jenis bahan bakar yang mempunyai tahap pencemaran yang rendah, dan pengambilkiraan faktor-faktor emisi. Selain daripada itu, untuk melihat kesan penstrukturan ke atas ukuran kecekapan, sebalik daripada menggunakan faktor konvensional, kajian ini menggunakan nilai input dan output yang dikira menggunakan peraturan dan undang-undang baru disebabkan oleh penstrukturan semula. Disebabkan sifat bukan homogen teknologi stesen janakuasa yang berlainan ini, kebanyakan kajian lepas mengukur kecekapan dan kecekapan-eko menggunakan kumpulan stesen janakuasa yang bersifat homogen sahaja. Oleh itu, untuk memberikan maklumat lebih menyeluruh bagi tujuan perancangan dan belanjawan masa hadapan serta memberikan gambaran penuh berkenaan tahap prestasi stesen janakuasa yang heterogen, kajian ini memperkenalkan model yang berupaya menangani isu firma bukan homogen yang seterusnya digunakan untuk mengukur kecekapan kos, kecekapan alokatif, serta kecekapan-eko stesen janakuasa.

Keputusan kajian ini menunjukkan peningkatan kecekapan-eko, kecekapan kos, dan kecekapan alokatif stesen janakuasa di sepanjang tempoh penstrukturan semula. Kajian ini juga menunjukan bahawa walaupun stesen janakuasa hidro mempunyai tahap kecekapan-eko yang lebih tinggi di Iran, stesen janakuasa kitaran-cantuman mempunyai kecekapan alokatif yang lebih baik berbanding dengan teknologi-teknologi janakuasa yang lain. Hasil kajian juga menunjukkan bahawa gas merupakan bahan bakar yang paling cekap dari segi kos, namun merupakan teknologi yang kurang cekap dari segi alokatif di Iran.

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List of Abbreviations

DEA	Data Envelopment Analysis
SFA	Stochastic Frontier Approach
AHP	Analytical Hierarchy Process
DMU	Decision Making Units
DDF	Directional Distance Function
SBM	Slack-Based Measure
RAM	Range Adjusted Measure
FDH	Free Disposal Hull
PMM	Performance Measurement Matrix
BSC	Balanced Scorecard
SMART	Strategic Measurement and Reporting Technique
EFQM	European Foundation for Quality Management
MODM	Multiple Objective Decision Making
MCDM	Multiple Criteria Decision Making
MADM	Multiple Attribute Decision Making
MBP	Material Balance Principle
WBCSD	World Business Council for Sustainable Development
MI	Malmquist Index
MLI	Malmquist Luenberger Index
CHP	Combined Heat and Power
PCA	Principal Component Analysis
IPPP	Independent Power Producer
TE	Technical Efficiency

CE	Cost Efficiency
BPG	Best Practice Gap
TGR	Technical Gap Ratio
TGC	Technical Gap Change
EC	Excessive Fuel Use
GE	Generated Electricity in a year
PYF	Power Plant yearly Yield Factor
HV	Heating Value
NGYF	Yearly Average of National Grid Yield Factor
RGHV	Regional Gas Heating [calorific] value
EFCH	Excessive Consumption Charge
GLP	Yearly Liberated Gas Price
RPGP	Regional Power Plant Gas Price
PGP	Yearly Power Plant Gas Price
AVGHV	Average of Countrywide Gas Heating [calorific] Value
Dev_d^t	Deviation from the generation plan on the day d of the period t
DAC	Declared available capacity
$BRCP$	Basic rate for capacity payment
CHM	Charge multiplier which is 20 or 25, depending on the type of deviation
Dev^t	Deviation charges of the year t
C_s	s^{th} Group
ML_n	ML index rate for nth power plant in a particular period

$PEFFCAP_n$	Effective Capacity for nth power plant in a particular period
S_{ML}	Aggregated Rate of Change of *ML* index by Effective Capacity
N	Number of DMUs
x	Inputs
y	Outputs
z	Bad Outputs
λ	Intensity Variable
g	Direction Vector
w	Vector of Weights
U	Outputs Vector of Weights
V	Inputs Vector of Weights
u	Weights Corresponding to each Output
u	Weights Corresponding to each Input
xh	high pollutant inputs
xl	low pollutant inputs
a	non-negative coefficients reflects the nutrient of the pollutant inside inputs
b	non-negative coefficients reflects the nutrient of the pollutant inside outputs
αh	pollutant part of the high polluting inputs
αl	pollutant part of the low polluting inputs
$D(x, y)$	Distance Function
$P(x)$	Production Possibility Set
φ	Good and Bad Output rate of change for Shephard Distance Function
θ	Good and Bad Output rate of change for Far et al. Distance Function
β	Rate of change for good outputs

γ	Rate of change for bad outputs
P^I	Intertemporal Production Possibility Set
P^G	Global Production Possibility Set
Superscripts	
I	Number of Inputs
J	Number of Good Outputs
K	Number of Bad Outputs
T	Time Periods
t	In the Period
Subscripts	
n	The n^{th} DMU
o	Under Evaluation DMU
i	i^{th} Input
j	j^{th} Good Output
k	k^{th} Bad Output

Chapter 1.

Introduction

The advent of the steam engine was an epoch-making invention of an extremely great magnitude whose contribution to industrialization is simply undeniable. The human society was industrialized and people's needs, deeds, requirements, and even views underwent fundamental changes gradually. They began to get used to consuming more and more, and suppliers not only had to produce more but also, in many cases, encouraged people and other industries in the supply chain to ask for more products. This entailed a tough competition for resources including energy, raw materials, manpower, and so on. However, increase of resource prices was not the only consequence of such a change in production manner, life style, and consumption behavior. Consequently, pollution started to develop dramatically not just in the form of household waste, but also industrial pollution such as toxic emissions, wastewater and, the most serious form of it, namely, the global warming.

As a result of the changes pointed out above, companies were forced to be more careful about their costs and monetary calculations and policies; in short, they had to enhance their accounting systems. In addition, companies had to monitor and measure their productivity to see if they were efficient enough to survive in the intensely competitive markets; however, that was not the endpoint.

Most companies were not individually aware of the environmental problems they had caused. Thus, governments as the main responsible bodies had to interfere and ameliorate the conditions. Meanwhile, environmental resources of life were going to be destroyed, and development and welfare were seriously jeopardized. Therefore, the international society decided to keep vigilant about sustainability of development which hinged upon the application of environmentally friendly methods and technologies. For this purpose, reports should be submitted to governmental and non-governmental organizations (NGO's) in compliance with all national and/or international rules, regulations, legislations, and protocols. Nonetheless, companies are not the only entities responsible for sustainable development; governments carry its burden in their own parts, too. In many countries, majority of public sector industries are not only controlled, but also owned by the governments. Thus, the government is not just responsible for surveillance of companies, but also it has to control them as their owner and manager and report to NGO's. Amongst all public sector industries, power industry has a vital role since it is both an energy consumer and producer at the same time.

Power industry is responsible for electricity supply in all countries, fulfills its duties through performing four main functions; namely, generation, transmission, distribution, and retailing. Since three decades ago, learning from the UK's valuable experiences, many countries decided to restructure their power industries. According to Ghazizadeh et al. (2007) and Eybalin and Shahidehpour (2003), increase of productivity, capital absorption, transpiration of interactions, following international rules and regulations, stabilization, and expansion of public ownership are the main goals of restructuring and power market establishment.

In line with this, performance evaluation of market participants has taken up a critical role. Independent Power Producers (IPPs); i.e. power plants, serve as the suppliers of the power markets. Therefore, each power market regulator, similar to regulators of other markets, have to measure efficiencies and inefficiencies or ecological efficiencies of power plants (by considering environmental factors) in order to operate the power markets effectively and ensure sustainable development.

During and after the restructuring period, all market regulators have been willing to measure the trend of critical factors of development such as economic efficiency and ecological efficiency, described by the term ‘eco-efficiency’.

1.1. A Brief about the Problem

One of the aims of power industry restructuring is to improve the performance of facilities in moving toward sustainable development. This is critical for every power system, to consume a lesser amount of fuel to generate more energy volume of emissions. Therefore, every country’s power industry authorities urge research on power industry efficiency measurement, which incorporate environmental factors so that they can report their endeavors for sustainability and compliance with the ecological rules and regulations. Therefore, it is crucial for a developing country to report statistically its trends of power generation eco-efficiency and sustainability during the period of restructuring. However, measuring and exhibiting this trend requires longitudinal studies as well as a great deal of relevant data. Furthermore, evaluation of the efficiency/eco-efficiency of power generation sector has always been challenging for the developing countries whose power sectors are still in the privatization phase. Sometimes, data unavailability aggravates the conditions. In some cases, data of only a limited period of time are available. This makes the researchers treat the units under evaluation differently in different periods of times. On the other hand, power plants are different in nature. Thus, application of popular efficiency measurement methodologies such as Data Envelopment Analysis (DEA) as a performance measurement tool, poses certain problems as such methodologies have been designed to suit homogeneous units. Actually, it is problematic to find the efficiency/eco-efficiency measures. It also seems interesting to observe that in the previous studies using real value of capital in efficiency/eco-efficiency measurement had been troublesome. This was mainly due to the fact that most of the data related to the firms' capital are generally financial data normally treated as highly confidential hence hardly accessible. The next paragraph discusses the above issues and begins with discussion on the effects of restructuring on power plant efficiency.

As addressed in Section 2.13, one of the main purposes of restructuring is to enhance the technical factors in order to reach sustainability. The main technical factors are increasing the efficiency of the power plants and decreasing the level of the emissions. Sustainable development inevitably leads to a treatment of both those factors simultaneously. According to Ghazizadeh, et al. (2007) restructuring in Iranian power industry follows the same aims. In such a developing country, power industry restructuring leaders search for studies which can illustrate the results of their efforts more prominently. This is critical for two parties: first for the Iranian government to support the restructuring efforts; second, for the world to be informed about the results of restructuring actions in a developing country. Therefore, if a study can exhibit the variation of eco-efficiency of the power plants during the period of restructuring, it will be highly beneficial for the power industry policymakers and planners not to stray off their path toward success in the restructuring paradigm. For the future planning and budgeting, it is necessary to measure the eco-efficiency of different power plants in a group; otherwise, it will not be possible to compare them. Besides, policy making for further development will be impossible, too.

If one chooses DEA as a popular tool for the eco-efficiency measurement, the research process will encounter major difficulties due to a notorious pitfall of DEA; namely, 'the Homogeneity Pitfall'. This pitfall rises from a very basic assumption of DEA methodology which takes for granted the similarity of units under evaluation. The pitfall awaits research in this area as power plants are different in nature: thermal power plants including gas, gasoline, steam turbine and combine-cycle, hydro power plants or dams, coal-fired, nuclear generators, wind turbine and many other types. Power plants utilize different types of fuel such as gas, gasoline, uranium, coal, and even wind and water. They produce different kind of emissions such as NO_x, SO_x and CO_x called 'undesirable outputs'. The problem will be worsened if eco-efficiency is considered; that is, if different inputs and outputs exist. This difficulty has been referred to in many studies (Estache et al., 2008; Jasch, 2004; Liu et al., 2010). From another perspective, this will be the case if in a longitudinal study of performance, one or more factors, which had not been recorded before, are required to be incorporated into the model. This problem would be more interesting if a research is being carried out on the measuring of the efficiency and eco-efficiency of power plants to illustrate the effects of a power industry restructuring plan on the main factors of sustainable development (Eybalin and Shahidehpour, 2003; Rudnick and Zolezzi, 2001; Srivastava and Shahidehpour, 2002).

In DEA literature, one can find many researches citing this pitfall or trying to overcome it. In a number of them, attempts were made to combine certain methods to fill this gap. In most of them, the new 'combinational' methods have been applied to a real case. Then, the results have been compared to those obtained using previous or other models (Azadeh et al. (2009)). In spite of all this, the Homogeneity pitfall has still persisted as DEA axioms are constructed on the Homogeneity Assumption (Brown, 2006; Dyson et al., 2001; S. Samoilenko and K. M. Osei-Bryson, 2010).

However, Dyson, et al. (2001) define the homogeneity assumption as a condition in DEA which keeps researchers from using the same inputs and outputs for their DMU's. Dyson et al. (2001) have considered a non-homogeneous environment, which leads in a way to heterogeneity in data. This heterogeneity in data can be normally tackled using cluster analysis (Samoilenko and Osei-Bryson, 2008; S. Samoilenko and K.-M. Osei-Bryson, 2010). Frontier approaches of efficiency evaluation such as DEA and Stochastic Frontier Approach[1] (SFA) may deal with decision-making units, which work in different environments; that is, when their data are heterogeneous.

As stated before, heterogeneity of DMU's happens in many situations; therefore, it is a critical problem in the real world. For instance, certain types of power plants use purchased gas as an input for producing electricity; some others use other sources of energy which are freely available in the nature, like wind. Ignoring the differences can be a serious threat to the accuracy of performance measurements and exerts a significantly negative effect on the validity of researches using DEA.

Turning to capital inputs, having a close look at Table 2-2, the majority of previous studies, have used installed capacity as a proxy for capital of a power plant due to a number of limitations. However, it is necessary for the power industry restructuring/privatization officials to deal with the real value of the power plant assets also known as firm value rather than an artificial one. This is because those officials are in the middle of privatization phase and it is necessary for them to show the private sector that the facilities which are going to be sold to them are profitable. Because of depreciation, installed capacity cannot be a proper proxy for the capital of the power plants with different lifetimes and technologies. This problem can be worsened if one considers the fact that power plants are different in nature and the value of 1MW of installed wind turbine is approximately 10 times more than that of a simple gas generator

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[1] See Section Frontier Methods of Performance Evaluation

of the same capacity.

1.2. Research Questions

Considering the aforementioned problems, the aim of this study is to measure the impact of the Iranian power industry restructuring on the performance of the country's power plants, incorporating environmental factors. In the emerging field of environmental management, it is possible to improve efficiency and at the same time control waste and emissions or decrease them; in other words, to be eco-efficient. Therefore, major questions of this study are as follows:

1. What is the relative economic and eco-efficiency trends of the Iranian power plants during the 2003-2010 period, when employing the existing models?
2. How to account for difference/heterogeneity and material balance principle in firms in measuring eco-efficiency change?
3. What are the trends of power plant eco-efficiency using a proposed model, following the power industry restructuring in Iran, prior to and during the reform period of 2003 to 2010?

1.3. Objectives of the Study

The objectives of this research can be listed as follows:

1. To measure the relative economic and eco-efficiency of the Iranian power plants during 2003 to 2010, employing existing models.
2. To propose new eco-efficiency models which accommodate the difference/heterogeneity in production technology amongst firms, and incorporate materials balance principle as well as the real value of assets as capital inputs, hence introducing a new highly applicable tool for performance measurement.

3. To measure the trends of ecological efficiency of the power plants prior to and during the reform period of 2003 to 2010, using the newly proposed models.

1.4. Significance of the Study

As it will be elaborated later in Section 2.5, there is a core hypothesis assuming a positive relationship between keeping up the efficiency of industries and maintaining or decreasing the environmental impact level. This hypothesis can be tested out in every country. In developing countries, environmental issues have attracted notice quite recently but only a few researches or applications can be found in the literature. This is because these countries are still at the initial phases of their journey to industrialization and have just started to pay attention to and record the detrimental impacts of industries on the environment.

Iran as a developing country is no exception to the above generalization. Authorities of power industry embarked on restructuring to enhance the efficiency of power facilities and increase the power reserve and supply in the early 2000. Naturally, they are eager to see the results of their endeavors. In addition, similar to other countries, Iran's Economic, Social and Cultural Development Plans mandate the authorities to act just in the sustainability lane, and this imposes a lot of environmental protection requirements. Therefore, environmental protection is an inevitable duty for them and they ought to report the results of their endeavors to the tax payers as well as the cabinet to receive permissions and reinforcements for further actions and proceed with further steps. Hence, in this study, for the first time in the history of researches on the Iranian power sector, ecological factors (emissions) are being incorporated as an index for in Power Plant efficiency measurement. This new measure is called eco-efficiency. In addition, as the kernel of this research, the impacts of power industry restructuring on power plant efficiency and eco-efficiency will be evaluated.

Nevertheless, this evaluation will not be that simple; neither theoretically nor practically. Firstly, as mentioned in Section 1.1, when using non-parametric relative methods, it will not be possible to measure the efficiency of the units which are different in nature and heterogeneous. This problem is known as homogeneity assumption pitfall. In order to introduce more accurate and suitable models for measuring the environmental efficiency of power producing units, this problem will be solved theoretically in this research. Yet, regardless of practical advantages associated with these sorts of new models which can accommodate heterogeneity across power plants, these models will be useful for other industries facing a similar problem. Again as discussed earlier, sometimes in longitudinal studies of relative efficiency, the researcher holds one or two input or output data only for a particular period of time. Solving the homogeneity assumption pitfall facilitates these types of researches. Hence, in this study a series of performance measurement tools will be introduced which is highly beneficial for cross-sectional and longitudinal performance studies suffering from what is called ‘homogeneity pitfall’.

In addition, in this research we use directional distance function (DDF) and slack-based type of DEA models to evaluate the eco-efficiency changes of the power plants. However, when researchers use the DDF to measure the eco-efficiency changes, a conventional infeasibility problem is likely to occur. In this research we introduce a slack-based model accompanied by an algorithm which successfully tackles this infeasibility problem.

Furthermore, since in our study we measure the eco-efficiency of the power plants, all DEA models have to be compatible with the nature of the power plants which are mechanical systems. To be compatible with the mechanical nature of the power plants, the Materials Balance Principle (MBP) is a requirement. For that reason, in this research we introduce a new generation of slack-based models which are MBP-enabled.

Finally, the method that the researcher is going to tackle the problem, theoretically, illuminates the path for the researchers who have stuck in a theoretical but serious pitfall.

1.5. Scope of the Study

This research is exploring a proper method to formulate the relative eco-efficiency measurement of the power plants of various types in Iran. These power plants are government-owned and use different electricity generation technologies such as steam, gas, combined cycle, hydro, etc. Second, due to the effective influence of depreciation on the real value of power plant capital, this study is investigating an appropriate method to measure the real asset value of power plants in order to incorporate the same into eco-efficiency measurement in Iran which is in the phase of power sector restructuring.

1.6. Organization of the Study

This research has been organized in six chapters. The first chapter provides a brief background of the research and the problem, research questions, objectives, significance, and scope. Then, the second chapter has been dedicated to literature review on different aspects of performance measurement and its evolution in course of time, eco-efficiency and efficiency measurement methods, Data Envelopment Analysis and efficiency and eco-efficiency evaluation of power plants. In Chapter 3, the research methodology, in addition to the new models and approaches which are introduced in this study are presented. Chapter 4 contains the results of the study which have been obtained through running the models presented in Chapter 3. Chapter 5 is allocated to the discussions about the results obtained. Finally, in chapter 6 we conclude the research by presenting the theoretical and empirical implications, limitations of the study and the suggested areas for further researches which can be conducted in the future.

Chapter 2.

Literature Review

2.1. Introduction

There is no doubt that all managers need information about how each part of their firm works. In addition, no one can refute the critical role of quantitative measures of performance in management. Therefore, performance measurement takes up a great deal of importance in management (Ahrens and Chapman, 2006). Franco Santos et al. (2007), conducted a comprehensive research on performance measurement system characteristics. In their research, a number of popular performance measurement systems were analyzed and their common features, roles, and processes were summarized. First, it was assumed that all performance measurement systems studied have two features: a set of performance measures and a supporting infrastructure. They also elicited 17 most common roles of the performance management system and found out that the most necessary one is the measure performance. Efficiency and newly the introduced eco-efficiency concept are two of the bold measures of performance evaluation of which requires a great deal of energy and research work.

Power plants are not exceptions. Efficiency and eco-efficiency of the power generation sector is a main infrastructure in every country which plays a critical role in short, mid and long term planning and budgeting.

In the following section, definitions of performance measurement are given.

2.2. Performance Measurement Definitions

According to Neely et al. (2002), due to the nature of performance measurement, it has found numerous applications in different fields such as accounting, operation management, economics, finance, psychology, sociology and many other areas. In fact, different definitions of performance measurement or performance evaluation can be found in different contexts with a little consensus on its components and characteristics (Ellen, 1994). David Otley in Neely et al. (2002), allude that in accounting, traditional approaches deploy quantitative measures for performance measures. They also mention that in the last two decades researchers have had grace to non-financial measures although financial measures still have their own advocates and popularity. In any case, it can be argued that the performance measurement plays a key role in management. In the kernel of an organizational control, performance measurement can reflect the targets and strategies (Chenhall, 2006). In addition, in a business context, performance management can be defined in operations and marketing areas. As stated in Kotler and Turner (1976), in marketing, customer satisfaction is the goal of organizations, they could be more efficient and effective if they perform better than their competitors in market.

Many researchers argue that performance measurement is the quantification process of efficiency and effectiveness (Lebas, 1995; Neely et al., 1995; Neely, 1998). Thus, the concepts of efficiency and effectiveness have to be well understood before moving further in a performance measurement study.

Kaplan (1983) defines efficiency as the ratio of input consumed to the level of output produced. However, Fried, Lovell and Schmidt (2008) point out that efficiency has two components: technical efficiency and input allocative efficiency. One can find other types of efficiency such as: cost-efficiency, eco-efficiency, economic efficiency, and the like in the relevant literature. Other than the first two components, here we will also consider eco-efficiency afterwards. Koopmans (1951) defines a technical efficient producer as a producer that could produce at least one more output consuming the same inputs or could produce the same outputs using at least one less input. It can be translated into the output to input ratio, which is the most popular definition of technical efficiency. In addition to technical efficiency, cost efficiency can also be defined as the ratio of minimum feasible cost to actual cost. Thus, allocative efficiency is defined as the ratio of cost efficiency to input-oriented measure of technical efficiency (Fried et al., 2008).

Considering Draker's definitions, if efficiency is doing things right, effectiveness is defined as doing the right things (Rämö, 2002). Same as efficiency, effectiveness has diversity in definitions. Some define effectiveness as doing a job toward achieving a goal.

Finally, productivity is defined as the amount of output that can be produced by a unit of input. Throughout this research, we shall hold with the very basic definitions. In the following section, a historical review of the background of the research is presented.

2.3. A Historical Review

Most managers and economists in many countries conceive the market of having three main factors: structure, behavior and performance. Moreover, most structuralists recognize market performance as a function of structure, behavior, internal organization and external conditions (Palma, 1987). This is called "Structuralism.” Meanwhile Chicago-U.C.L.A. School, defines structure as a function of external condition, behavior and performance[1]. On the other hand, behaviorism implies that the structure never interferes with market performance, and that the behavior plays the main role (Fox and Pitofsky, 1991).

Bain (1951), Demsetz (1973), Cowling and Waterson (1976) have dealt with the relationship between market concentration and its performance. Clark and Davis theorized efficiency and market power in 1982 and 1984; Clark published a book in this field under the title of "Industrial Economy" in 1990.

A large number of market monitoring reports such as Rahimi & Sheffrin (2003), Sheffrin (2002), Borenstein, Bushnell, & Wolak (2002), Newbery, Green, Neuhoff, & Twomey (2004) have focused on performance analysis and dealt with concentration, price, supply, demand, reliability and the market power indices. Meanwhile, there is a vast area of research on the success of market in gaining its main purposes and effective and robust performance evaluation. Estache, Rossi, Ruzzier (2004) conducted a research in aforementioned area, which was organized by the World Bank in 2004. The report of 'Implementing Power Rationing in a Sensible Way: Lessons Learned and International Best Practices' (Maurer et al., 2005) merits acknowledgement, too.

From another point of view, all of the studies mentioned above have excluded the behavior of the players (such as Power Plants, IPPs) or simply tried to analyze the performance not based on their patterns in which they behave. From this point, as it will be mentioned, researchers focus on the results of experiments and try to explain the problems in order to find a practical solution to test them in practice. This gives us an

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[1] Here school refers to school of thought, see Fox and Pitofsky (1991, p. 43)

impetus to concentrate more on the performance management and the measurement of performance delivered by individuals or players in a market.

As mentioned before, performance management has its own applications and definitions in different contexts such as operation management, human resource management, market regulation, monitoring and so on. Fried, et al. (2008) present a huge number of applications of performance measurement from fishing to World Health Organization. Therefore, one can find a diversity of approaches toward performance measurement in different contexts and times as well. In the next section, we are going to explore the performance measurement concept, exhibit its evolution during the past three decades and show how performance management methods and indices can integrate other popular methods and indices.

2.4. Performance Measurement

Every information and control system deals with performance measures. In this section, in addition to a concise history of performance measurement systems, the new performance measurement system is going to be discussed as well.

2.4.1. Performance Measurement Systems

Having conducted a literature review, Kennerley and Neely (2002) demonstrated the evolution of performance measurement systems, starting from singular financial measures through addition of non-financial ones, a need for balance between financial and non-financial measures, Performance Measurement Matrix (PMM) and Balanced Scorecard (BSC) and finding a causal relationship amongst derivers to strategies. This study has been continued with Strategic Measurement and Reporting Technique (SMART), and finally ended up in integrating different measures to find one comprehensive measure for performance; that is, EFQM[1]. Traditionally, performance measurement systems have relied on financial measures to meet the requirements set by the government or external bodies. However, since the very early 1980s non-financial measures also showed their importance to the researchers (Jusoh et al., 2006). In 1992, many executives recognized that there had to be a balance between financial and operational and non-financial factors and it was necessary to find a causal relationship between strategies and environmental forces to the performance measures in their businesses. (Kaplan and Norton, 1992; Kaplan and Norton, 1996). Therefore, Kaplan and Norton introduced the BSC methodology to the performance measurement literature, which gained a noticeable popularity afterwards (Kennerley and Neely, 2002). However, in spite of its popularity, people criticize BSC due to its lack of comprehensiveness. Actually BSC does not comprise competitiveness, product and service quality, environmental and community, supplier performance, results and determinants and human resource measures (Kennerley and Neely, 2002). One should notice that recently people have tried to incorporate missing factors in BSC to enhance its comprehensiveness (Figge et al., 2002, 2003; Möller and Schaltegger, 2005). Although methods such as EFQM cover most dimensions of an organization, these reward oriented methods and their analogues in the USA, Malcolm Baldrige National Quality Award, do not take efficiency measures into account.

In the meantime, there still exist new factors such as undesirable inputs and outputs, new models such as frontier models, and new approaches toward performance management which will be addressed in the next sections.

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[1] European Foundation for Quality Management

2.4.2. Undesirable factors

In efficiency measurement, inputs have to be minimized whereas outputs are maximized; however, in some cases some (good) inputs must be maximized or some (bad) outputs must be minimized. In the literature, these kinds of factors are called 'undesirable' (Jahanshahloo et al., 2005). In addition, one can find some examples of undesirable outputs such as the amount of overdue debts in banking (Amirteimoori et al., 2006), delayed flight (Coli et al., 2011), poverty rate (Bruni et al., 2011), patient deaths (Yawe and Kavuma, 2008). Many studies have incorporated SO_x Gases (Burnett and Hansen, 2008; Korhonen and Luptacik, 2004; Zhou et al., 2007), NO_x (Oggioni et al., 2011; Tyteca, 1996) CO_x (Oude Lansink and Bezlepkin, 2003; Zaim and Taskin, 2000). Nevertheless, only a few instances (Hadi Vencheh et al., 2005) of undesirable inputs can be found in the previous studies. Hadi Vencheh, et al. (2005, p. 2) asserts, "the aim of a recycling process is to use maximal quantity of the input waste". A useful literature review on undesirable factors in efficiency measurement can be found in Seiford and Zhu (2002).

There are numerous methods which include the undesirable factors in the efficiency measurement studies. If emission factors are integrated in the efficiency measurement, then it will be named eco-efficiency, which is a highly interesting area for research now with the pollution reaching disastrous dimensions in the contemporary era. The notion of eco-efficiency is going to be explored in Section 2.5.

2.5. Eco-efficiency

In many cases, it has been observed that cleaner productions are apt to be more efficient (Schaltegger et al., 2008). In addition, not only incorporating environmental factors can decrease the cost but also it has been shown that, in many cases, it is possible to lower the costs and alleviate the environmental harms simultaneously (Burritt et al., 2004). Therefore, including these new aspects and hypotheses, a new concept of efficiency, has been introduced; that is, ‘ecological efficiency’, or as the abridged blend goes, ‘Eco-efficiency’.

The concept of eco-efficiency has its root in the definition of sustainable development. Brundtland (1987), in World Commission on Environment and Development defined sustainable development as “to meet the needs of the present generation without compromising on the ability of future generations to meet their own needs”. Taking into the account Kyoto Protocol[1] to the United Nations Framework Convention on Climate Change, eco-efficiency claims that, it is possible to be efficient or increase the efficiency and maintain a certain level of environmental performance or improve it simultaneously[2] (Jan et al., 1999).

Eco-efficiency has various definitions, but Schmidheiny (1992) introduced one of the earliest definitions as "competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life-cycle to a level at least in line with the Earth's estimated carrying capacity" under World Business Council for Sustainable Development (WBCSD)[3]. Up to the date, this definition has evolved; however, all definitions, according to Lovins (2008, p. 34), have covered almost the same dimensions which are:

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[1] This is a protocol on reducing emission 5% from the level of year 1990 to over a 5 years period from 2008 to 2012. http://unfccc.int/kyoto_protocol/items/2830.php

[2] STATE OF THE WORLD, 2008, Innovations for a Sustainable Economy, 25th Anniversary Edition

[3] www.wbcsd.org

- A reduction in the material intensity of goods or services;
- A reduction in the energy intensity of goods or services;
- Reduced dispersion of toxic materials;
- Improved recyclability;
- Maximum use of renewable resources;
- Greater durability of products;
- Increased service intensity of goods and services.

Lovins (2008, p. 33) argues "Eco-efficiency is the easiest component of the transition to sustainability to implement". Toward operationalization, Schaltegger and Sturm (1990, p. 240) as one the earliest formula defines efficiency as below:

Eco-efficiency=Economic Value Creation / Environmental Impact Added

Using this fractional definition, Huppes and Ishikawa (2007) present four types of Eco-efficiency as shown in Table 2-1.

Table 2-1: Four Basic Variants of Eco-efficiency

	Product or production prime	*Environmental improvement prime*
Economy divided by environment	Production / consumption value per unit of environ-mental impact: **1 environmental productivity**	Cost per unit of environ-mental improvement **3 environmental improvement cost**
environment divided by Economy	Environmental impact per unit of production/consumption value or: **2 environmental intensity**	Environmental improvement per unit of cost: **4 environmental cost-effectiveness**

This definition paved the way for different industries to conduct a lot of researches on eco-efficiencies in their own industries such as, power plants (Korhonen and Luptacik, 2004), industrial system of a country (Zhang et al., 2008), farming (Picazo-Tadeo et al., 2011), eco-tourism, world cement industry (Oggioni et al., 2011) and many other analogues. Jasch (2004) defines the comprehensive processes, which are engaged in pollution and presents a comprehensive list of input and output measures of pollution.

Eco-efficiency has turned the eyes into technical and relative efficiency measures. In recent years, a number of researches have been conducted on eco-efficiency using DEA, which is one the most popular methodologies for efficiency measurement. DEA uses the first row concept in Table 2-1. In next sections, DEA's background and theory will be discussed more. First, frontier methods are going to be mentioned briefly in Section 2.6.

2.6. Frontier Methods of Performance Evaluation

Charnes, Cooper and Rhodes (1978), using a previous work introduced by Farrell (1957), presented a new model for performance evaluation of similar decision making units, called CCR model later. This preliminary model conduced to a new methodology named Data Envelopment Analysis (DEA), for evaluating the performance of decision-making units. During the same period, another methodology for performance evaluation, called Stochastic Frontier Analysis (SFA), was developed based on the statistical theories (Richmond, 1974). DEA is considered as a non-parametric method since multipliers of production function are assumed to be unknown. Thus production functions in these methods are non-parametric. However, SFA is categorized as parametric methods.

2.7. Data Envelopment Analysis

In this section, a brief summary of DEA's underlying theory and applications is presented.

2.7.1. Inception

Charnes, Cooper and Rhodes' seminal paper (1978) on performance evaluation of Decision Making Units (DMU) redounded to the development of the first model for efficiency measurement of a DMU in comparison to the performance of other DMU's. As a matter of fact, that paper, which was the basis of DEA, was called CCR later. This mathematical programming method was built on the assumption that DMU's under evaluation consume similar inputs and produce similar outputs, that is, the homogeneity assumption (Dyson et al., 2001; Haas and Murphy, 2003). These DMU's can be branches of a commercial bank (Giokas, 1991), schools of a city(Ahn et al., 1988), industry of a country (Oral et al., 1991), economy evaluation (Charnes et al., 1989), power plants (Cook and Green, 2005), (Hjalmarsson and Veiderpass, 1992), universities or academic departments. (Beasley, 1995), sport federations (Sueyoshi et al., 1999).

2.7.2. Applications

Adding the concept of return to scale (Banker, 1984) was an important extension for DEA, which enabled it to yield a realistic measure for efficiency with operative and applicative techniques to improve the performance. In the same paper, Banker succeeded to determine the units with 'Most Productive Scale Size'. This capability induced researchers to use DEA to introduce new models for their own purposes such as fuzzy DEA (Hatami-Marbini et al., 2011), weight restriction models (Jahanshahloo and Soleimani-Damaneh, 2005; Podinovski, 2004), stochastic efficiency evaluation (Sueyoshi, 2000; Wu and Lee, 2010), multiple objective programming (Lotfi et al., 2011; Lotfi et al., 2010; Yang et al., 2009) and many other purposes which can be found in some DEA bibliographies and review papers (Cook and Green, 2005; Emrouznejad et al., 2008).

In addition to direct applications by some researchers, some others succeeded to customize DEA to obtain a new family of methods. Free Disposal Hull or FDH is the most famous method obtained through using this type of manipulations (Deprins et al., 1984). This method won its own popularity soon after its introduction (De Borger and

Kerstens, 1996; Ruiz-Torres and López, 2004; Soleimani-damaneh and Mostafaee, 2009).

In Section 2.7.3, very basic theoretical foundations of DEA will be presented.

2.7.3. Theoretical Foundations

DEA is a mathematical optimization objective is efficiency evaluation for each DMU in a DMU group. Consider *n* DMU's that we want to evaluate using *m* similar inputs to produce *s* similar outputs. In fact, efficiency is the answer of a DMU to this question: "How to employ multiplicative inputs for producing multiplicative outputs?"

Let $X_j = (x_{1j},...,x_{mi})$ and $Y_j = (y_{1j},...,y_{mi})$ be input and output vectors corresponding to *j*th DMU, respectively. Then, consider that $X = (X_1,...,X_n)_{m\times n}$ and $Y = (Y_1,...,Y_n)_{s\times n}$ to be the input and output matrices. We indicate the collection of these technologies by $P = \begin{bmatrix} Y \\ -X \end{bmatrix} = [p_1, p_2,..., p_n]$ and sorted DMU's by $J = \{DMU_1, DMU_2,..., DMU_n\}$. $D = (J, P)$ is called 'field of data'. Let *U* and *V* be nonnegative nonzero vector with *s* and *m* components. So $w = \begin{bmatrix} U \\ V \end{bmatrix}$ is called virtual multiplier (weight) vector, in which *w* is named *D*-proper if (1) $U^T Y_j > 0$ for at least one *j*, (2) $V^T X_j = 0$ for all *j* if $U^T Y_j = 0$. We call the collection of such multiplier as multiplier space and denote it by *W*. Now for $w \in W$ and *j=1,…,n*, we define:

$$h_j(w) = \begin{cases} \dfrac{U^T Y_j}{V^T X_j} & V^T X_j > 0 \\ undefined & V^T X_j = U^T Y_j = 0 \end{cases} \tag{2-1}$$

We call this 'the ratio of output to input for collection of multipliers' (weights). This fractional programming leads to the following linear programming problem model, CCR. Then, consider the non-Archimedean input oriented CCR model in which we try to find the maximum ratios (between 0 and 1) of inputs of DMU under evaluation that produces at least the same outputs.

$$Maximize\ f = \sum_r y_{rp} u_r \tag{2-2}$$

s.t.

$$\sum_i x_{ip} v_i = 1$$

$$\sum_r y_{rj} u_r - \sum_i x_{ij} v_i \leq 0 \quad j = 1,\dots,n$$

$$\begin{array}{l} r = 1,\dots,s \\ i = 1,\dots,m \end{array} \quad u_r, v_i \geq 0$$

Where *u* and *v* are weights with respect to each output and input respectively. From another point of view, we can obtain DEA models such as CCR from some economic postulates. Banker and Thrall (1992) presented the five postulates of DEA (axioms) as follows:

Consider *X* as the input vector and *Y* as the output vector of a firm. If *Y= f(X),* showing the maximal amount of the outputs that can be produced with the inputs given, the production possibility set can be defined as $P(x) = \{(X, Y) \,/ Y \leq f(X)\} he$ where *f* is defined as the Production Function.

Postulate 1 (Convexity): *If* (*X'*, *Y'*) $\in P(x)$ *and* (X", *Y"*) $\in$*T, then for any scalar* $\theta \in [0,1]$, ($\theta X'$+(1-θ)X'', $\theta Y'$+(1-θ)Y'') $\in P(x)$.

Postulate 2 (Monotonicity): (a) *and* $X' \geq X$, *then* (*X'*, *Y*) $\in P(x)$.

(b) *If* (*X*, *Y*) $\in$*T and* $Y' \leq Y$, *then* (*X*, *Y'*) $\in P(x)$.

Postulate 3 (Ray unboundedness): *If* (*X*, *Y*) $\in$ *T then* (*kX*, *kY*) $\in P(x)$, *for* $k \geq 0$.

Postulate 4 (Inclusion): *The observed* $(X_j, Y_j) \in P(x)$ *for all DMUs j = 1,..., n.*

Postulate 5 (Minimum extrapolation): *If a production possibility set* $P_1(x)$ *satisfies Postulates 1, 2, 3 and 4 above, then* $P_1(x) \subseteq P(x)$.

Using the well-known Pareto optimality theorem, these postulates can be converted to a mathematical programming model, and eventually a CCR model.

Heretofore, people have introduced different DEA models and approaches for different purposes. As mentioned earlier, one can find many papers on DEA theories, models, and applications. A number of these articles have been cited in DEA bibliographies(Emrouznejad et al., 2008; Hatami-Marbini et al., 2011). As already maintained in Section 1.1, DEA suffers from a problem called 'homogeneity assumption pitfall'. In Section 2.18, the possible ways to tackle this problem will be discussed but the approaches to include undesirable factors will be introduced in Section 2.8.

Now we go through the literature concerning DEA models and approaches applied in the present study.

2.8. Different Approaches toward Incorporating Undesirable Outputs and Measuring Eco-efficiency

Using DEA, people have introduced and deployed different approaches to integrate undesirable outputs. As it was already elaborated upon in Section 2.4.2, bad or undesirable outputs are the ones which drop when efficiency increases. Therefore, they cannot be treated as normal outputs. Here, a number of models which have been deployed to include such outputs in efficiency measurement studies will be briefly discussed.

Scheel (2001) categorized the aforementioned models into direct and indirect ones.

Indirect models are those which change or customize undesirable factors so that they can be included in the model. However, the direct ones treat the undesirable factors as they are. When adopting indirect approaches, we can count and use the additive inverse of undesirable factors (Berg et al., 1992), use undesirable outputs as inputs (Tyteca, 1997a) and adopt multiplicative inverse (Lovell et al., 1995) and some other approaches. From among the direct approaches, the more popular ones are as follows: Hyperbolic Efficiency model (Boyd and McClelland, 1999), Slack-Based Measure (SBM) model (Tone, 2001), Range Adjusted Measure (RAM) model (Zhou et al., 2006) and the most popular of all, the Directional Distance Function (DDF) model (Chung et al., 1997). This approach has found many applications in eco-efficiency measurement studies (Färe and Grosskopf, 2010a; Färe et al., 2007; Picazo-Tadeo et al., 2005). What has been important for many is the relationship between national and international environmental rules, regulation and protocols and the eco-efficiency of industries (Macpherson et al., 2010; Picazo-Tadeo et al., 2005). Yet, many studies are required to determine the true nature and specifications of this relationship, which is of course so critical for policy makers. In the following section, the focus is moved onto the DDF.

2.9. Directional Distance Function

Based on the Malmquist Index approach to efficiency and technology change, Chung et al. (1997) developed the Malmquist-Luenberger Index (MLI). The MLI incorporates undesirable outputs, to evaluate productivity change when a longitudinal study is conducted. In the same manner as Malmquist Index which is calculated using a series of DEA models (Färe et al., 1994); the MLI deploys Directional Distance Function to solve the four linear problems. These LPs calculate distance functions to identify changes in technology and productivity during the period of study.

Using Shephard, Gale, and Kuhn's (1970) definition of distance function incorporating undesirable outputs as below:

$$D_o(x, y, z)=inf\{\varphi: ((y,z)/\varphi) \in P(x)\} \tag{2-3}$$

where $x \in \mathrm{P}^I$, $y \in \mathrm{P}^J$ and $z \in \mathrm{P}^K$ are inputs, outputs and bad outputs of Decision Making Units (DMUs), φ denotes the expansion or contraction proportion of good and bad outputs, and D_o expands them simultaneously as much as feasible. $P(x)$, production possibility set, is defined as:

$$P(x) = \{(y,z): x\ can\ produce\ (y,z)\} \tag{2-4}$$

However, Chung, et al. (1997) define D_o as:

$$D(x, y, z;g)=sup\{\theta: (y,z) + \theta g \in P(x)\} \tag{2-5}$$

Where θ plays the same role as φ in (2-3). Here if g is the vector of directions and is defined as $g=(y,-z)$, using this $D,$ the outputs can be expanded while bad outputs are contracted. Thus, the weak disposability implies:

$$(y, z) \in P(x)\ and\ 0 \leq \theta \leq 1\ imply\ (\theta y, \theta z) \in P(x) \tag{2-6}$$

This means that in order to remain feasible, good outputs should be decreased in the same proportion as bad outputs should. Free disposability is also written as below:

$$(y, z) \in P(x)\ and\ y' \leq y\ imply\ (y', z) \in P(x) \tag{2-7}$$

This also implies that good and bad outputs are freely disposable. In addition, it is also assumed that good and bad outputs are produced jointly; that is, "null-joint". This means that it is not possible to produce good output without producing any bad output. Now, according to Chung, et al. (1997), $P(x)$ can be rewritten as below to be compatible with

(2-4), (2-5), (2-6), and (2-7):

$$P(x) = \{(y, z): \sum_{n=1}^{N} \lambda_n x_{in} \leq x_{io} i = 1,2, \dots, I; \sum_{n=1}^{N} v_n y_{jn} \geq y_{jo} + \theta y_{jo} j = 1,2, \dots, J; \sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \theta z_{ko} k = 1,2, \dots, K; \lambda_n \geq 0 \, ; n = 1,2, \dots, N\} \qquad (2\text{-}8)$$

where $\lambda_n$are intensity variables. Now, using (2-8) a linear programming model to find *D(x, y, b;g)*, *g*=(*y*,-*z*) is written as below:

$$D_o(x, y, z; g) = Max\ \theta \qquad (2\text{-}9)$$

Subject to

$$\sum_{n=1}^{N} \lambda_n x_{in} \leq x_{io} \, ; i = 1,2, \dots, I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo} + \theta y_{jo} \, ; j = 1,2, \dots, J$$

$$\sum_{n=1}^{N} \lambda_n b_{kn} = z_{ko} - \theta z_{ko} \, ; k = 1,2, \dots, K$$

$$\lambda_n \geq 0 \, ; n = 1,2, \dots, N$$

Here the efficiency score can be calculated by 1-*D*

2.10. Slack-Based Measure of Efficiency

Thus far, a number of models have been introduced to measure the distance function. The slack-based measure of efficiency, calculated by DEA, is one the models which was introduced by Tone (2001). A super efficiency model was introduced by Tone (2002) as well. This approach has also been implemented to measure the environmental performance of 30 OECD countries (Zhou et al., 2006)The slack-based measure and its variations were employed to measure productivity factors in many fields reported by Tone (2010). One of the latest models of this family which was recently introduced by Färe and Grosskopf (2010a; 2010b) is presented in the following:

$$D_o(x, y) = Max \sum_{i=1}^{I} \alpha_i + \sum_{j=1}^{J} \beta_j \qquad (2\text{-}10)$$

$$st$$

$$\sum_{n=1}^{N} \lambda_n x_{in} \leq x_{io} - \alpha_i .1; i = 1,2,\ldots,I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo} + \beta_j .1; j = 1,2,\ldots,J$$

$$\lambda_n \geq 0 \ ; \ \beta_j \geq 0; \ \alpha_i \geq 0; \ n = 1,2,\ldots,N; \ I = 1,2,\ldots,J$$

where, $\alpha_1,\ldots,\alpha_I$ and $\beta_1,\ldots,\beta_J$ are slack variables. Later in Section 3.4, having incorporating bad outputs into Model (2-10), we will show how this model is equivalent to a DDF model, and how it helps solve a serious infeasibility problem with directional distance models. In addition, in model (2-10) efficiency score can be calculated by $1 - D_o$

In the following section, a meta-frontier approach which is an approach to handle heterogeneity amongst DMU's is presented.

2.11. Meta Frontier

Although meta-frontier was presented by Hayami and Ruttan (1971, p. 82) as: ''The meta-production function can be regarded as the envelope of commonly conceived neoclassical production functions'', it was Meeusen and van Den Broeck (1977) who introduced a stochastic meta-frontier model as one the first and foremost applications. Furthermore, (Battese and Rao, 2002) employed the concept of stochastic meta-frontier for the first time along with providing a comprehensive literature review. As a comparative study, Battese, Rao, and O'Donnell (2004) presented a linear programming model for meta-frontier and successfully applied it to analyze the technical inefficiency effects of garment firms in different areas of Indonesia over a six-year period (1990-1995). Pastor and Lovell

(2005) for the first time employed the meta-frontier and distance functions together. They implemented the new approach to measure MI and developed a number of related factors based on the concept of distance function. Recently Oh and Lee (2010) introduced a new Malmquist meta-frontier approach to depict the productivity and technology gap changes of 58 countries in different continents over a period of 31 years (1970-2000). Oh (2010b) replicated the aforementioned study incorporating undesirable environmental factors; the approach was named Malmquist-Luenberger Meta-frontier.

In Section3.5, we have proposed a new slack-based measure for Malmquist-Luenberger meta-frontier approach and its decomposition for eco-efficiency measurement purposes.

In the next section, a brief literature on the Malmquist and Malmquist-Luenberger indices is presented.

2.12. Malmquist and Malmquist-Luenberger Indices

The Malmquist Index was first introduced by Malmquist (1953). He defined the index as below:

$$M^{t+1} = \frac{D_o^{t+1}(x^{t+1},y^{t+1})}{D_o^{t+1}(x^t,y^t)} \qquad (2\text{-}11)$$

Where *t* denotes time periods and *D* is the distance function which is defined as follows:

$$D_o^t(x^t, y^t) = \inf\left\{\theta : x^t, \frac{y^t}{\theta} \in P^t(x)\right\} = (\sup\{\theta : (x^t, \theta y^t) \epsilon P^t(x)\})^{-1} \qquad (2\text{-}12)$$

where $P^t(x)$ is the production possibility set.

According to Chung et al. (1997), the ML Index can be calculated as follows:

$$MLEFFCH_t^{t+1} = \frac{\left(1+D_o^t(x^t,y^t,z^t;y^t,-z^t)\right)}{(1+D_o^{t+1}(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})} \qquad (2\text{-}13)$$

$$MLTECH_t^{t+1} = \left[\frac{\left((1+D_o^{t+1}(x^t,y^t,z^t;y^t,-z^t)\right)}{\left((1+D_o^t(x^t,y^t,z^t;y^t,-z^t)\right)}\frac{\left((1+D_o^{t+1}(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})\right)}{\left(1+D_o^t(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})\right)}\right]^{1/2} \quad (2\text{-}14)$$

$$ML_t^{t+1} = MECOEFFCH_t^{t+1}.MTECH_t^{t+1} \quad (2\text{-}15)$$

$$ML_t^{t+1} = \left[\frac{\left((1+D_o^t(x^t,y^t,z^t;y^t,-z^t)\right)}{\left((1+D_o^{t+1}(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})\right)}\frac{\left((1+D_o^{t+1}(x^t,y^t,z^t;y^t,-z^t)\right)}{\left(1+D_o^t(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})\right)}\right]^{1/2} \quad (2\text{-}16)$$

where *t=1..T* denotes the periods of study. Phrasing in words, $D_o^{t+1}(x^t, y^t, z^t; y^t, -z^t)$, for example, represents the distance function for a DMU from period *t* in respect to technology in period *t+1*. Therefore, the LP's corresponding to $D_o^{t+1}(x^t, y^t, z^t; y^t, -z^t)$ and $D_o^t(x^{t+1}, y^{t+1}, z^{t+1}; y^{t+1}, -z^{t+1})$ are called 'mixed period models' since the DMU's under evaluation and the frontier are from the two subsequent periods.

In the following section, Materials Balanced Principle which is recently included in DEA literature by incorporating bad outputs into the models is going to be briefly explained.

2.13. Materials Balanced Principle

According to the first law of thermodynamics, matter can neither be created nor destroyed; for the first time Ayres and Kneese (1969) added this concept to the glossary of economics. However, due to the complicated operational problems involved in the research at that time, the factors and process combinations which allow for curbing a high level of emissions only by a small increase in cost could not be clearly characterized. Nevertheless, the operational approach is far less complex today.

Ecological system includes the economic and social systems which comprise production and consumption (Van der Hamsvoort and Latacz-Lohmann, 1998) or a natural environment determined by materials and energy flows including extraction, use, recycling and waste disposal (Field, 1994). The conservation of matter/energy law is an essential biophysical condition expressing that flows from and into the environment are equivalent or balanced(Field and Olewiler, 2005; Field, 1994). Hence, the fundamental concept of material balance condition essentially states that: "what goes in must come out". Applying linear programming models, (Tyteca, 1997a) described standardised, aggregated performance indicators for firms which are adjusted for pollution and used in the frontier eco-efficiency models. Two different frontier-based eco-efficiency models were presented by. First, the usual parametric (e.g. Stochastic Frontier Analysis) and nonparametric (e.g. Data Envelopment Analysis) frontier efficiency models were adjusted for pollution. The next model called 'the Normalised Undesirable Output Approach' in which the relations between the ecological outcomes with respect to the economic outcomes explained regardless of conventional inputs and desirable outputs. Lauwers (2009) called these two types of models the 'Environmentally adjusted Production Efficiency (EAPE) models and the 'Frontier Eco-Efficiency' (FEE) models. Based on some earlier empirical work by of Lauwers et al. (1999) on the nutrient balance in pig production, Coelli et al. (2007) worked out the theoretical and methodological aspects of the MBP incorporation.

Besides the usual technical efficiency and economic efficiency scores, Lauwers et al. (1999) made use of an analogy with the cost-minimizing models to calculate environmental efficiency scores from which allocative components could be derived. The material flow information was used in the same way as price information was.

As before, as a result of emerging concerns about the detrimental effects of humankind activities, a new approach toward incorporating undesirable outputs of production processes into the performance measurement methods came into focus for research. Whilst any performance measurement models should be compatible with the production technology and environmental outcomes, it is equally important for these models to be consistent with the material flow in the real system as well (Lauwers, 2009). However, according to Lauwers (2009), MBP has been neglected in the majority of previous studies and there is a need to fill this gap and thereby enhance the accuracy of the eco-efficiency measurement models. Lauwers, in 2009, proposed a frontier eco-efficiency modelling via incorporation of the Material Balance Principle (MBP) in a way that the environmental outcome derived from the production process is similar to the economic outcome. The diagnostic power of eco-efficiency measurement is improved by comparing the economic and environmental outcomes of the same technology.

Materials Balance Principle is considered a linear relationship between inputs consumed and outcomes produced. Since mass cannot be destroyed in the production process, summation of the input nutrients, for example energy or emission that can be generated from, should be equal to summation of the outcomes, including both good ones and bad ones. Murty et al. (2012) opined that linearity is not a necessity and accordingly they introduce a non-linear modeling for pollution generating technologies. Although there are some criticisms against the linear relationship, it sheds some light on the trade-offs between economic and environmental characteristics of conventional models. Nevertheless, these criticisms do not pose a challenge to the linearity of MBP formulation since it reduces the complexity of the non-linear relationship between economic and environmental aspects of the system and makes it possible to model and apply them (Lauwers, 2009).

In addition to non-linear pollution generating modeling, Murty et al. (2012) and Pethig (2006) modeled the abatement technologies incorporating materials balance conditions. Furthermore, Färe et al. (2011) applying a network approach, successfully formulated the abatement technology used in coal-fired power plants taking MBP conditions into consideration. Moreover, (Coelli et al., 2007)formulated the abatement technologies in an MBP-enabled DEA approach.

After a comprehensive literature review on the evolution of MBP in his paper, Lauwers (2009) discussed the diagnostic power and allocative aspects of MPB which are also ignored in the conventional eco-efficiency measurement methods (Coelli et al., 2007) have also introduced a workable method to analyze the economic-environmental trade-offs of a pollution generating system. In line with this, using the approach adopted by (Coelli et al., 2007)to include input and output emission coefficients, Lauwers (2009) maintains that social costs of pollution generating firms can be evaluated and minimized. The MBP-adjusted method, compared with the eco-efficiency frontier model, takes advantage of considering the underlying production technology and simultaneously explains its economic and ecological outcomes in an unbiased and clear manner. Hence, the gap between conventional concepts of production efficiency and eco-efficiency is bridged by using the MBP-adjusted method (Lauwers, 2009).

In summary, it is necessary for every eco-efficiency measurement tool to be compatible with MBP requirements; otherwise a bold argument remains unanswered in any study; that is, whether the production technology employed is compatible with the nature of the industry or not. In this study our focus is on non-parametric frontier DEA methods. We consider merits and flaws of the conventional methods and introduce an MBP-enabled DEA model. Next, a review of the related DEA literature is given in the following section.

2.14. Power Industry Restructuring and Its Implications for Efficiency and Eco-efficiency of Power Generation Facilities

Iran started a reform in its power in early 1990’s by some preliminary studies (Ghazizadeh et al., 2007; Khosroshahi et al., 2009). A new interpretation of the 44th Article of the Islamic Republic of Iran’s Constitution paved the way for the power industry to establish the Iranian Grid Management Company (IGMC) in 2003 to allow for private sector investment in new power generation facilities[1], privatization of 10% of the current generation capacity each year, and restructuring of Tavanir, Iran's specialized holding company for power generation, transmission and distribution management.

Similar to what was done in other countries, vertical integration of generation, transmission, distribution and retailing utilities was broken down in three steps: financial separation by separation of accounting systems, establishment of every utility as an independent legal entity (except for the transmission sector which is a natural monopoly and must remain in the government's ownership according to the new interpretation of Article 44 of the Islamic Republic of Iran's Constitution), and IGMC providing all market participants with open access to the national grid (Ghazizadeh et al., 2007). By taking these three steps, according to (Ghazizadeh et al., 2007), the two following objectives were pursued by the leaders and planners of the electricity sector restructuring:

1. "It is expected that the restructuring and consequently privatization improve the performance and efficiency of the present industry";
2. "It is expected that the development of a new competitive paradigm in the electricity industry could make the sector more attractive for potential independent investors."

The power market was inaugurated on 23 October 2003 to promote the competition; firstly, for the power plants to sell their energy to IGMC; secondly, for the distribution companies to purchase their demanded energy under a pay-as-bid regime. Preliminary studies for establishment of an electricity stock market are also being conducted by the

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[1] Third program law for economic, social, and cultural development of the Islamic Republic of Iran, Paragraph b of Article 122-1998

power market regulatory board. By capacity payment policy, power plants are encouraged to keep their available capacity at a maximum level and keep a reasonable reserve margin of the national grid. These are all supported by the “executive bylaw of guaranteed electricity purchase mechanism and conditions”, subject of the Clause "b" of Article (25), of the Fourth, validated by the Fifth, Economic, Social and Cultural Development Plan Act of the Islamic Republic of Iran”. By Article 9 of the same bylaw, to encourage consumption of a cleaner and cheaper fuel, (natural) gas was determined as the major fuel for thermal power plants, and marginal price difference of gas and the second fuel was decided to be paid back if they happened to have no choice but to consume liquid fuels.

According to Article 10 of the same bylaw, green electricity generation is also supported by payments for nonpolluting and as equivalent to fuel that has not been combusted to generate the same amount of energy as a thermal power plant with national grid average of the Yield Factor. To support green electricity, “Executive Bylaw for Guaranteed Wholesale Electricity Mechanisms and Conditions in the Iranian National Grid” also mandates IGMC to buy the electricity generated by renewable energy power plants, whenever they happen to be ready or have to generate electricity. This happens, for example, when a hydro power plant has to open the sluice to irrigate its downstream[1].

These are not the only rules and regulations related to power industry restructuring. Since 23rd October 2003, power market’s official inauguration date, the power market regulatory board has ratified many procedures and instructions to conduct the process of the reform. A number of these acts which determine the formulas for calculation of the

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[1] The conditions and mechanisms have been stipulated in Article 6-6 of the same bylaw.

awards and charges will be addressed later in Chapter 3.

2.15. Power Industry and Environmental Concerns in Iran

Like the majority of the developing countries, Iran should pay more attention to the environmental issues. As a result of industrial development, exploitation of natural resources increases and the environment is exposed to more pollutants. Thus, if a developing country does not prevent, occurrence of natural crises, the environment will be unavoidably endangered thereafter. According to *Initial National Communication* to UNFCC 2010, the energy industries in Iran account for a noticeable share of CO_2 emissions, amounting to 33% in 2007. According to the country's energy balance sheet in annual reports, power generation sector has produced 192733 tons of SO_2 in 2005 and this amount has increased to 497354 in 2009. This is while the contribution of power plants to SO_2 production amongst all energy industries has increased from 23.01% to 36.68% during the same years[1]. Moreover, the emission rate for each kWh of electricity generated is demonstrated in the following graph:

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[1] Iran's Energy Balance Sheet Annual Reports, 2005 and 2009

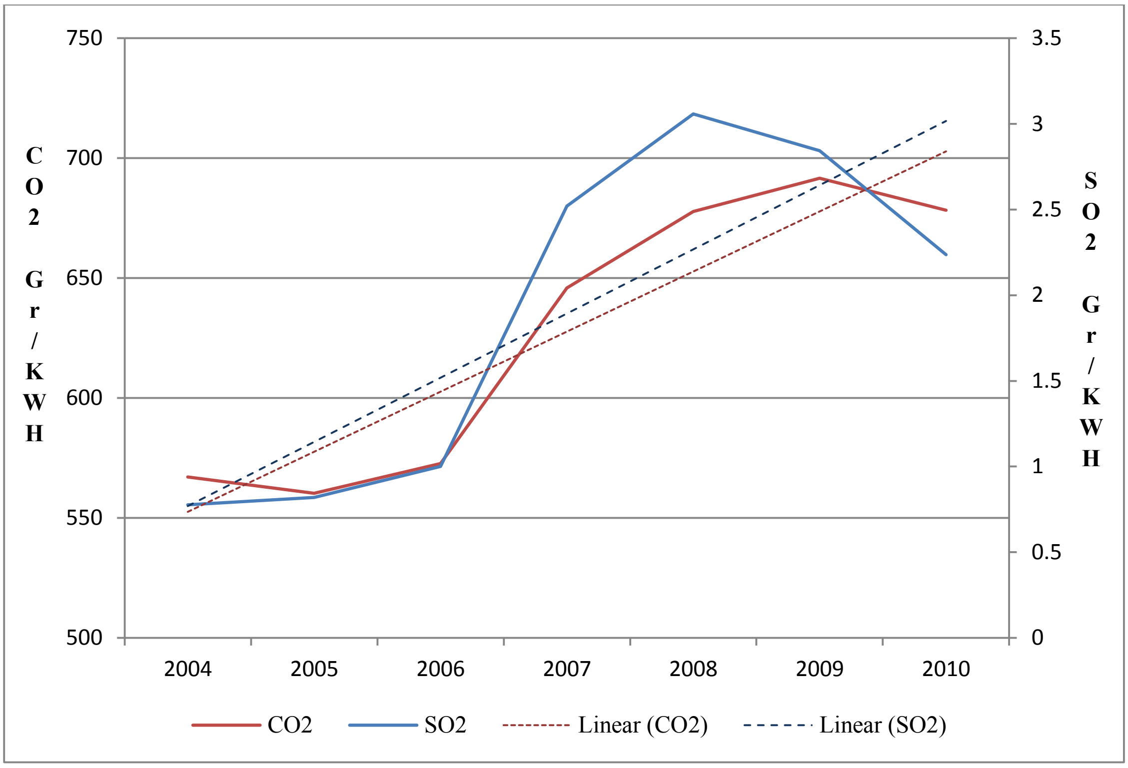

Figure 2-1: Gr/kWh SO2 and CO2 Produced by the Iranian Power Plants, 2004-2010

As observed in Figure 2-1, although the amount of SO2 per kWh of generated electricity declined in the last two years and CO_2 per kWh of generated electricity decreased slightly in 2010, the trend lines still show a steep slope. A similar trend can be observed for the other types of emissions such as CO and NO_x.

Mazandarani et al. (2011) showed from another perspective that the emission by power generation industry would have been controlled by 2025 through promotion of green electricity technologies. In their study, Mazandarani et al. (2011) predicted by constructing three scenarios that although power generation installed capacity would be increased by 215.75% from 2010 to 2025, the emission would grow 149.83%, 226.08%, and 174.81%[1] respectively in each of the three scenarios.

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[1] Scenario 1, power plant composition in the future, forecast based on the government policies to develop different types of power plant, so in this scenario, the nominal capacities of different compositions of types of power plants

To ensure that emission of pollutants is curbed natural resources are consumed optimally, There are a number of other environment protection laws and regulations in addition to the laws and regulations cited already. First, Article 15 of the Air Pollution Prevention Act[1] can be referred to, which determines the maximum allowed amount of emission to be produced by all polluting industries, including power plants. Then, the Articles 104, 121 and 134 of the Third Five-year Economic, Social, and Cultural Development Plan Act of the Islamic Republic of Iran, (2000), validated and extended to the Fourth and Fifth National Development Plan (2004 and 2009) can be mentioned, which emphatically mandate reduction of fuel consumption and emissions by all means. As a result of this article, executive bylaws for paragraph "c" of Article 104 and article 134 of the law of third plan of economic, social and cultural development of Iran ratified by Department of the Environment (October 2001). In the instructions attached to this executive bylaw, the mechanism for calculation of charges to be imposed on the industrial units which exceed the allowed emission amount has been stipulated.

In short, Iran has ratified a number of laws and regulations to mandate power generation facilities to be greener in their production. Nevertheless, it is necessary to conduct studies like the present study to decide whether or not these legal efforts have been successful. In so doing, the methodology of this research is going to be elaborated in the next section.

In Section 2.16, a brief history of power plant efficiency measurement is going to be reported.

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would be different from now. Scenario 2, old composition, has been designed to address future development based on current composition of different types of power plant in terms of nominal capacity, so emission increase rate will be the same as nominal capacity growth rate. Scenario 3, fuel switching, which predicts the trend of using the new policies for using alternative fuels for power plants.

[1] Air Pollution Prevention Act, for emission standards of factories and workshops passed in the year 2003.

2.16. Power Plants Efficiency and Eco-efficiency Measurement

In this industrial age, everyone is aware of the critical role of electricity as a public service or public goods (Nathan, 1998; Shahbaz et al., 2006; Yoo, 2006). Electricity as a public service has three different sectors: generation, transmission and distribution. In this research, generation and power plants are our point of interest.

2.16.1. Power Plant Prior Efficiency/Eco-efficiency Evaluation Experiences

Power plants performance evaluation has various aspects. Chatzimouratidis and Pilavachi (2009) believe that there are a large number of important factors for performance measurement of power plants which. This makes it so complicated to determine and weight them from different perspectives. They also express that, apart from technical factors, economic, socioeconomic, and political factors have also a great impact on power plants performance evaluation. The bodies of research by Chatzimouratidis and Pilavachi (2008), Hubbard (1991), Paehlke (1996) and many other studies support this view. Thus, it seems necessary to find a way to deal with all factors at once. However, it is obviously difficult to incorporate a large number of important indices in the process of decision making. Hence, there has always been willingness for integration, and MODM, MCDM, or MADM[1] have always been a solution.

A very simple measure for power plant performance is the Yield Factor, which is ‘the ratio of energy produced to energy consumed’ (Hayman et al., 2008). The definition seems to be simple, but it is very hard to evaluate accurately. As one of the main factors of performance, it is still evaluated by researchers in different projects (Ravelli et al., 2008; Schaefer and Hagedorn, 1992; Tan et al., 2009). However, this ratio has not been

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[1] Multiple Objective, Criteria and Attribute Decision Making respectively

the only factor in power plant performance evaluation. Analytical Hierarchy Process - AHP - (Chen, 2009; Kaya and Kahraman, 2011; Xu et al., 2011), SFA (Chang et al., 2009; Iglesias et al., 2010; Rubin et al., 2005), TOPSIS (Garg et al., 2007; Montanari, 2004), Principal Component Analysis - PCA - (Azadeh et al., 2007b; Azadeh et al., 2008), Neural Networks (Azadeh et al., 2011; Kesgin, 2004) and many other methods and systems have been employed to evaluate power plant performance. Nevertheless, amongst all the above-cited methods, DEA has gained a considerable popularity.

2.16.2. Power Plant Efficiency/Eco-efficiency Measurement, Using DEA

One of the earliest bodies of research, in which DEA was chosen as the main methodology for evaluation of the efficiency of power plants was a project undertaken by Golany, Roll and Rybak (1994). Thereafter, using the valuable outcomes and indices in the research by Golany et al, DEA models were deployed to evaluate relative power plant efficiencies across different countries (Athanassopoulos et al., 1999; Chitkara, 1999; Goto and Tsutsui, 1998; Jha and Shrestha, 2006; Sarica and Or, 2007). There can be also found a number of other studies on power plant eco-efficiency measurement in the literature (Korhonen and Luptacik, 2004; Sueyoshi and Goto, 2011; Yang and Pollitt, 2009, 2010).

However, in the last decades, for all monitoring or surveillance bodies in different countries which have been in charge of providing proper reports for decision making authorities such as ministries and energy or power market regulators, drawing comparisons between power plant of different types and of heterogeneous natures has always been a barrier to providing satisfactory reports to submit to decision makers, (Korhonen and Luptacik, 2004; Walls et al., 2007). This type of analysis is critical for power industries due to the importance of budgeting and resource allocation for short, mid and long term planning. In like manner, using the same yardstick in efficiency measurement has always been critical for regulatory authorities in all power industries.

2.16.3. Input/Output Factors for Power Plants Eco-efficiency Measurement

Further to presentation of a number of power plant efficiency and eco-efficiency measurement studies in the previous section, a table containing the inputs and outputs related to those studies is given and analyzed in this section.

As it can be seen in Table 2-2, the installed capacity of a power plant has been used a proxy of the capital in the majority of studies as. The other problem which can be observed is the natural heterogeneity of the power plants that has always enforced researchers to categorize them prior to evaluation and measurement. Heretofore, one can find a number of researches in which efforts have been oriented toward overcoming the natural heterogeneity in power plant performance measurement systems (Cook et al., 1998; Walls et al., 2007).

At any rate, researchers have dealt with these limitations to measure the efficiency of the power plants in different countries, while considering the specific conditions of each case. In this vein, however, it would be safe to treat Iran’s case as a special one.

Table 2-2: A Brief Summary of Inputs and Outputs Incorporated in Efficiency/Eco-efficiency Evaluation of Power Plants Using DEA

No	Title	Author/s	Year	Inputs	Outputs
1.	Measuring efficiency of power plants in Israel by data envelopment analysis	Golany, B. Roll, Y. Rybak, D.	(1994)	1. Installed Capacity 2. Fuel Consumption 3. Man Power	Undesirable: 1. SO_2 emission 2. Deviation from operational parameters Desirable: 1. Generated Energy 2. Operational availability
2.	Comparison of productive and cost efficiencies among Japanese and US electric utilities	Goto, M. Tsutsui, M.	(1998)	1.Nameplate generation capacity 2.quantity of fuel used 3.total number of employees 4. quantity of power purchase	Desirable: 1. quantity sold to residential customers 2. quantity sold to non-residential (commercial, industrial, others, and wholesale) customers
3.	Data envelopment scenario analysis for setting targets to electricity generating plants	Athanassopoulos, A.D. Lambroukos, N. Seiford, L.	(1999)	1. Fuel 2. Controllable Costs 3. Capital Expenditure	Undesirable: 1.Generated pollution 2. Accidents Incurred Desirable: 1. Electricity Produced 2. Plant availability

No	Title	Author/s	Year	Inputs	Outputs
4.	Eco-efficiency analysis of power plants: An extension of data envelopment analysis	Korhonen, Pekka J. Luptacik, Mikulas	(2004)	Total costs	Undesirable: DUST, NOx and SO_2 Desirable: electricity generation
5.	Characteristics of a polluting technology: Theory and practice	Färe, R., Grosskopf, Sh. Noh, D-W, Weber, W.	(2005)	1. Labour 2. Installed capacity 3. Fuel	Undesirable: 1. SO_2 emission Desirable: 1. Generated Energy
6.	Efficiency assessment of Turkish power plants using data envelopment analysis	Sarica, K. Or, I.	(2007)	For Thermal Power Plants 1.fuel cost 2.production For renewable Power Plants 1.Operating costs	Thermal Power Plants Undesirable: 1. environmental cost 2.Carbon monoxide (CO) Desirable: 1. availability 2. Thermal efficiency Renewable Power Plants 1. production 2. utilization
7.	Eco-efficiency: Defining a role for environmental cost management	Burnett, R. D. Hansen, D. R.	(2008)	1. Capital 2. Fuel costs 3. Operating costs	Undesirable: 1. SO_2 emission Desirable: 1. Generated power

No	Title	Author/s	Year	Inputs	Outputs
8.	Measuring efficiency and productivity change in power electric generation management companies by using data envelopment analysis: A case study	Fallahi A., Ebrahimi R., Ghaderi S. F.	(2011)	1. Installed Capacity 2. Fuel Consumption 3. Labour 4. Electricity used 5. Average operational time	Desirable: 1. Net electricity produced
9.	DEA approach for unified efficiency measurement: Assessment of Japanese fossil fuel power generation	Sueyoshi,T. Goto, M.	(2011)	1. Generation capacity 2. Number of employees 3. Coal 4. Oil 1. LNG	Undesirable: 1. CO_2 emission Desirable: 1. Generation
10.	Operational and non-operational performance evaluation of thermal power plants in Iran: A game theory approach	Jahangoshai Rezaee M., Moini A, Makui A.	(2012)	Operational inputs 1. Generation capacity 2. Total hours of operation 3. Internal consuming 4. Fuel consumption Non-operational inputs 1. No. Nonoperational employees 2. No. Operational employees 3. Cost of Generated Energy 4. Total cost of training	1. Total revenue 2. Total amount of electricity generated 3. CO_2 emission

When paying close attention to on the data given in Table 2-2, one notices that in the majority of researches, either the installed capacity has been incorporated as a proxy for capital or the capital has not been incorporated at all. In Section 2.18, this issue is going to be elaborated upon.

2.16.4. Power Plant Efficiency Evaluation in Iran

A decade ago, the Iranian Ministry of Energy began to restructure the country's power industry, breaking up the vertical integration of generation, transmission and distribution, deregulating, establishing a wholesale power market and privatizing generation and distribution and having researchers measure the important power industry factors before, during and after the implementation of each restructuring module. Of course, ower generation and power plants have always been the first and foremost components of the power sector to be evaluated and measured in terms of efficienty.

In Iran, as in other countries, in the early stages of evaluation it was just the 'yield factor' used as the main performance measure to fulfill the common instructions of turbine producers and the requirements of the government for preparation of the reports and receive the budgets for operation, maintenance and development. These types of reports are prepared for every turbine in power plants individually and are based on the technical measures available in the operation and maintenance manuals. However, the academic researches on the power plant performance measurement were being conducted concurrently. Unfortunately, the majority of the practical and scientific articles on these endeavors have been written in Farsi, like what Alirezaee et al presented for evaluation of technical efficiency in hydro, gas, and steam power plants in 1996[1] and performance

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[1] http://www.ensani.ir/fa/content/16533/default.aspx

evaluation of thermal power plans by Khameneh A. and Javaheri Z. in 2007[1]. As it can be seen in the majority of the researches of this kind, the term 'Performance Evaluation' has been taken as 'Efficiency Evaluation' carried out almost entirely through DEA method.

In the meantime, one can find a number of researches in the scientific databases which have been conducted on the efficiency evaluation of power plants in Iran. Azadeh et.al (2007a) assessed the power generation system in IRAN using Neural Network and PCA techniques. Elsewhere, Alirezaee (2005) conducted an experiment using a partition based algorithm. Azadeh et.al presented other experiments on power plant performance evaluation using DEA (2008; 2009).

Referring to our previous discussion about the homogeneity assumption pitfall, the researchers reported above suffer from power plant heterogeneity conditions, and the researchers had to deal with this pitfall in some practical manners.

The researcher, organized as the staff of the Secretariat of the Iranian Power Market Regulatory Board and having worked for the Market Monitoring Unit for two years, directed the Surveillance and Licensing Department in the Iranian Ministry of Energy, has faced a need for power plants efficiency evaluation, not be carried out in a categorized manner, but all as one group. This provides an opportunity for officials to allocate the resources in a fair and productive manner.

Finally, significant efforts were made to introduce and implement rules and regulations to controls power generation emissions. It could be concluded that eco-efficiency would

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[1] http://www.civilica.com/Paper-POWERPLANT01-POWERPLANT01_005.html

be one of the most important factors used for evaluation of the Iranian power generation sector.

Before dealing with the main gaps in the research, it is necessary to concentrate on the Malaysian context and see what similar researches are there in this field.

2.17. Previous Related Researches in Malaysia

In Malaysia, there can be found numerous applications of DEA, many of which have been conducted in the banking sector (Bennett et al., 2004; Burritt et al., 2004; Gray et al., 1993; Schaltegger and Burritt, 2000). However, DEA has shown its popularity in other contexts in Malaysia such as electricity distribution (Cormier and Magnan, 2003), road transportation system (Sumiani et al., 2007), measuring productivity growth of manufacturing industries (Cormier and Magnan, 2007), water supply system (Kim, 2004), education system (Schaltegger et al., 2009) and so on. Meanwhile, the closest one to this research is what Gurcharan[1] did for obtaining his PhD from the University of Malaya. Using DEA and a number of similar models, he measured the impacts of Malaysian Central Bank's policies, on the efficiency of different Malaysian banks during the economic crisis periods. As it will be addressed in Chapter 3, in this research, attempts will be concentrated on a longitudinal study, as done in the aforementioned research.

In the field of environmental management, Ahmed (2006), employing growth accounting methods, evaluated the Malaysian manufacturing sector's TFP, incorporating CO_2 as an input. Evaluating green productivity indicators, he found out that a growing level of CO_2 was related to industrial activities of the manufacturing sector in Malaysia during 1970 to

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[1] http://www.pendeta.um.edu.my/uhtbin/cgisirsi/bo02RvICuQ/P01UTAMA/219940067/9

2011. Halimahton and Elsadig (2010) achieved the same result, but for Carbon Monoxide (CO), Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Ozone (O_3) and Particulate Matter (PM10), during 1996 to 2006 in each quarter. They also exhibited that the economic growth had a direct impact on the increasing rate of the abovementioned emission factors in Malaysia. Ahmad also showed the impact of organic water contaminations on the Malaysian economic growth[1].

Still another body of reseach which is similar to this study is what Goh Eng, Suhaiza, and Nabsiah Abd (2006) carried out to show the relationship between ISO-14001 as an EMS certification and a firm's environmental performance in Malaysia. Through a survey, they found out that these certifications had had a positive impact on both environmental and economic performances of the firms. Of course, more similar researches in the Malaysian context can be found in the academic databases (Abdul Rani, 1995; Chua and Oh, 2011; Hezri and Hasan, 2004; Ong et al., 2011).

2.18. The Homogeneity Assumption Pitfall

Homogeneity assumption means to take the similarity of the units under evaluation for granted. However, Dyson et al. (2001) define it as a condition in DEA which limits researchers to using the same inputs and outputs in their DMU's. They also consider the environment to be non-homogeneous, and this redounds to heterogeneity in data. Heterogeneity in data can be normally tackled through using a cluster analysis (Amin et al., 2011; Po et al., 2009; Samoilenko and Osei-Bryson, 2008; S. Samoilenko and K.-M. Osei-Bryson, 2010).

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[1] http://www.econ.kobe-u.ac.jp/jepa-kansai/IC2004/paper/3%20Ahmed.pdf

The frontier approaches to efficiency evaluation such as SFA and DEA may involve the decision-making units which work in different environments; that is, their data are heterogeneous. This situation can be depicted as below:

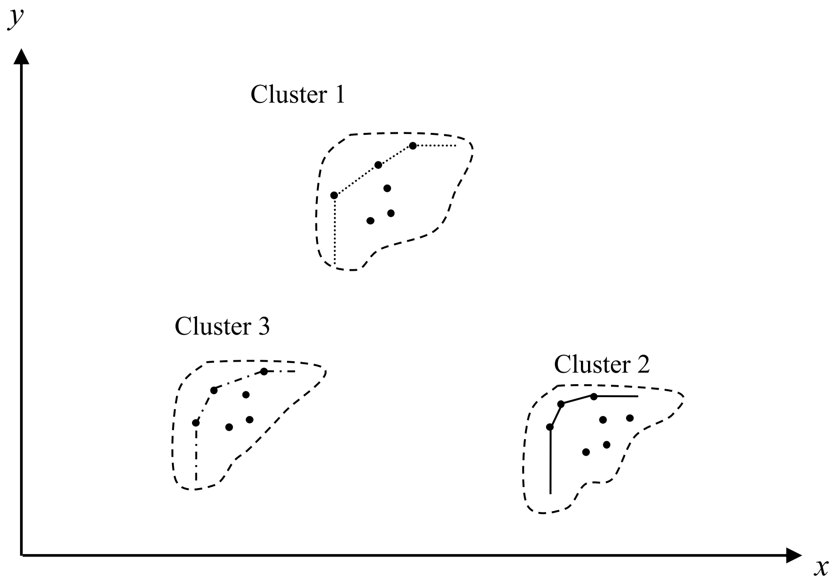

Figure 2-2: Illustration of Data Heterogeneity in DEA

In Figure 2-2, suppose we have just one input, *x*, and one output, *y* and the points show the DMU's which consume *x* to produce *y*. In these cases, the researchers have carried out a cluster analysis and defined different frontiers for each cluster (Samoilenko and Osei-Bryson, 2008). In this sample, we have used BCC model to draw each frontier (Banker, 1984). However, our case in question is far more different.

Suppose we have a set of decision-making units which produce one output, namely *y*, using one input. This is whereas a number of the units consume the input type 1, namely, x_1, and the rest of the units consume the input type 2, namely, x_2. This situation can be shown as below:

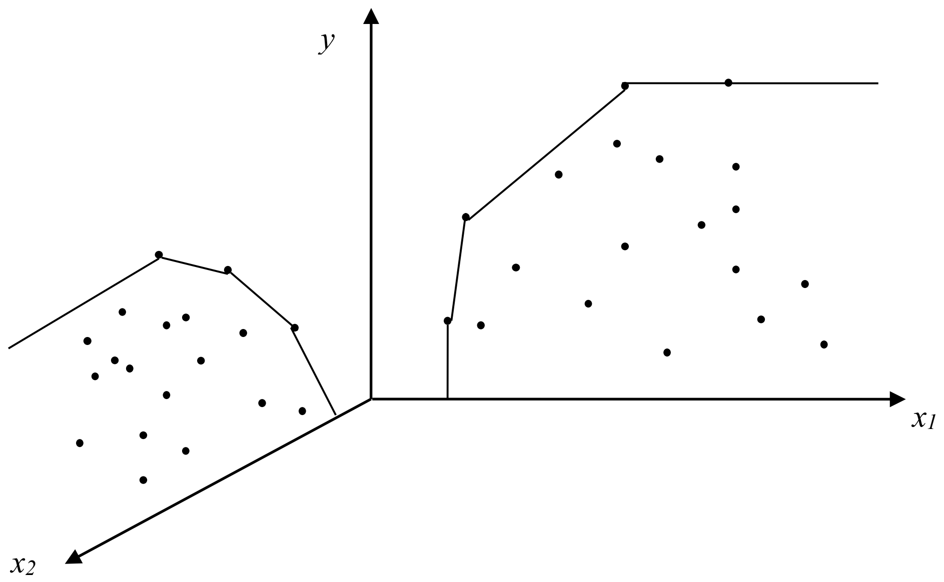

Figure 2-3: Illustration of Heterogeneous Units with a Very Simple Sample

As shown in Figure 2-3, we cannot sketch one frontier for both sets of DMU's because they are in different spaces, x_1y and x_2y planes. As already asserted, this case happens in many situations, so this is a critical problem in the real world.

2.18.1. Importance of Homogeneity Assumption Pitfall

Initiators and leaders of every newly established market, particularly a power market, pay special attention to the correct and effective performance matched to the goals. Therefore it seems so vital to design a comprehensive method that is able to assure people as the receivers of public services, leaders and government of stability and improvement of the power market. The entire task should be based on previous experiments and documentations as well as the answer to the question that "What caused the previous methods not to be successful?" Hence, this method must not only be able to deal with structural, performance indices and general behavior of the players from different points of view (such as: customer orientation, production orientation and stability), but also provide the decision makers with practical outcomes by means of effective and accurate indices.

Adopting this approach is particularly helpful when conducting research on the governmental firms as the researches will be able to handle the problems more effectively learning from the experiences of the previous cases.

As a result, upgrading DEA models with the aim of solving the Homogeneity Assumption Pitfall will help regulatory and monitoring organizations with more careful selection of the best decision making units from amongst all units - power plants, for instance – as well as accurate diagnosis of their weaknesses hence prescribing more viable solutions to them for their advancement.

2.18.2. Current Methods to Tackle the Homogeneity Assumption Pitfall

There are a number of ways to this tackle this problem.

Dyson (2001) enumerates three protocols to solve the problem, which are listed below:

- If different departments within an organization are to be capered, to find an external comparator and then compare them in terms of their standings (Sarrico and Dyson, 2000);
- To cluster the units in homogeneous groups and determine the efficiency within the clusters(Athanassopoulos and Thanassoulis, 1995) or to find a/the meta-frontier after clustering, like what Battese, Rao and O'Donnell (2004, p. 93) did and depicted in the following figure:

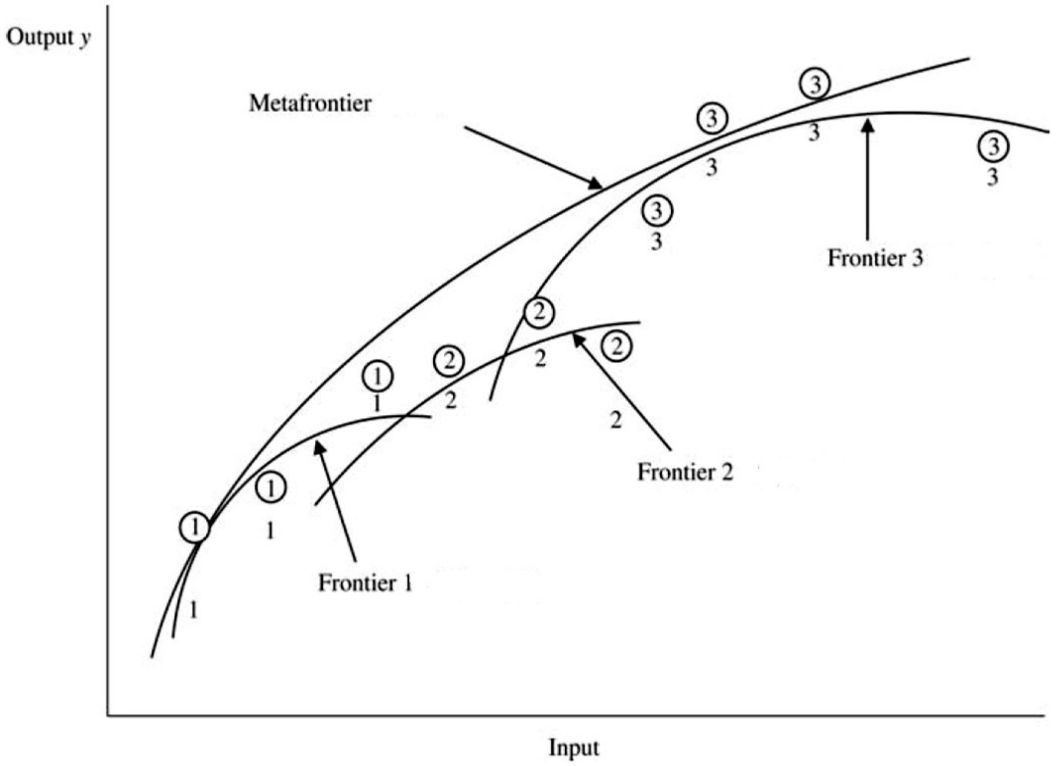

Figure 2-4: Meta-Frontier Approach When Clustering the Situations

- If the two approaches explained above were not viable, the validity of the efficiency evaluation would be at stake. However, Barr, et al. (2000), using a 'layering' approach, proposed a method to overcome this third case.

Dyson, et al. (2001), also considered non-homogeneity of the environment a case of heterogeneity and proposed the inclusion of the environmental or non-discretionary factors in an assessment.

These are even more ways to manage the Homogeneity Assumption Pitfall. Some researchers have chosen Dynamic DEA (Zheng et al., 1998), or Longitudinal approach in DEA to tackle this trouble. Nonetheless, they still use DEA as the principal methodology to approach the homogeneity assumption pitfall.

2.19. Installed Capacity as a Proxy for the Capital

In quest of a more accurate measure for the efficiency and/or eco-efficiency, the capital has always been one of the most important input factors. It has been previous studies, as shown in Table 2-2. Some scholars such as Yaisawarng and Klein (1994) tried to simulate the capital by Handy-Whitman Electric Plant Price Index; however, again they had to use the nameplate capacity after multiplying it by 1973 dollars (the cost of 1 KW of installed capacity). Shanmugam and Kulshreshtha (2005) introduced another formula to estimate the capital: CAPITAL = $(S \times T)/10^3$, where S is the installed capacity of a plant in MW, and T is the number of hours in a year. But as it can be seen, again the measure is almost a linear function of the installed capacity. Consequently, if we conduct a correlation analysis under the normal conditions, we will find a very high amount for them; that is to say, they would still rather employ the installed capacity as a proxy for the capital.

2.19.1. Importance of Incorporation of Real Value of Assets for the Capital

As in the previous efficiency measurement studies, in a majority of cases the capital was included as an input (Golany et al., 1994; Korhonen and Luptacik, 2004; Yaisawarng and Klein, 1994). Therefore, it is safe to claim that it has been a critical factor in every efficiency measurement study. From another perspective, if we return to the very basic definition of efficiency, the capital shows up as a non-detachable factor for inputs which show consumption (Kaplan, 1983). On the other hand, researcher attach the greatest importance to the capital since, in terms of financial matters and at least in industrial systems, it is not comparable with other common inputs, such as manpower and technology, or even operating costs.

2.19.2. Depreciation

Clearly, evaluation of depreciation may not be a proper solution, if a power generation facility has had the experience of an overhaul in its life cycle; however, the value of a facility by itself cannot be a suitable measure given the present conditions of the liberated electricity market. Therefore, the value of a firm or enterprise would be a more desirable measure due to the fact that the financial measures of a facility are more appealing to the private sector.

2.19.3. Estimations

As the first method, Value of an enterprise or firm, as a corporate asset value in the market, is defined as below:

Enterprise value = common equity at market value + debt at market value + minority interest at market value (if any), - associate company at market value(if any) + preferred equity at market value - cash and cash - equivalents (Hendriksen, 1977).

Second choice is what A. Emrouznejad (2000) has introduced in his thesis for the capital change in the dynamic performance measurement models. Through the definition of the capital input (Griliches and Jorgenson, 1966), Emrouznejad argues that employing the capital may not be suitable in a longitudinal or dynamic study of performance; instead, using an estimation, which is proposed by Sengupta (1995) can be more appropriate in such studies. Sengupta, in most cases, uses allocative efficiency instead of technical efficiency, and asserts that the capital input can be more effective when applied to the outputs.

The first one, which is more popular, has evolved in course of the time, and different versions of it have been developed for different occasions. It may also be a more suitable measure for privatized conditions since investors are more interested in financial factors. However, the drawback of this kind of measures is their dependency on completeness of data; that is, accuracy can be undermined in the conditions of data shortage. On the other hand, the second one has been designed for the research conditions, when the researcher cannot access full financial data however not highly accuracy ones.

2.20. Summary

In this chapter, we elaborated the needs for performance evaluation, and explored the performance measurement systems and performance measures, which have always been the non-detachable factors of information and control systems. Then, through NPM Theory for satisfying sustainable development conditions, it was maintained that it is necessary to include environmental factors in our performance evaluation and measurement attempts. Next, the concept of eco-efficiency was introduced, and it was elucidated that how efficiency and relative efficiency measures are employed to measure eco-efficiency. Sustainable development, which is advocated by power industry restructuring leaders so ardently, obliges them to report the outcomes of restructuring the power generation efficiency/eco-efficiency.

As one of the most important methodologies for efficiency/eco-efficiency measurement, DEA and its capabilities, theories and application were introduced afterward. A review of efficiency measurement systems of power plants, as our field of interest for performance, was exhibited, and it is pinpointed that the real value of the capital has not been incorporated in the previous studies.

Finally, a summary of the prior relevant researches in Malaysia were presented. In so doing, a very similar research conducted in the University of Malaya was addressed in more detail.

Chapter 3.

Methodology

3.1. Introduction

The present study focuses on finding the correlation between power industry restructuring and eco-efficiency of power plants. However, there are two barriers on this way. The first one is the natural heterogeneity of power plants, and the second one is the application of the installed capacity as a proxy for the capital in the eco-efficiency measurement studies. In this chapter, some methods will be suggested to find a relatively accurate measure for eco-efficiency of power plants and their correlation with power sector restructuring.

A series of actions have to be taken to restructure the power sector. Restructuring is a paradigm including deregulation, unbundling, privatization, and introduction of a power market. When focusing on privatization which is one the main modules/ components of restructuring, the following tasks on the power companies (generation, transmission distribution, and retail) have to be fulfilled (Ghazizadeh et al., 2007):

- Financial separation (accounting separation)
- Establishment as an independent legal entity
- Promoting competition
- Transfer to the private sector

These actions, as observed in many countries, take a long time, sometimes more than one or even two decades (Bulent Tor and Shahidehpour, 2005; Eybalin and Shahidehpour, 2003; Rudnick et al., 2005). Iran has not been an exception; from the start of the preliminary studies till now, the process of transferring to the private sector has taken about 20 years (Ghazizadeh et al., 2007). Therefore, evaluation of the eco-efficiency of the Iranian power plants requires a longitudinal study.

3.2. Data and Documents

Making references to the Table 2-2 depends on the availability of data, theoretical and empirical matters along with a summary of data selected from the data sources under Table 3-1. The data, collected from 2003 for an eight-year period, are on almost 52 Iranian power plants under privatization. Obviously, the data are entirely secondary.

Table 3-1: Inputs and Outputs required for the Study, the Sources of the Relevant Data

Inputs	Source
1. Installed or Operational	http://amar.tavanir.org.ir/pages/report/index90.php
Capacity	http://amar.tavanir.org.ir/pages/report/index90.php
2. Fuel Consumption	http://amar.tavanir.org.ir/pages/report/index90.php
3. Manpower	National Iranian Grid Company
4. Capital Expenditure	National Iranian Grid Company
5. Quantity of Power Purchase	http://amar.tavanir.org.ir/pages/report/index90.php
6. Operating Cost for Renewable Power Plants	

Outputs	Source
Undesirable:	
1. SO_2, NO_x, CO_x emissions	Tavanir Environment Bureau
2. Deviation from operational parameters	National Iranian Dispatching
Desirable:	http://amar.tavanir.org.ir/pages/report/index90.php
1. Generated electricity	National Iranian Dispatching
2. Operational availability	National Iranian Grid Company
3. Quantity sold to residential customers	National Iranian Grid Company
4. Quantity sold to non-residential (commercial, industrial, others, and wholesale) customers	http://amar.tavanir.org.ir/pages/report/index90.php National Iranian Grid Company
5. Thermal efficiency	National Iranian Grid Company
For renewable power plants:	
6. Production	
7. Utilization	

As it has been already addressed in the present research, the effects of restructuring on power plant performance are investigated through observing the effects of changes in the rules on the performance measurement factors. Since two different sets of DEA models, eco-efficiency and cost efficiency, are adopted, definitions of the factors, formula, required data, data sources and the rules related to each factor are presented in technical and cost categories. In Table 2-2, we have reported a number of previous power plant efficiency measurement researches using DEA which were studied to choose the input and output factors of DEA models adopted in this study. In addition, a conceptual approach is also being introduced in order to choose the most proper factors for the power plants eco-efficiency and cost efficiency measurement.

3.3. Cost and Eco-Efficiency Measurement Conceptual Model

Hayman et al. (2008) define the Yield Factor as a basic and very simple measure for power plant performance comprised of 'the ratio of energy produced to energy consumed'. This can be interpreted as a simple definition of technical efficiency which is written as below:

$$TE = \frac{Generated\ Electricity}{Fuel} \qquad (3\text{-}1)$$

where *TE* stands for technical efficiency. From another perspective, by a simplification, power plant technical efficiency can also be measured by the following formula:

$$TE = \frac{Generated\ Electricity}{Installed\ Capacity} \qquad (3\text{-}2)$$

This ratio can be decomposed as:

$$TE = \frac{Generated\ Electricity}{Operational\ Availability} . \frac{Operational\ Availability}{Installed\ Capacity} \qquad (3\text{-}3)$$

In the right hand side of Equation (3-2), the denominator is not affected by restructuring. In the right side of Equation (3-3), the right fraction is not fully affected by restructuring. In the left side, however, the numerator and denominator both can be altered due to the implications of restructuring. Therefore, in addition to the generated electricity, fuel and installed (effective) capacity (as a proxy for the capital), we consider operational availability as an output. Moreover, deviation from generation plan is incorporated in the model since operational availability is declared by the power plant owners to the dispatching unit, and deviations from generation plan show whether or not the power plant can generate as much as it has claimed it can. Furthermore, to examine the adverse effects of the power plant on the environment, emissions are also incorporated in the model as a bad output. In view of the foregoing inclusions, the eco-efficiency (the technical efficiency) model can be depicted as below:

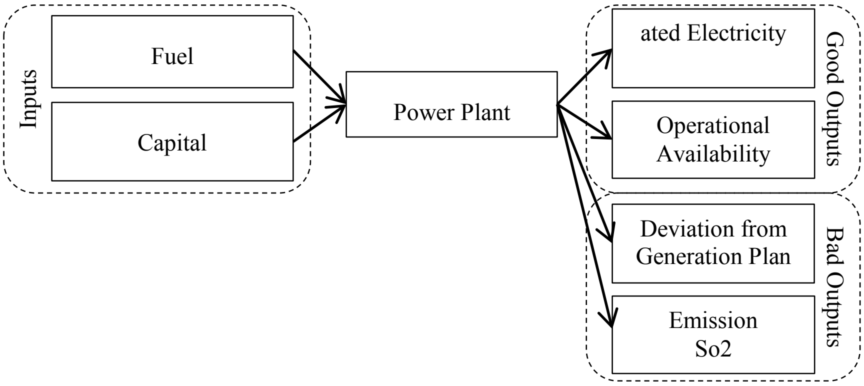

Figure 3-1: Conceptual Eco-Efficiency (Technical Efficiency) Measurement Model

Similar to Figure 3-1, we draw the conceptual cost efficiency model as below:

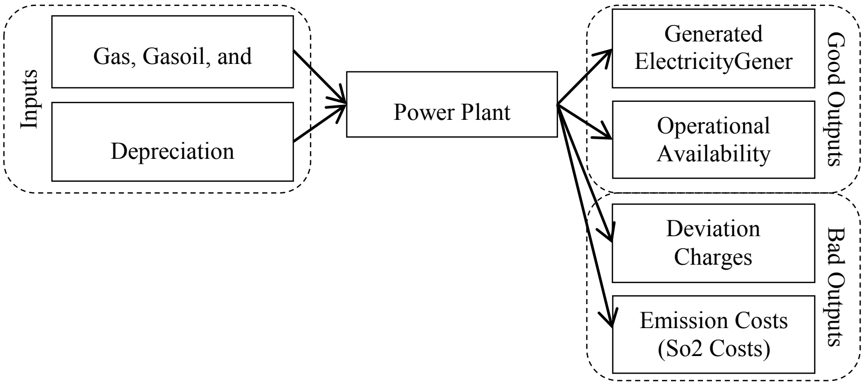

Figure 3-2: Conceptual Cost Efficiency Measurement Model

In the following section, it is explained how to calculate each factor.

3.3.1. Fuel

In Iran, gas, gasoil and fuel oil are consumed as fuels in the power plants. There is no coal-fired power plant in Iran and the only nuclear power plant has not been completed and operated as of the time of the present study. Iran holds the second largest natural gas resources in the world after Russia; therefore, natural gas has been determined as the main fuel for the country's thermal power plants. It has been also declared that if in urgent situations a power plant is forced to consume gasoil or fuel oil which are more expensive than gas, the power plants will be reimbursed for the margin price of gasoil and fuel oil in the end of each year[1].

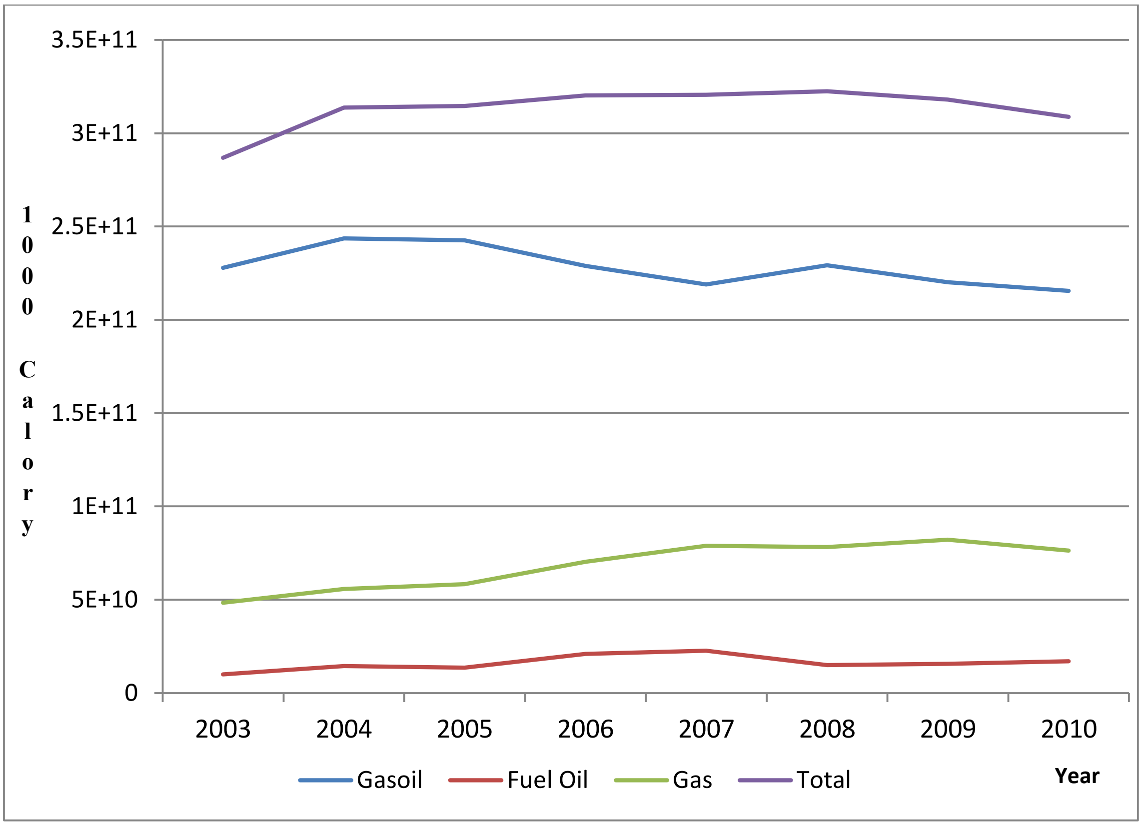

Figure 3-3: Fuel Consumption by the Thermal Power Plants

Moreover, for the sake of unification, calorific values of different fuel types are considered in the eco-efficiency (technical efficiency) measurement. These calorific values are identical across the country and if the refining technology changes, the new

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[1] Executive bylaw for electricity guaranteed purchase mechanism and conditions, subject of clause "b" of Article (9), of the Fourth, validated by the Fifth Economic, Social, and Cultural Development Plan Act of the Islamic Republic of Iran , 2003

calorific value will be reported to the Ministry of Energy for the required actions. However, as gas is extracted from three different resources, there are different calorific values. Similar to gasoil and fuel oil, if the extraction process and/or refining technology cause(s) any changes in the calorific value, the new value will be measured and reported to the Ministry of Energy by National Iranian Gas Company (see Table 6-2 and Table 6-3). Yearly fuel consumption data for every power plant is available on the Website of Tavanir Company[1]. The calorific values can also be found on the same website.

3.3.2. Fuel Costs

It is conventional in cost efficiency measurement to multiply the fuel price by the volume of the fuel consumed to calculate the fuel cost. In Iran, however, a specific module has been envisaged in the restructuring project based on which price signals are sent to power plants helping them minimize their fuel consumption and optimize their generation process. The module works like this: the power plants are surcharged if they consume more than the authorized grid fuel consumption limit and rewarded if they manage to consume lower than the same limit. Therefore, the fuel price is calculated using the following formula:

$$EC=GE.((1/PYF)-(1/NGYF))/(RGHV) \tag{3-4}$$

$$EFCH=EC.(GLP-RPGP) \tag{3-5}$$

$$RPGP=PGP.RGHV/AVGHV \tag{3-6}$$

---

[1] Iran Generation, Transmission, and Distribution Holding Company, http://amar.tavanir.org.ir/pages/report/index80.php

Where *EC* is the Excessive Fuel Use, *GE* is the generated electricity in a year, *PYF* is the power plant yearly Yield Factor (see Table 6-1), *NGYF* is the yearly average of national grid Yield Factor, *RGHV* is the regional gas heating [calorific] value (see Table 6-3), *EFCH* is the excessive consumption charge, *GLP* is the yearly liberated gas price, *RPGP*[1] is the regional power plant gas price (Remember that the Iranian natural gas is extracted from four different resources and then supplied to four different regions across the country), *PGP* is the yearly power plant gas price (see Table 6-1), and *AVGHV* is the average of countrywide gas heating [calorific] value (see Table 6-3). *GE*, *PYF*, *NGYF*, and *RGHV* are available on the website of Tavanir Company, and *GLP* and *PGP* can be found in Iran's Energy Balance Sheet Report which is an annually published journal.

It is worth reminding that the fuel and fuel cost factors for the hydro power plants are supposed to be zero.

3.3.3. The Capital (Effective Capacity)

As it can be observed in Appendix 1, in the majority of previous studies, researchers have used the installed capacity as a proxy for the capital input. However, because the installed capacity remains constant for several years in most of the cases and the power plant capital is affected by some factors such as depreciation, overhauls, and even the power plant market value, the installed capacity cannot be a proper surrogate for the capital. Therefore, some researchers such as Yaisawarng and Klein (1994), tried to simulate the capital by the Handy-Whitman Electric Plant Price Index. Nevertheless, they, too, had to use the nameplate capacity and multiplied it by 1973 dollars (the cost of 1 KW of installed capacity). Shanmugam and Kulshreshtha (2005) introduced another formula to estimate

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[1] In Iran there is different gas prices for different use, also liberated means the unsubsidized gas price

the capital: CAPITAL = $(S \times T)/10^3$, where S is the installed plant capacity in MW, and T is the number of hours in a year. But as it can be seen again, this measure is almost a linear function of the installed capacity. As a result, we use the effective capacity as a better proxy for the installed capacity in this study. By definition, effective capacity is an empirical function of the aging factor, ambient temperature, and altitude[1]. This factor is evaluated yearly and renewed when a power plant undergoes an overhaul. Therefore, effective or operational capacity of a power plant can be a more accurate proxy for the capital[2].

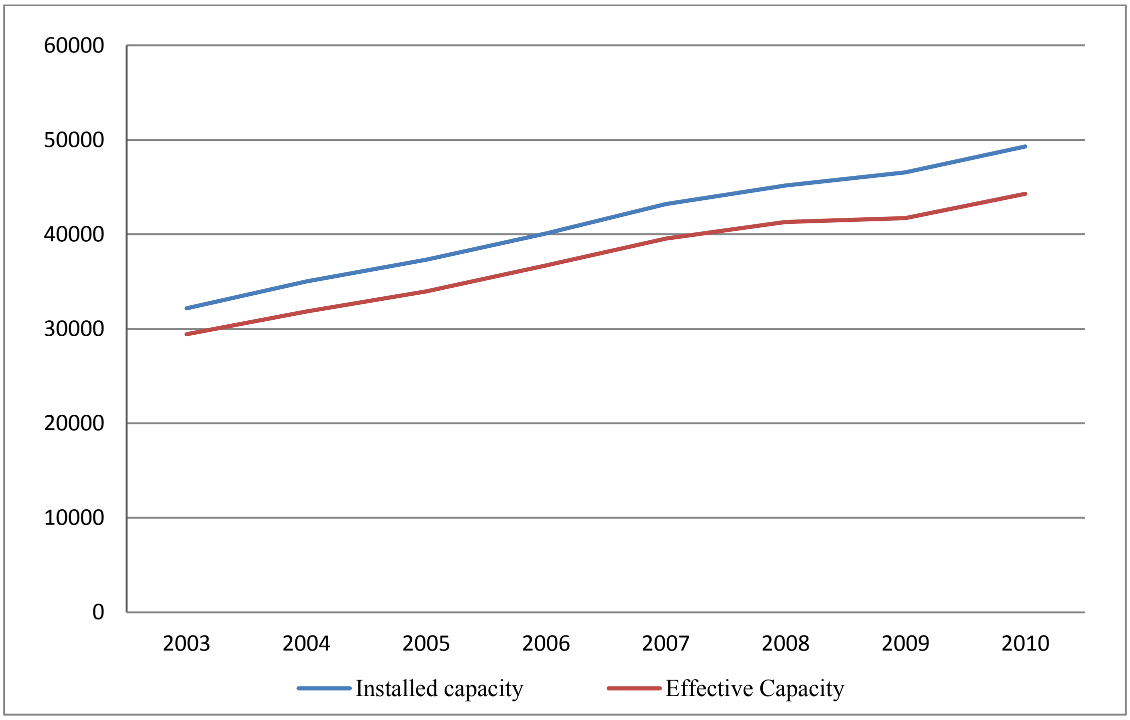

Figure 3-4: Installed and Effective Capacity Trends

In Figure 3-4 a clear growth for both factors can be observed.

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[1] http://www2.tavanir.org.ir/info/stat84/sanatfhtml/page17.htm

[2] ISIRI 13375 1st. Edition http://www.isiri.org/Portal/Home/

3.3.4. Depreciation

We take deprecation as the cost of capital used by a power plant. The data for this factor has been collected the power plant owners. In Iran, the regional electricity companies are the owners of the governmental power plants. In order to evaluate the capital cost of a power plant for further incorporation in the cost efficiency measurements, book values of the country's power plants are reevaluated every 10 years. The corresponding depreciation is evaluated by power plant owners in the end of each fiscal year[1].

3.3.5. Operational Availability

Still another important factor is operational availability which is defined as the average yearly electricity which can be generated during the daily peak hour, as declared by the power plant management to the national dispatching unit. Generated electricity is encouraged to be increased by the power market mechanisms, and enhancement of operational availability is of the power plant owners' interest due to the capacity payment[2] reasons. The data on operational availability of the power plants are recorded by the country's national dispatching unit.

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[1] The depreciations are evaluated using the revised table of the Article 151 of Direct Taxes Act ratified in 2002.

[2] In Iran, power plants are paid for their availability (Capacity Payment) which is declared by themselves to Iran Grid Management Company (IGMC), they also are charged if they cannot generate as much as they declared.

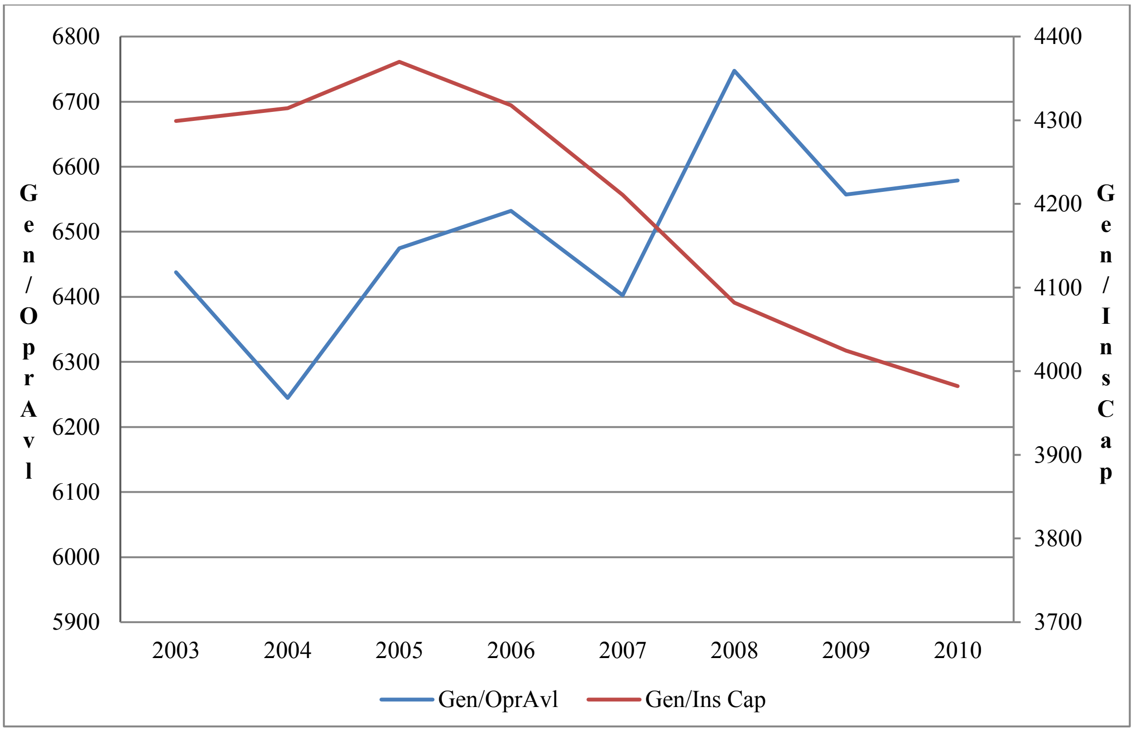

Figure 3-5: Generated Electricity over Operational Availability and Installed Capacity Trends

Figure 3-5 depicts that the reserve margin in peak hours have increased during the eight-year restructuring period since in spite of the installed capacity growth (Figure 3-4), the ratio of the generated electricity to the installed capacity has dropped. It can also be seen that the ratio of the generated electricity to operational availability has increased despite the fluctuations in the graph.

3.3.6. Electricity Generated

This factor, as one of the most common factors, is incorporated in every performance measurement study. Besides, one of the good outputs in the present study is defined as the yearly electricity generated by every power plant in Mega Watt Hours. Data for this factor are also available on the Website of Tavanir Company.

3.3.7. Emissions

In this study, SO_2 has been considered a proxy for all gases emitted. This gas is also a major cause of acid rains and has a predominant role in human respiratory diseases. The data on SO_2 emission have been acquired from Tavanir Environmental Affairs Bureau. Therefore, emission is signified by the yearly SO_2 produced by each power plant in tons.

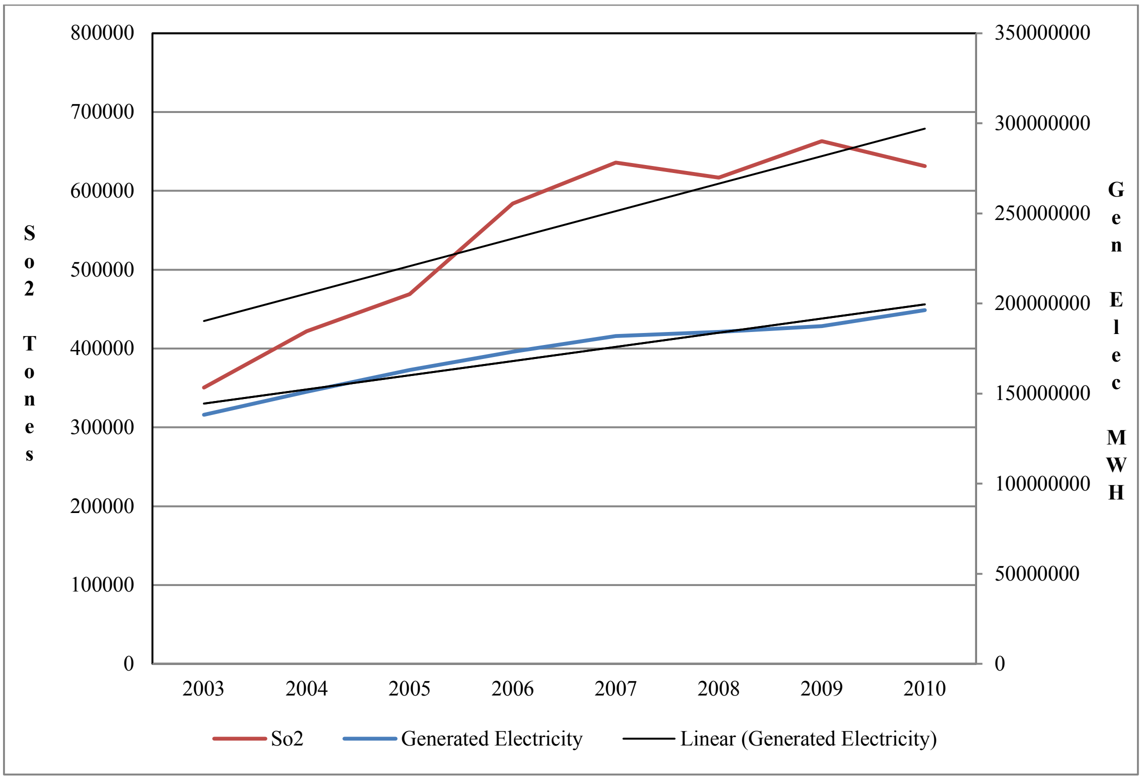

Figure 3-6: SO_2 Produced over Generated Electricity

As observed in Figure 3-6, the power industry has not succeeded in controlling the fuel type used originally meant to control the emissions consequently. In addition, SO_2 emission growth rate has been more than generated electricity growth rate, during 2003-2007, however this rate has been less than generated electricity growth rate during 2008-2010 in average. In order to incorporate MBP requirements in the DEA model, as it will be seen later in Section 3.7, the emission factors or pollutant parts of each type of fuel needed to be known. The emission factors are given in Table 6-4.

3.3.8. Emission Costs

A number of rules and regulations have been ratified in Iran to control the industrial emissions. The most important of such legislations is the executive bylaws of Paragraph

(C) of Articles 104 and 134 of the Third Economic, Social and Cultural Development Plan Act of the Islamic Republic of Iran ratified by the Department of the Environment in October 2001. Although in this executive bylaw the mechanism for calculation and levying emission charges have been declared, these charges are not imposed in practice because all power plants are governmental, their operation, maintenance and optimization budgets are not large enough and there is no specific budget allocated to apply abatement technologies to the power generation industry. Consequently, no price signal is sent to the power plants to warn them about their emissions. Thus, we adapted the models using two different approaches. The first approach deals with the problem from a power generation industry point of view. In this case, the cost of emission is presumed to be zero since the power plants are not supposed to pay any charges for the emissions produced. The second approach deals with the problem from a national perspective as there are social costs incurred by the society as a result of the emissions. These social costs of each emission type can be obtained from the Iranian Yearly Energy Balance Sheet Journal.

3.3.9. Deviation from Generation Plan

As addressed in Section 3.3.3, the power plants must declare to the dispatching unit their available capacity. This availability is affected by their operation and maintenance programs, contingencies or even mismanagement and human faults. Therefore, deviations from the generation plan are calculated by the yearly summation of actual energy generated minus the declared available capacity during the daily peak hour. This ratio will be multiplied by zero if the related contingency is not due to mismanagement or human faults.

3.3.10. Deviation Charges

If power plants fail to generate as much as they declared to the dispatching unit, they are charged based on the rate of deviation[1]. The formula for calculation can be briefly written as below:

$$Dev_d^t = (DAC - GE).BRCP.CHM \qquad (3\text{-}7)$$

$$Dev^t = \sum_d Dev_d^t \qquad (3\text{-}8)$$

Where:

Dev_d^t = Deviation from the generation plan (declared available capacity) on the day *d* of the period *t*

DAC= Declared available capacity

GE= Actual energy generated

BRCP= Basic rate for capacity payment[2]

CHM= Charge multiplier which is 20 or 25, depending on the type of deviation

Dev^t= Deviation charges of the year *t*

Dev^t is incorporated in cost efficiency measurement models.

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[1] This charge is calculated and imposed based on the Executive Bylaw for the Guaranteed Electricity Purchase Mechanism and Conditions, subject of Clause "b" of Article (5), of the Fourth, validated by the Fifth Economic, Social, and Cultural Development Plan Act of the Islamic Republic of Iran, 2003, and its attachment as well as the procedure attached to the 20th and 22nd minutes of the Iranian Power Market Regulatory Board, July and August 2004.

[2] Basic rate for capacity payment is calculated based on the market energy price, reserve margin of each day of a year, temperature of the day and whether it is a working day or holiday, procedures attached to minutes 22, 45, 61, 78, 88, 92 and executive bylaw for electricity guaranteed purchase mechanism and conditions, subject of clause "b" of Article (25), of fourth, validated by fifth, program law for economic, social, and cultural development of the Islamic Republic of Iran laws

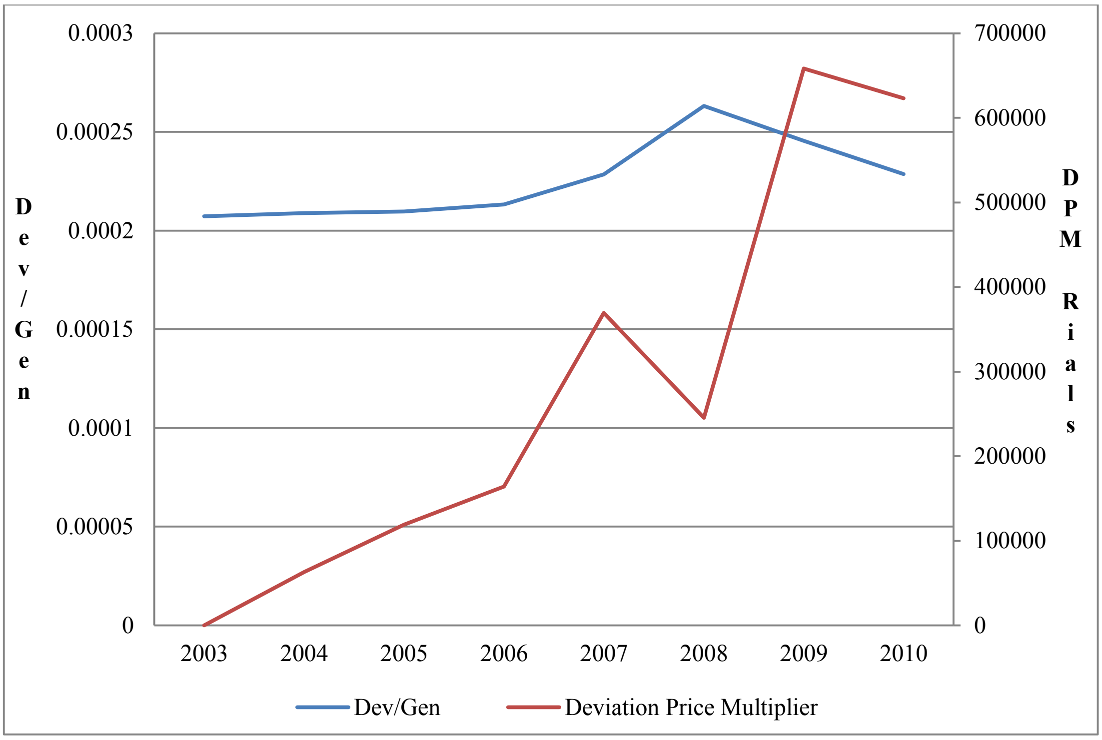

Figure 3-7: Deviation from Generation Plan to Generated Electricity and Deviation Charge Multiplier (DCM)[1]

Figure 3-7 exhibits the relationship between charge signals sent to the power plants and the ratio of the deviations to the electricity generated. Except for 2008, DCM shows growth, but the charges have not been significant enough for power plant to make them avoid further deviations. But in 2009, DCM was dramatically increased by the regulator. This became a major cause of the decrease in deviations from 2009 onward.

Before we proceed further, we need to address a problem which usually occurs when the Malmquist Leunberger index is calculated.

3.4. An Infeasibility Problem in ML Index using DDF Model

As explained in the previous section, in order to calculate ML_t^{t+1} or ML_{t+1}^t, a number of

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[1] $DCM = BRCP.CHM$

mixed period models need to be constructed. This can lead to a situation of infeasibility since in some cases one or more DMU's are located beyond the efficiency frontier and $g=(y,-z)$ or other arbitrary directions, which are the same for all DMU's and cannot project those DMU's to the frontier (Chung et al., 1997). An illustration of this problem can be found in Färe, Grosskopf, and Pasurka Jr (2001). In many studies the same problem may be encountered, like what Chung, et al. (1997), Färe, et al. (2001), and Oh (2010a) did when studying the Swedish pulp and paper industry, American coal-fired power plants, and other studies in 26 countries respectively. The same problems can occur when super efficiency is calculated using DDF DEA models.

To tackle this problem, a number of strategies have been introduced. Färe et al. (2007) used just $t+1$ frontier as the reference technology; however, in addition to the possibility of infeasibility which still exists when reference technology t period occurs over $t+1$ frontier, this approach is an arbitrary strategy and just one reference technology is employed. Färe et al. (2007) have employed a joint technology reference from t and $t+1$ period, where the data from $t+1$ are added to the reference technology. Although this approach can eliminate the infeasibility problem, the frontier is still arbitrary. Using this joint technology approach, Oh (2010a) introduces Global Malmquist-Luenberger index (see Equation (3-21)) which is always feasible since it joints all the reference technologies, so all the DMU's for the different periods fall under the frontier. However, by a simple example, we show here that this may lead to serious Malmquist-Luenberger index miss-measurements. In addition, contemporaneous Malmquist-Luenberger index and Global Malmquist-Luenberger index are indeed different measures with their own applications, so comparing these two measures may be seriously questionable.

We use a set of 6 DMU's with equal inputs and just one good and one bad output as exhibited in the following table:

Table 3-2: A Set of 6 DMU's used to Show the Global ML Deficiencies

Period / DMU	1		2	
	z	y	z	y
1.	2	1	3	3
2.	$\frac{10-4\sqrt{5}}{5}$	$\frac{4\sqrt{10\sqrt{5}+4}}{5}$	$\frac{10-4\sqrt{5}}{5}$	$\frac{4\sqrt{10\sqrt{5}+4}}{5}$
3.	$3-\sqrt{2}$	$3+\sqrt{2}$	3	2
4.	5	6	8	4
5.	8	6	7	3
6.	10	5	10	5

Using DDF model (Model (2-9)), and DMU's presented in Table 3-2, we can draw the following diagram:

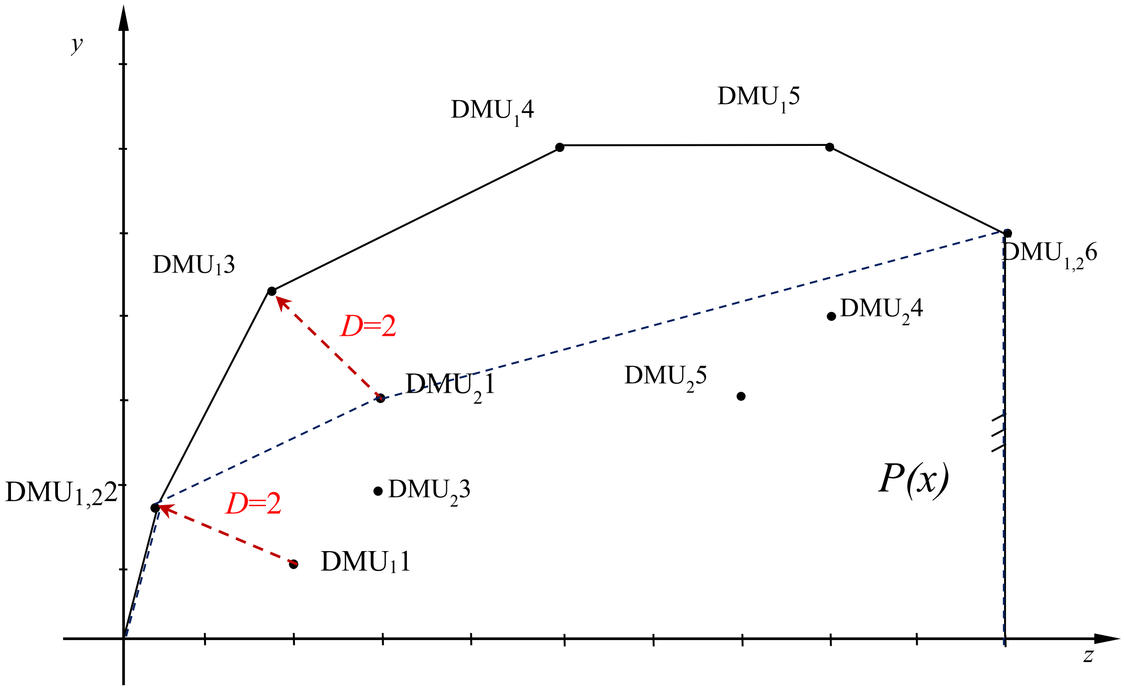

Figure 3-8: Table 3-2 Illustration with DDF Frontiers

In Figure 3-8, the frontier composed of DMU$_{1,2}$2, DMU$_1$3, DMU$_1$4, DMU$_1$5, and

$DMU_{1,2}6$ (black line) represents the technology frontier for period 1, and the frontier composed of $DMU_{1,2}2$, $DMU_{2}1$, and $DMU_{1,2}6$ (blue dotted line) represents the technology frontier for period 2. By using the DDF technique to compute the Global ML index for DMU_1 for both periods, distance (*D*) to the frontier provides an index equal to 1. Thus, we obtain the following:

$$ML^G = \sqrt{\frac{1+2}{1+2}} = 1$$

On the other hand, in the case of the contemporaneous ML, ML_1^2 we have:

$$ML_1^2 = \sqrt{\frac{1+2}{1+0}.\frac{1+2}{1+2}} = \sqrt{3} = 1.73$$

As it is obvious from the data, DMU_1 has had a clear improvement from period 1 to period 2 because in period 1 it has produced more bads in comparison with goods whereas in period 2 it has produced as many bads as goods. In addition, in period 1, DMU_1 was inefficient, but in period 2 it is efficient. Therefore, on both counts, DMU_1 has improved, but the Global Malmquist-Luenberger index has failed to show this improvement indicating no change in eco-efficiency.

To summarize, Global Malmquist-Luenberger index is not a proper measure to compute the contemporaneous Malmquist-Luenberger and show the trend. In fact, these are two different measures, and the approach in Oh (2010) cannot be a proper solution for the infeasibility problem.

In the next section, we are going to introduce a method to eliminate this kind of infeasibility problems using types of DDF and slack-based models and render a non-arbitrary frontier as well.

3.4.1. An Approach to Eliminate the Infeasibility Problem

When a DMU falls beyond the frontier, there is possibility of infeasibility. This has two reasons; first due to good outputs and bad outputs expanding and contracting respectively with the same proportion; second, because in a standard DDF model the same direction, *g=(y,-z)*, is applied to all DMU's. Thus, we define a new direction function based on a new set; *P′(x)*, for the DMU's which lie above the boundary as below:

$$P'(x)=\{(y,z):(y,z)\notin P(x),(y,z)\geq 0\} \quad (3\text{-}9)$$

$$D'(x,y,z;g)=inf\{|\delta|:(y,z)+\ \delta\ g\in P'(x)\} \quad (3\text{-}10)$$

where δ represents the minimum contraction of both good and bad outputs, which can draw the DMU to the boundary. Here we adopt Model (2-10) to include bad outputs as below:

$$D_o(x,y,z)= Max\ \ \beta_1+\cdots+\beta_J+\ \gamma_1+\cdots+\gamma_K \quad (3\text{-}11)$$

$$St$$

$$\sum\nolimits_{n=1}^{N}\lambda_n x_{in}\leq x_{io}\ ;i=1,2,\dots,I$$

$$\sum\nolimits_{n=1}^{N}\lambda_n y_{jn}\geq y_{jo}+\beta_j.1\ ;j=1,2,\dots,J$$

$$\sum\nolimits_{n=1}^{N}\lambda_n z_{kn}=z_{ko}-\gamma_k.1\ ;k=1,2,\dots,K$$

$$\lambda_n\geq 0\ ;\ \gamma_k\geq 0;\ \beta_j\geq 0;\ n=1,2,\dots,N;\ j=1,2,\dots,J;k=1,2,\dots,K$$

Where, $\beta_1,\dots,\beta_J$ and $\gamma_1,\dots,\gamma_K$ are slack variables. Model (3-11) which is an output-oriented one, still suffers from the infeasibility problem when employed to evaluate MLI. Here, efficiency score is calculated by $1-Do$. Therefore, we can rewrite (3-11) for these DMU's as below:

$$D'(x, y, z)= Min\, \beta_1 + \cdots + \beta_J + \gamma_1 + \cdots + \gamma_K \tag{3-12}$$

Subject to

$$\sum_{n=1}^{N} \lambda_n x_{in} \le x_{io}\,; i = 1,2, \dots, I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \ge y_{jo} + \beta_j.1\,; j = 1,2, \dots, J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \gamma_k.1\,; k = 1,2, \dots, K$$

$$\lambda_n \ge 0\,;\ \gamma_k \ge 0;\ \beta_j \ge 0;\ n = 1,2, \dots, N;\ j = 1,2, \dots, J; k = 1,2, \dots, K$$

Therefore, (3-12) can be used for the infeasibility cases to find efficiency measures for DMU's, which are beyond the frontier. Actually, (3-12) seeks the nearest direction toward frontier. Hence, from an economic point of view, amongst the DMU's outside the frontier, the nearer a DMU to the frontier, is less efficient.

To find the direction vector using Färe and Grosskopf (2010a) model (3-12) we introduce:

$$D'(x, y, z)=Min\ \theta \tag{3-13}$$

Subject to

$$\sum_{n=1}^{N} \lambda_n x_{in} \le x_{io}\,; i = 1,2, \dots, I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \ge y_{jo} - g_{yj}.\theta\,; j = 1,2, \dots, J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - g_{zk}.\theta\,; k = 1,2, \dots, K$$

$$\sum_{j=1}^{J} g_{yj} + \sum_{k=1}^{K} g_{zk} = 1$$

$$\lambda_n \ge 0\,;\ g_{yj} \ge 0;\ g_{zk} \ge 0;\ n = 1,2, \dots, N;\ j = 1,2, \dots, J; k = 1,2, \dots, K$$

By replacing $g_{yj}.\theta=\beta_j$ $g_{zk}.\ \theta=\gamma_k$, it can easily be seen that (3-13) is transformed to (3-12). Then, in order to transform (3-12) to (3-13), if DMU$_o$ is located on the frontier, then: $G=(g_{yj},g_{zk})$, the direction vector, can be any direction, else if we solve (3-13) and if we take $g_{yj}.\theta=\beta_j^*$ $g_{zk}.\ \theta=\gamma_k^*$ we can obtain:

$$\theta = \frac{\beta_1^*}{g_{y1}} = \frac{\beta_2^*}{g_{y2}} = \cdots = \frac{\beta_J^*}{g_{yJ}} = \frac{\gamma_1^*}{g_{z1}} = \frac{\gamma_2^*}{g_{z2}} = \cdots = \frac{\gamma_K^*}{g_{zk}}$$

Then, we can get:

$$\beta_1^* \cdot g_{y2} = \beta_2^* \cdot g_{y1}, \beta_2^* \cdot g_{y3} = \beta_3^* \cdot g_{y2}, \dots, \beta_J^* \cdot g_{z1} = \gamma_1^* \cdot g_{yJ}, \dots, \gamma_{K-1}^* \cdot g_{zk} = \gamma_K^* \cdot g_{zK-1} \tag{3-14}$$

Next, we achieve:

$$\begin{gathered}
\beta_1^* \cdot g_{y2} - \beta_2^* \cdot g_{y2} = 0, \\
\beta_2^* \cdot g_{y3} - \beta_3^* \cdot g_{y2} = 0, \\
\dots, \\
\beta_J^* \cdot g_{z1} - \gamma_1^* \cdot g_{yJ} = 0, \\
\dots, \\
\gamma_{K-1}^* \cdot g_{zk} - \gamma_K^* \cdot g_{zK-1} = 0 \\
\sum_{j=1}^{J} g_{yj} + \sum_{k=1}^{K} g_{zk} = 1
\end{gathered} \tag{3-15}$$

(3-15) is a system of equation with first similar *J*+*K*-1 equations and *J*+*K* unknowns. Thus, together with $\sum_{j=1}^{J} g_{yj} + \sum_{k=1}^{K} g_{zk} = 1$ we have *J*+*K* equations and *J*+*K* unknowns with first *J*+*K*-1 pair-wise linearly independent equations. Furthermore, no linear combination of the first *J*+*K*-1 equations can generate the last equation, since the first *J*+*K* equations have zero in their RHS, but the last equation has unity in the same place. Therefore, this is a system of linear equations with a unique solution which is $(g_{y1}, \dots, g_{yJ}, g_{z1}, \dots, g_{zk})$. As a result, we can achieve optimal directions by solving (3-13) and (3-15). It can also be shown that if we take $g_{yj}.\theta=\beta_j$ $g_{zk}.\ \theta=\gamma_k$, together with $\sum_{j=1}^{J} g_{yj} + \sum_{k=1}^{K} g_{zk} = 1$ which does not affect the frontier and just normalizes the directions; we can transform Model (3-12) to (3-13). Therefore, (3-12) and (3-13) are equivalents.

Here, we illustrate the infeasibility case with a very simple example including 5 DMU's in two consequent periods with a single input and two outputs – one good and the other bad. In this example, for simplification we assume all inputs equal unity. The data and efficiency scores using different models for this example, is presented in Table 3-3 below:

Table 3-3: A Simple Example, Data and Efficiencies

DMU	Data				Efficiency Score				
	Good Outputs		Bad Outputs		Model (2-9)		Model (3-11)		Using MLIA
	t	t+1	t	t+1	t	t+1	t	t+1	t+1
1	1	4	1	4	.667	na	.75	na	1.5
2	2	2	1	1	1	1	1	1	1
3	3.5	3.5	2	2	1	1	1	1	1
4	3	3	3	3	1	1	1	1	1
5	1	**3.5**	2	**3.5**	.4	na	.625	.625	**1.25**

na refers to not available

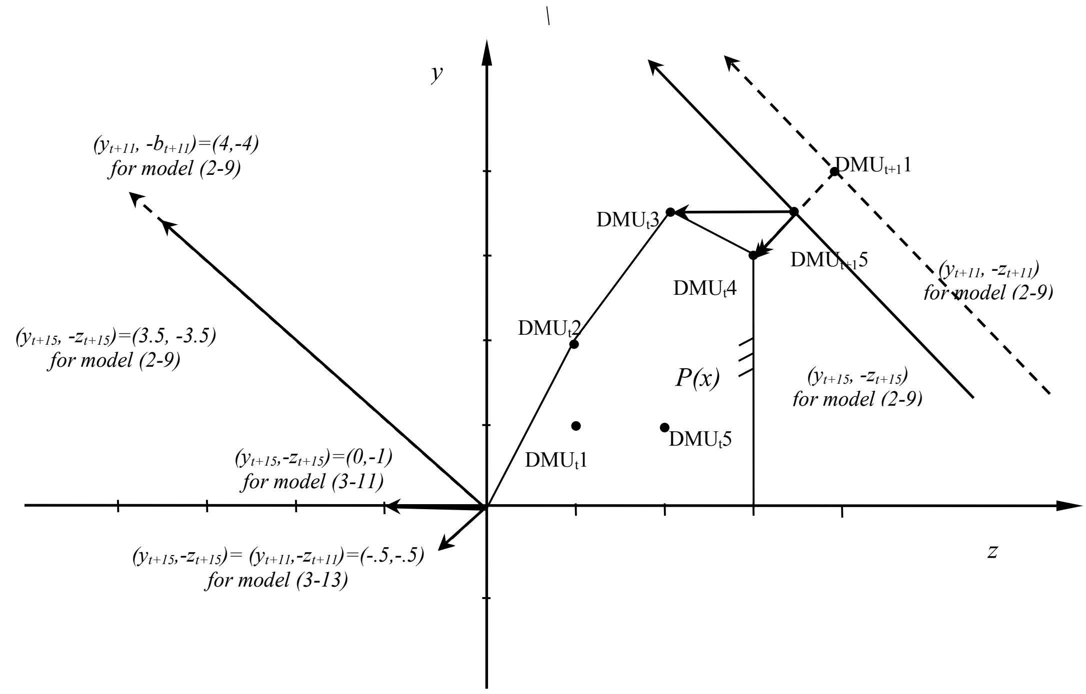

Figure 3-9: Table 3-3 Illustration

Based on Figure 3-9, if we deploy Model (2-9), the direction for DMU$_{t+1}$ 5 does not intersect *P(X);* therefore, the Model (2-9) is infeasible whereas if Model (13) is adopted using (-.5,-.5) as the optimal direction, DMU$_{t+1}$ 5 will be feasibly drawn to DMU$_t$ 4 on the border of *P(X)*.

From another perspective, if (2-9) is employed to calculate $D_o^t(x^{t+1}, y^{t+1}, z^{t+1})$, DMU$_{t+1 5}$ will turn out to be infeasible, however, if (3-11) is employed to calculate $D'^t_o(x^{t+1}, y^{t+1}, z^{t+1})$, an efficiency score of 1.25 will be achieved. In this particular case, Model (10) is feasible for DMU$_{t+1\ 5}$ and it is projected to DMU$_{t\ 3}$. However, as seen in the Figure 3-9, Model (3-13) evaluates its distance value in a more reasonable way since the distance to the frontier is minimized.

Focusing on Figure 3-9, one can see that Models (2-9) and (3-11) get infeasible for DMU$_{t+1\ 1}$, since for model (2-9), (4,-4) does not intersect *P(x),* and Model (3-11) cannot find any feasible direction to intersect *P(x)*. Yet, employing Model (3-13), -0.5 and 1.5 can be achieved as the distance value and the efficiency score respectively.

Thus, we propose the following three-step algorithm to avoid infeasibility problem when calculating MLI:

1. Examine if there are DMU's which occur beyond the efficiency frontier[1]
2. If so, use (3-13) to calculate $D_o^t(x^{t+1}, y^{t+1}, z^{t+1})$, and $D_o^{t+1}(x^t, y^t, z^t)$ for the same DMU's.[2]
3. Or else, employ (3-11) to compute $D_o^t(x^t, y^t, z^t)$, $D_o^t(x^{t+1}, y^{t+1}, z^{t+1})$, $D_o^{t+1}(x^t, y^t, z^t)$ and $D_o^t(x^{t+1}, y^{t+1}, z^{t+1})$ for all DMU's.

For convenience purposes, we will refer to this algorithm by the acronym 'MLIA'.

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[1] It has already been proven that (3-11) is feasible for all DMUs located under the frontier.

[2] $D_o^t(x^t, y^t, z^t)\ and\ D_o^t(x^{t+1}, y^{t+1}, z^{t+1})$ are calculated using (3-11)

3.4.2. Feasibility Conditions Considerations

One last thing to be proved is the model feasibility. Toward this aim, we write the following lemma:

Lemma1: if $(y_1, z_1) \in P'(x)$ then model (3-13) is feasible.

Proof: to prove lemma1, it will be sufficient if we find at least one vector like (Z, B, Γ) which satisfies constraints of (3-13). Toward this aim, we take $(y_1, z_1) \in P'(x)$ then $y_1 > y_0$ or $z_1 \neq z_0$ for at least one $(y_0, z_0) \in P(x)$ and (y_0, z_0) is on the frontier. In fact, since $(0,0) \in P(x)$(null jointness property),
$z_1 \neq z_0$ just result in $z_1 > z_0$, otherwise $0 < z_1 < z_0$ which means $0 < z_1$. Hence if $y_1 > y_0$ or $z_1 > z_0$, if $y_1 = (y_{11},.., y_{J1})$ and $z_1 = (z_{11},.., z_{K1})$ there exist at least one $y_{j1} > y_{j0}$ or $z_{k1} > z_{k0}$ or if $0 < z_1 < z_0$ then $0 < z_{k1} < z_{k0}$. Thus, $(0, y_1, z_1)$ $y_1 \neq 0$ and $z_1 \neq 0$ satisfies all the constraints, which means Model (3-13) is feasible.

Generally speaking, if Model (3-11) (or even Model (2-9)) proves infeasible for a particular DMU, we can find its distance to the frontier hence the efficiency and MLI measures using Model (3-13).

From this point onwards, when we evaluate a Malmquist Leuenberger index, we will use MLIA to tackle the infeasibility problem. Model (3-11) can be replaced by a model which is supposed to run.

In the next section, we are going to make use of an evolution continuum to introduce new DEA models as more applicable tools to solve our problem.

3.5. Malmquist-Luenberger Meta-frontier

Suppose we have S different groups with different technologies; namely, R_s $s=1,...,S$, each containing C_s firms or DMU's. Then using (3) and what Oh (2010b) has defined, we can redefine *contemporaneous* benchmark technology for group s within the period t as $P_s^t(x^t)=\{(y^t, z^t): x \text{ can produce } (y^t, z^t)\}$. Then, altering the definition of *intertemporal* benchmark technology by Oh and Lee (2010), we redefine *intertemporal* benchmark technology of group s as P^I_s =conv$\{P^1_s \cup P^2_s \cup ... \cup P^T_s\}$. Then, the global benchmark technology of all groups can be defined as P^G =conv$\{P^I_1 \cup P^I_2 \cup ... \cup P^I_S\}$. Therefore, we take (9) as contemporaneous MLI and redefine intertemporal MLI as:

$$ML_s^I(x^t, y^t, z^t) = \frac{1+D_o^I(x^t,y^t,z^t)}{1+D_o^I(x^{t+1},y^{t+1},z^{t+1})} \tag{3-16}$$

Where $D_o^I(x, y, z)=\sup\{\theta:(y, z)+\theta g \in P(x)\}$ which is the distance of DMU$_o$ to the intertemporal frontier of group s, where g is the direction vector. Similar to what was done in Oh (2010b), we can decompose ML_s^I as below:

$$ML_s^I(x^t, y^t, z^t) = \frac{\left(1+D_o^t(x^t,y^t,z^t)\right)}{\left(1+D_o^{t+1}(x^{t+1},y^{t+1},z^{t+1})\right)} \left\{ \frac{\frac{\left(1+D_o^I(x^t,y^t,z^t)\right)}{\left(1+D_o^t(x^t,y^t,z^t)\right)}}{\frac{\left(1+D_o^I(x^{t+1},y^{t+1},z^{t+1})\right)}{\left(1+D_o^{t+1}(x^{t+1},y^{t+1},z^{t+1})\right)}} \right\} \tag{3-17}$$

TE^t and BPG^t are defined as below:

$$TE^t = 1/(1 + D_o^t(x^t, y^t, z^t)) \text{ and } BPG^t = \frac{1+D_o^I(x^t,y^t,z^t)}{1+D_o^t(x^t,y^t,z^t)} \tag{3-18}$$

From (3-18), it is obvious that $BPG \geq 1$; BPG equals 1 if and only of the particular DMU is located on the intertemporal frontier. Hence, we achieve:

$$ML_s^I = \frac{TE^{t+1}}{TE^t} \cdot \frac{BPG^t}{BPG^{t+1}} \tag{3-19}$$

Then, we can write:

$$ML_s^I = EC.BPC \tag{3-20}$$

where *TE*, *BPG*, *TC*, and *BPC* stand for technical efficiency, best practice gap, technology change, and best practice gap respectively.

Meta-frontier MLI is defined as below:

$$ML^G(x^t, y^t, z^t) = \frac{1+D_O^I(x^t,y^t,z^t)}{1+D_O^I(x^{t+1},y^{t+1},z^{t+1})} \tag{3-21}$$

Similar to the intertemporal MLI, we can decompose the meta-frontier MLI as below:

$$ML^G(x^t, y^t, z^t) = \frac{\left(1+D_O^t(x^t,y^t,z^t)\right)}{\left(1+D_O^{t+1}(x^{t+1},y^{t+1},z^{t+1})\right)} \left\{ \frac{\frac{\left(1+D_O^I(x^t,y^t,z^t)\right)}{\left(1+D_O^t(x^t,y^t,z^t)\right)}}{\frac{\left(1+D_O^I(x^{t+1},y^{t+1},z^{t+1})\right)}{\left(1+D_O^{t+1}(x^{t+1},y^{t+1},z^{t+1})\right)}} \right\} \left\{ \frac{\frac{\left(1+D_O^G(x^t,y^t,z^t)\right)}{\left(1+D_O^I(x^t,y^t,z^t)\right)}}{\frac{\left(1+D_O^G(x^{t+1},y^{t+1},z^{t+1})\right)}{\left(1+D_O^I(x^{t+1},y^{t+1},z^{t+1})\right)}} \right\} \tag{3-22}$$

Here, we redefine *TGR* as:

$$TGR^t = \frac{1+D_O^G(x^t,y^t,z^t)}{1+D_O^I(x^t,y^t,z^t)} \tag{3-23}$$

Then, we can obtain:

$$ML^G = \frac{TE^{t+1}}{TE^t} \cdot \frac{BPG^t}{BPG^{t+1}} \cdot \frac{TGR^t}{TGR^{t+1}} \tag{3-24}$$

and we can achieve:

$$ML^G = EC.BPC.TGC \tag{3-25}$$

where *TGR* and *TGC* stand for technology gap ratio and technology gap change respectively. Here $ML^G > 1$ if a DMU shows an eco-efficiency and technology improvement with respect to other DUM's from different groups in all periods; $ML^G = 1$ if the DMU does not show any growth or drop and $ML^G < 1$ if it shows a decrease in the same factors with respect to other DMU's from different groups in all periods. From (3-23), it is obvious that *TGR≥1*; *TGR* equals 1 if and only of the particular DMU's is located on the global frontier. To calculate *D* function, again we use (3-11) applying *MLIA*.

3.6. Different Productivity Indices and Heterogeneity amongst Power Plants

Although Cobb and Douglas (1928) considered the capital and labor factors of production, many others such as (Kurz and Salvadori, 1997) added land to this compound. These are not the only main factors of production that have been presented in the production theory. This is while new growth theory takes the technology as a factor of production (Aghion and Howitt, 1997; Cornwall and Cornwall, 1994). In so doing, heterogeneity amongst power plants is highlighted, particularly when the objective of the study is to compare different power plants in terms of their productivity.

Hydro power plants in this research are treated as a special case since a hydro power plant neither consumes fuel nor does it produce any emissions. Therefore, in the nature, they use one less input (fuel) to produce one less bad output (emission). In fact, they consume zero fuel, to produce zero emission. Although this may increase their eco-efficiency in comparison with the thermal power plants, it also reflects the reality of green electricity that is generated by this type of power plant.

Furthermore, different power plant technologies have different prices. The deprecation of the facilities employed by a power plant, successfully proxies the difference amongst the technologies used. By cost efficiency analysis, we depict which type of power plant pays less to generate the same level of electricity.

Finally, by evaluating allocative efficiency, we exhibit which type of power plants, from the cost point of view, allocated the proportions of inputs to produce the same level of outputs more successfully.

In the next section, we present the indices of productivity and productivity changes and discuss how these factors enable the researcher to perform/draw a comprehensive comparison between the firms performing similar jobs using different technologies.

3.6.1. Malmquist Luenberger Index and Cost and Allocative Efficiency Changes

Malmquist and Malmquist Luenberger indices have already been addressed in Section 2.12. However, to examine the productivity of the different power plants from every angle, observing the cost and allocative efficiency seems to be necessary. Toward this end, we define good input and bad output requirements set as $L^t(y^t)=\{(x^t,z^t)$, where x can produce y together with $z\}$. If $C^t(x^t,z^t,w^t)=min_{x^t,z^t}\{\sum_{i=1}^{I} w_{xi}^t x_i^t + \sum_{k=1}^{K} w_{zk}^t z_k^t , \in L^t(y^t)\}$ indicates the minimum possible cost to produce y^t, in period t, wherew_{xi}^t is the cost of one unit of the ith input consumed and $w_{zk}^t$is the charge of one extra unit of the kth bad output produced in the period t. Farrell (1957) defines the cost efficiency as the ratio of the minimum possible cost to the actual cost, which is formulated in many studies (Ball et al., 2005; Jahanshahloo et al., 2007; Maniadakis and Thanassoulis, 2004; Mostafaee and Saljooghi, 2010) as follows:

$$CE^t = \frac{C^t(x^t,z^t,w^t)}{c^t} \tag{3-26}$$

Where CE^t denotes cost efficiency in the period t and $c^t = \sum_{i=1}^{I} c_i^t(x_i^t) + \sum_{k=1}^{K} c_k^t(z_k^t)$ indicates the actual cost in the period t, in which $c_i^t(x_i^t)$ is actual cost of the ith input and $c_k^t(z_k^t)$ is actual charge of the kth bad output in the period t. In addition, under the weak disposability conditions, we use the following model to calculate $C^t(x^t,z^t,w^t)$:

$$C^t(x^t, z^t, w^t) = \min_{x^t, z^t} \sum_{i=1}^{I} w_{xi}^t x_i^t + \sum_{k=1}^{K} w_{zk}^t z_k^t \tag{3-27}$$

St.

$$\sum_{n=1}^{N} \lambda_n x_{in}^t \leq x_i^t; i = 1,2, \dots, I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn}^t \geq y_{jo}^t j = 1,2, \dots, J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn}^t = z_k^t; k = 1,2, \dots, K$$

$$\sum_{i=1}^{I} HV_i^t x_{in}^t = \sum_{i=1}^{I} HV_i^t x_{io}^t$$

$$\lambda_n \geq 0 \,; n = 1,2, \dots, N$$

Where $\sum_{i=1}^{I} HV_i^t x_{in}^t = \sum_{i=1}^{I} HV_i^t x_{io}^t$ guarantees the minimum heating value needed to generate y_{jo}^t is supplied to the turbines. Without this constraint, all x_{in}^t for fuel inputs can get zero value which is impossible in real world because for thermal power plants no fuel combustions means no electricity generation.

In addition, (Fried et al., 2008)define allocative efficiency as the ratio of the cost efficiency to the input-oriented measure of technical efficiency, if based on Chung et al. (1997) the technical efficiency is formulated as:

$$TE^t = \frac{1}{1 + D_o^t(x^t, y^t, z^t)} \tag{3-28}$$

In order to measure $D_o^t(x^t, y^t, z^t)$ as an input oriented, Model (3-11) be rewritten as below:

$$D_o(x, y, z) = Max \sum_{l=1}^{L} \alpha l_l + \sum_{h=1}^{H} \alpha h_h + \sum_{m=1}^{M} \alpha_m + \sum_{k=1}^{K} \gamma_k \qquad (3\text{-}29)$$

st

$$\sum_{n=1}^{N} \lambda_n x l_{ln} \le x l_{lo} + \alpha l_l . 1 \; ; l = 1,2, \dots, L$$

$$\sum_{n=1}^{N} \lambda_n x h_{hn} \le x h_{ho} - \alpha h_h . 1 \; ; h = 1,2, \dots, H$$

$$\sum_{n=1}^{N} \lambda_n x_n \le x_{mo} - \alpha_m . 1 \; ; m = 1,2, \dots, M$$

$$\sum_{l=1}^{L} \alpha l_l - \sum_{h=1}^{H} \alpha h_h = 0$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \ge y_{jo} j = 1,2, \dots, J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \gamma_k . 1 \; ; k = 1,2, \dots, K$$

$$\lambda_n \ge 0 \; ; \; \alpha l_l \ge 0; \alpha h_h \ge 0; \alpha_m \ge 0; \gamma_k \ge 0; n = 1,2, \dots, N;$$

$$l = 1,2, \dots, L; \; h = 1,2, \dots, H; m = 1,2, \dots, M; \; j = 1,2, \dots, J; k = 1,2, \dots, K$$

Where, *xh* and *xl* denote high and low pollutant inputs, determined by the magnitude of their pollutant parts, and *x* represents the nonpolluting inputs such as the capital. As such, *αh* and *αl* are defined in terms of the rate of contraction and expansion of high and low pollutant inputs respectively, and *α* is the rate of contraction in nonpolluting inputs. Also, *αh* and *αl* are the pollutant parts of the high and low pollutant inputs respectively. It is evident that *αh>αl* and if *αh=αl,* there is no need for distinction between high and low pollutants. Consequently, we should have *H+L+M=I,* the total number of inputs. We add $\sum_{l=1}^{L} \alpha l_l - \sum_{h=1}^{H} \alpha h_h = 0$ to the model to guarantee that the same level of the fuel is delivered to the turbines to generate the same amount of electricity as the output. Otherwise, there is a possibility for all fuel input types to get zero, something which can happen practically.

Using the equations (3-26) and (3-28), we write the allocative efficiency formula as below:

$$AE^t = \frac{CE^t}{TE^t} = \frac{C^t(x^t,z^t,w^t)\left(1+D^t(x^t,y^t,z^t)\right)}{c^t} \tag{3-30}$$

Then, according to (Ball et al., 2005), the cost efficiency change is defined as:

$$CEFFCH_t^{t+1} = \frac{CE^{t+1}}{CE^t} = \frac{C^{t+1}(x^{t+1},z^{t+1},w^{t+1})}{C^t(x^t,z^t,w^t)}\frac{c^t}{c^{t+1}} \tag{3-31}$$

And the cost technical efficiency change is defined as:

$$CTECH_t^{t+1} = \left[\frac{C^t(x^{t+1},z^{t+1},w^{t+1})}{C^{t+1}(x^{t+1},z^{t+1},w^{t+1})}\frac{C^t(x^t,z^t,w^t)}{C^{t+1}(x^t,z^t,w^t)}\right]^{1/2} \tag{3-32}$$

Then, Malmquist cost productivity change (MCP) is defined as:

$$MCP_t^{t+1} = CEFFCH_t^{t+1}.CTECH_t^{t+1} = \left[\frac{C^t(x^{t+1},z^{t+1},w^{t+1})}{C^t(x^t,z^t,w^t)}\frac{C^{t+1}(x^{t+1},z^{t+1},w^{t+1})}{C^{t+1}(x^t,z^t,w^t)}\right]^{1/2}.\frac{c^t}{c^{t+1}} \tag{3-33}$$

Finally, we define the allocative change as:

$$AEFFCH_t^{t+1} = \frac{AE^{t+1}}{AE^t} = \frac{\left(1+D^{t+1}(x^{t+1},y^{t+1},z^{t+1})\right)C^{t+1}(x^{t+1},z^{t+1},w^{t+1})}{\left(1+D^t(x^t,y^t,z^t)\right)C^t(x^t,z^t,w^t)}.\frac{c^t}{c^{t+1}} \tag{3-34}$$

Finally, the indices presented in this section are applied to draw a complete picture of the environmental efficiency change of the power generation industry during the period of restructuring. In the next section, we will discuss how these indices allow for the possibility to compare power plants with different technologies.

3.7. Materials Balance Conditions and DEA Models

To operationalize MBP, Coelli et al. (2007) formulated the MBP requirements as below:

Let *a* and *b* be ($I\times 1$) and ($J\times 1$) non-negative coefficients of *x* and *y* respectively, which reflect the nutrient of the pollutant inside inputs and outputs base on MBP, the amount of pollutant should be written as:

$$z=a'x-b'y \tag{3-35}$$

This equation plays a key role in letting one decide whether or not a model is compatible with MBP. Coelli et al. (2007) introduced an input-oriented constant return to scale model which is compatible with MBP. This DEA-MBP model was successfully adopted to measure environmental efficiency of pig finishing farms, and later to electricity generation plants by Welch and Barnum (2009). This model was not the only successful approach toward incorporating MBP in DEA models. Färe et al. (2011), by employing a network DDF model which was consistent with MBP, measured the eco-efficiency of US coal-fired power plants using abatement technologies. In that study, it was admitted that the weak disposability axiom[1] as one of the core concepts of DDF was hardly consistent with MBP, so they created a relaxed condition to examine the possibility of using abatement technologies[2].

Coelli et al. (2007) have already shown that some previous models, in their general forms, were not consistent with MBP. Here, we consider one of the most popular forms of DDF model introduced by Chung et al. (1997) to demonstrate the incompatibility. Similar to other directional distance models, the DDF model seeks for the largest value of θ which

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[1] Weak disposability can be written as: $(y, z) \in P(x)$ and $0\leq\theta\leq 1$ imply $(\theta y, \theta z) \in P(x)$, while free or strong disposability can be defined as: $(y, z) \in P(x)$ and $y'\leq y$ imply $(y', z) \in P(x)$

[2] In this case, whereas electricity is the good output and SO_2 is the bad one, *b* which is the nutrient coefficient of good output is 0. Sulfur is not a part of electricity.

can keep the vector ($x, y+\theta y, z-\theta z$) inside the PPS. If we apply this vector to Equation(3-35), we will get: $z-\theta z=a'x-b'(y+\theta y)$. After some simplifications, we obtain: $z=a'x-b'y-\theta(b'y-z)$: here MBP holds only if $\theta(b'y-z)=0$. If $\theta=0$, then the unit has been located on the frontier; thus, the MBP holds. However, for non-efficient units in the interior of the PPS, the MBP conditions are not valid. On the other hand, if $b'y-z=0$, then $b'y=z$. It implies that the actual pollutant amount should be equal to the amount of pollutant released from the good outputs. This condition occurs only in a very limited number of circumstances because in the production technologies it is very hard to find an analogue with equal amount of generated pollutant and the pollutant that is generated by the good outputs. This situation is worsened when $b=0$, for example when electricity is the sole output. If so, $b'y=z$ implies $z=0$, which is explicitly a contradiction when a pollution generating technology is being dealt with.

On the other hand, the DEA-MBP model introduced by Coelli et al. (2007), in spite of its advantages, has its own limitations when applied in different industries. Coelli et al. (2007) DEA-MBP model for N decision making units (DMU) is as below:

$$min_{\lambda x_o^e} E x_o^e \tag{3-36}$$

$$st$$

$$\sum_{n=1}^{N} \lambda_n x_{ni} \le x_{oi}^e \qquad i=1,\dots,I$$

$$\sum_{n=1}^{N} \lambda_n y_{nj} \ge y_{oj} \qquad j=1,\dots,J$$

$$\lambda_n \ge 0, n=1,\dots,N$$

where the script o denotes the under-assessment of DMU, and x_o^e is the variable vector which is being calculated to find the best composition of the inputs generating the lowest amount of the pollutant. E is the nutrient vector.

There are several shortcomings in this DEA-MBP model. Firstly, this model neglects the real amount of the pollutant, which is hard to measure in the agricultural context. It is calculated by using the nutrient coefficient of inputs such as the emission factor, whereas in many fields of study – for instance, the electricity generation - the emission can be gauged directly. In addition, the model has a level of simplicity in using nutrients and cost coefficients to find the amount of the pollutant generated and the total cost of the production, which is a useful formulation to find trade-offs between the amount of the pollutant generated and the cost of the ingredients used. Nevertheless, this simple model cannot reflect the complexity existing in generation and disposing of the pollutant, like when abatement facilities are installed, or when a reward and charge mechanism, as mentioned in the calculation of total cost of fuel based on the fuel consumption rate[1], is used. Furthermore, this model can only be used for the input orientation category of efficiency measurement. Finally, in the case that the technology uses different ingredients to generate more than one pollutant, this model will still help find the optimal composition of the input required to generate the minimum amount of pollutant or run in the minimum cost condition., However, when the number of inputs is increased dramatically; the sensitivity of the model can be reduced and the validity of a DEA efficiency measurement system can be challenged seriously.

In sum, there still remains a need for a more comprehensive eco-efficiency measurement model to be consistent with MBP. Also, this type of models should not lose the comprehensiveness after under MBP conditions. In the next section, an approach to successful incorporation of MBP requirements in directional distance and slack-based

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[1] In many industries these types of incentives are imposed to control fuel which is consumed and to force the industries to improve their combustion technologies or run them in their best condition

DEA models will be introduced.

3.7.1. Incorporating MBP in DEA Models: a Discussion

In this section, we present a full disscussion of the pros and cons of including MBP requirements into the slack-based DEA and directional distance models. We focus on these types of models since this study aims for development of a more comprehensive and flexible MBP- enabled DEA model in order to measure ML index, and these two types of models are the popular choices in measuring the ML index.

We customize Model (2-10) to include bad outputs as below[1]:

$$D_o(y,\ z) = Max \sum_{j=1}^{J} \beta_j + \sum_{k=1}^{K} \gamma_k \tag{3-37}$$

$$st$$

$$\sum_{n=1}^{N} \lambda_n x_{in} \leq x_{io}\ ; i = 1,2,\dots,I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo} + \beta_j.1\ ; j = 1,2,\dots,J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \gamma_k.1\ ; k = 1,2,\dots,K$$

$$\lambda_n \geq 0\ ;\ \gamma_k \geq 0;\ \beta_j \geq 0;\ n = 1,2,\dots,N;\ j = 1,2,\dots,J; k = 1,2,\dots,K$$

Here, α, β and γ are vectors of variables, and D_o denotes the distance of DMU$_o$ from the frontier. Here in Model (3-37), we use $(x,y+\beta,z-\gamma)$ to draw the DMU toward the eco-efficiency frontier. Thus, by replacing $(x,y+\beta,z-\gamma)$ in Equation (3-35), we obtain: $z-\gamma=a'x-b'(y+\beta)$ which implies $z=a'x-b'y-b'\beta+\gamma$. Therefore, In order for the model to be MBP-

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[1] The third constraint guarantees null jointness property which is defined as: if $(y, b) \in P(x)$ and $b=0$ then $y=0$. Good and bad outputs are jointly produced (Chung et al., 1997)

compatible, we should either have $b'\beta-\gamma=0$ or $b'\beta=\gamma$. In this case, it means that the decreasing rate of the bad input should be equal to the increasing rate of the pollutant part in the good outputs. If $b=0$, in the case of electricity generation for example, we will get $\gamma=0$. This is because the firms cannot keep their inputs at the same level, increase their output and decrease the bad outputs at the same time, unless the technology is improved[1]. This will be possible only if the composition of inputs used is changed. Thus, Model (3-37) is customized as below:

$$D_o(x, y, z)= Max \sum_{i=1}^{I} \alpha_i + \sum_{j=1}^{J} \beta_j + \sum_{k=1}^{K} \gamma_k \tag{3-38}$$

$$st$$

$$\sum_{n=1}^{N} \lambda_n x_{in} \leq x_{io} - \alpha_i .1 \,; i = 1,2,\dots,I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo} + \beta_j .1 \,; j = 1,2,\dots,J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \gamma_k .1 \,; k = 1,2,\dots,K$$

$$\lambda_n \geq 0 \,; \ \alpha_I \geq 0; \beta_j \geq 0; \gamma_k \geq 0; n = 1,2,\dots,N; \ j = 1,2,\dots,J; k = 1,2,\dots,K$$

Then, to be consistent with MBP requirements, we should have $z-\gamma=a'(x-\alpha)-b'(y+\beta)$ so that we can get: $z=a'x-b'y-a'\alpha-b'\beta+\gamma$. Then, it is inevitable to have $a'\alpha=\gamma-b'\beta$. In this case, if $b\neq 0$, then we will get $\gamma-b'\beta>0$ since $a'\alpha>0$ for inefficient DMU's. This implies $\gamma>b'\beta$, which means the decrease in pollutants, should be strictly higher than the increase in the pollutant parts of the good outputs ($b'\beta$ is the amount of pollutant which is inside the good outputs). On the other hand, if $b=0$, then we will obtain $a'\alpha=\gamma$ which is the normal

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[1] Here, the technology is assumed to be fixed.

condition when good outputs do not generate any pollutants. As a result, Model (3-38) does not meet MBP requirements since the technology cannot expand the good inputs and contract the bad outputs with a drop in the inputs. However, in industries such as electricity, it is possible to do so with a change in the composition of the inputs.

Now, taking the input-oriented model into account, we obtain:

$$D_o(x,\, y,\, z) = Max \sum_{i=1}^{I} \alpha_i + \sum_{k=1}^{K} \gamma_k \tag{3-39}$$

$$st$$

$$\sum_{n=1}^{N} \lambda_n x_{in} \le x_{io} - \alpha_i .1\, ; i = 1,2,\dots,I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \ge y_{jo}\, ; j = 1,2,\dots,J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \gamma_k .1\, ; k = 1,2,\dots,K$$

$$\lambda_n \ge 0\, ;\ \alpha_i \ge 0; \gamma_k \ge 0; n = 1,2,\dots,N;\ i = 1,2,\dots,I; k = 1,2,\dots,K$$

Model (3-39) contracts inputs and bad outputs simultaneously. Again using equation (3-35), we achieve: $z-\gamma=a'(x-\alpha)-b'y$ which implies: $z=a'x-b'y-a'\alpha+\gamma$. Therefore, to be MBP-compatible, it is necessary to have $-a'\alpha+\gamma=0$. This implies $\gamma=a'\alpha$ which is the ordinary condition if output remain constant because it guarantees that the rate of decrease in inputs and pollutants will be identical.

We also introduce Model (3-40) below:

$$D_o'(x,y,z) = Max\ \theta \tag{3-40}$$

$$st$$

$$\sum_{n=1}^{N} \lambda_n x_{in} \leq x_{io} - g_{xi}.\theta; i = 1,2,\dots,I$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo} + g_{yj}.\theta\ ; j = 1,2,\dots,J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - g_{bk}.\theta\ ; k = 1,2,\dots,K$$

$$\sum_{i=1}^{I} g_{xi} + \sum_{j=1}^{J} g_{yj} + \sum_{k=1}^{K} g_{bk} = 1$$

$$\lambda_n \geq 0;\ g_{xi} \geq 0; g_{yk} \geq 0;\ g_{bj} \geq 0;\ n = 1,2,\dots,N;$$

$$i = 1,2,\dots,I, j = 1,2,\dots,J; k = 1,2,\dots,K$$

Model (3-40) is an equivalent to Model (3-38). This can simply be verified by $g_{xi}.\theta = \alpha_i$, $g_{yj}.\theta = \beta_j$ and $g_{bk}.\theta = \gamma_k$, where g_{xi}, g_{yj} and g_{bk} are the variable direction for the inputs, good and bad outputs respectively.

On the other hand, however distinct the advantages of the aforementioned models are, Coelli's DEA-MBP model has a significant advantage over them all. The DEA-MBP is designed to find the best composition of different fuel types to generate lesser pollutants. As understood from the above discussion, there is a variety of models which meet the MBP requirements, and one can choose one or more of them depending on the nature of the problem. However, due to the inherent properties of the distance and slack-based models, they fail to find the optimum composition of different fuel types required for generating the least possible amount of pollutants since inputs are altered simultaneously.

We also adopt Model (3-41) from Briec (1997), incorporating bad outputs:

$$Max\ \theta \tag{3-41}$$

st

$$\sum\nolimits_{n=1}^{N} \lambda_n x_{in} \leq x_{io}(1 - a_i.\theta)\ ; i = 1,2,\dots,I$$

$$\sum\nolimits_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo}(1 + b_j.\theta)\ ; j = 1,2,\dots,J$$

$$\sum\nolimits_{n=1}^{N} \lambda_n z_{kn} = z_{ko}(1 - c_k.\theta)\ ; k = 1,2,\dots,K$$

$$\lambda_n \geq 0\ ;\ n = 1,2,\dots,N;\ j = 1,2,\dots,J; k = 1,2,\dots,K$$

where a_i, b_j and c_k contain the price of the normalized input as well as the prices of good and bad outputs, which are called the orientation of the Farrell proportional distance. In our case, Materials Balance Principle, a_i, b_j and c_k are the same coefficients as in equation (3-35) with c_k=1 for k=1,..,K. These coefficients, instead of the price information of Briec's model, reflect the pollutant parts of inputs and output. Similar to the prices, it is of our interest to keep the pollutants in the minimum level. Without loss of generality, here we assume constant return to scale contrary to Briec's original model. By $x_{io}.a_i = g_{xi}$, $y_{jo}.b_j = g_{yj}$ and $z_{ko} = g_{zk}$, we can see that Model (3-40) and (3-41) are equivalent[1]. Accordingly, one can observe that the directions in Model (3-40) can reflect the magnitude of the pollutant part of the inputs and outputs, but in their normalized form[2].

The discussion provided in this section sheds light on the incorporation of MBP in the

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[1] Here, we can omit $\sum_{i=1}^{I} g_{xi} + \sum_{j=1}^{J} g_{yj} + \sum_{k=1}^{K} g_{bk} = 1$, which does not change the frontier, but plays the role of a scaling constraint to keep inefficiency variable, θ, inside [0,1].

[2] See Briec (1997) Equation (6)

directional distance and slack-based models. In the next section, a more comprehensive model is introduced to incorporate MBP in DEA models for eco-efficiency measurement.

3.7.2. Alternative DEA-MBP Model for the Eco-Efficiency Measurement

To formulate the eco-efficiency measurement problems incorporating MBP, we categorize inputs into high and low pollutant inputs and introduce the following model:

$$D_o(x,y,z) = \ Max \sum_{l=1}^{L} \alpha l_l + \sum_{h=1}^{H} \alpha h_h + \sum_{m=1}^{M} \alpha_m + \sum_{j=1}^{J} \beta_j + \sum_{k=1}^{K} \gamma_k \qquad (3\text{-}42)$$

st

$$\sum_{n=1}^{N} \lambda_n x l_{ln} \leq x l_{lo} + \alpha l_l .1 \, ; l = 1,2,\dots,L \qquad (3\text{-}42\text{-}1)$$

$$\sum_{n=1}^{N} \lambda_n x h_{hn} \leq x h_{ho} - \alpha h_h .1 \, ; h = 1,2,\dots,H \qquad (3\text{-}42\text{-}2)$$

$$\sum_{n=1}^{N} \lambda_n x_n \leq x_{mo} - \alpha_m .1 \, ; m = 1,2,\dots,M \qquad (3\text{-}42\text{-}3)$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo} + \beta_j .1 \, ; j = 1,2,\dots,J \qquad (3\text{-}42\text{-}4)$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \gamma_k .1 \, ; k = 1,2,\dots,K \qquad (3\text{-}42\text{-}5)$$

$$\sum_{l=1}^{L} \alpha l_l - \sum_{h=1}^{H} \alpha h_h = 0 \qquad (3\text{-}42\text{-}6)$$

$$\gamma_k - \sum_{j=1}^{J} b_{jk} \beta_l = \sum_{h=1}^{H} a h_{hk} \alpha h_h - \sum_{l=1}^{L} a l_{lk} \alpha l_l \, ; k = 1,2,\dots,K \qquad (3\text{-}42\text{-}7)$$

$$\lambda_n \geq 0 \, ; \ \alpha l_l \geq 0; \alpha h_h \geq 0; \alpha_m \geq 0; \beta_j \geq 0; \gamma_k \geq 0; n = 1,2,\dots,N;$$

$$l = 1,2,\dots,L; \ h = 1,2,\dots,H; m = 1,2,\dots,M; \ j = 1,2,\dots,J; k = 1,2,\dots,K$$

where, *xh* and *xl* denote high and low pollutant inputs, determined by the magnitude of their pollutant part: and *x* represents the nonpolluting inputs such as the capital. As such, *αh* and *αl* are defined as the rate of contraction and expansion of high and low pollutant inputs respectively, and *α* is the rate of contraction in nonpolluting inputs. Also, *ah* and *al* are the pollutant part of high and low pollutant inputs respectively. It is evident that *ah>al;* and if *ah=al,* there will be no need for any distinction between high and low pollutants. Consequently, we should have *H+L+M=I, the total number of inputs*. As a requirement for every mathematical programming model, it can be simply proven that Model (3-42) is feasible. Toward this aim, (3-42-1) to (3-42-5) are conventional slack-based model adopted from Färe and Grosskopf (2010a); Färe and Grosskopf (2010b). The constraint (3-42-6) is also consistent since at least we have $\alpha h=\alpha l=0$ for all $h=1,2,\ldots,H$ for the efficient DMU's, and $l=1,2,\ldots,L$ implies $\sum_{l=1}^{L}\alpha l_l-\sum_{h=1}^{H}\alpha h_h=0$. Besides, the constraint (3-42-7) is also consistent with other constraints, since otherwise there would be no DMU's in PPS which could operate under the first and second law of thermodynamics.

Model (3-42), (3-42-1) and (3-42-2) represent the model orientation toward increasing the consumption of the low-pollutant inputs and decreasing the high-pollutant ones simultaneously. This is accompanied by (3-42-6) which guarantees that minimum the actual amount of inputs are consumed to generate at least the same amount of good outputs and maximum the same amount of pollutants while trying to increase low-pollutant inputs and decrease the high-pollutant ones simultaneously (This property is achieved by the first and second constraints). (3-42-3) and (3-42-5) are conventional constraints of the adopted slack-based model and Model (3-21) imposed on nonpolluting inputs, good, and bad outputs respectively. Finally, (3-42-7) verifies the MBP-compatibility[1]. A thorough discussion on incorporation of MBP constraint is provided in the following.

The vector ($xh-\alpha h$, $xl+\alpha l$, $y+\beta$, $z-\gamma$) should be in the PPS. Thus, testing with equation (3-35), we obtain: $z=ah'.xh+al'.xl-b'.y+\gamma-ah'.\alpha h+al'.\alpha h-b'\beta$. Then, to be MBP-consistent, we

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[1] It can be directly seen that, (9-7) is neutral if k is a nonpolluting bad output.

should have:

$$\gamma\text{-}b'\beta = ah'.\alpha h\text{-}al'.\alpha l \tag{3-43}$$

where $ah' > al'$ together with (3-42-6) implies that the right hand side of (3-26 is strictly positive. Thus, the drop in the total pollutant amount - the left side - should be equal to the drop in the pollutant part of the inputs. This is because $b'\beta$ as the pollutant part of the good output remains constant since the amount of inputs has been kept constant by (3-42-6). Therefore, it is implies that $\gamma > b'\beta$. As a result, a drop in pollution should be strictly more than the growth in the pollutant part of the good outputs, which is something favorable. It is worthwhile to say that Model (3-40) and Model (3-41) can also be customized as Model (3-42). The distance function for these two models falls within the unity interval, [0,1].

3.8. An Alternative Approach to Discover the Underlying Productivity Index Trends

Here, we introduce an alternative method to observe the changes in of the power plants productivity index trends. We use the productivity index changes such as *ML*, *MCP* and *ALEFFCH* as the rate of change; and then, by including their effective capacity, we can calculate the aggregated rate of change for each period, S_{ML}, as follows:

$$S = \sum_{n=1}^{N}(ML_n.PEFFCAP_n - PEFFCAP_n) / \sum_{n=1}^{N} PEFFCAP_n \tag{3-44}$$

where:

ML_n= ML index rate for n^{th} power plant during a particular period[1]

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[1] Here ML is contemporaneous index

$PEFFCAP_n$= Effective Capacity for n^{th} power plant during a particular period

S= Aggregated Rate of productivity index change index by Effective Capacity

This index was introduced because the productivity index changes for each power plant did not provide a clear general trend during the 2003-2010period. It should be noted that a productivity index change is multiplied by effective capacity (as the magnitude of change), $PEFFCAP_n$, since the rate of change itself is useless in comparative analyses unless the capacity is taken into account.

3.9. Summary

In this chapter, we introduced the scope of the study: then, we devised the conceptual models of our DEA analysis and determined the input and output factors needed. In the next sections, input and output factors were defined and the formulas to calculate them as well as the data sources were presented. A method to tackle the common infeasibility problem in the Malamquist Luenberger Index measurement was introduced in Section 3.4. Meta frontier and three analyses of eco-efficiency, cost efficiency and allocative efficiency along with their corresponding trends, where the methods using the slack based models were already introduced in the sections 3.5 and 3.6. Moreover, in Section 3.7, we introduced a materials balanced principle for the slack based model to measure the eco-efficiency and eco-efficiency change indices. Finally, to have an overall view of the productivity index changes, we introduce a method to aggregate the rate and magnitude of change and draw a complete picture of the productivity change over a period.

Chapter 4.

Results and Analyses

4.1. Introduction

In this chapter, formulas and models introduced in Chapter 3 are applied to measure the productivity indexes changes of the Iranian power plants over an eight-year period of restructuring. As we mentioned earlier in Chapter 3, an evolution model was postulated for the purpose of this study, so different sets of inputs and outputs were employed to adopt the models. In the meantime, AIMMS 3.11, 3.12 and 3.13 were employed to adopt DEA models.

4.2. A Malmquist Luenberger Meta-Frontier Approach

In this stage of the study, we employed Model (3-12) to calculate distance measures. A conceptual representation of the eco-efficiency measurement model including its related input and output factors is presented as below:

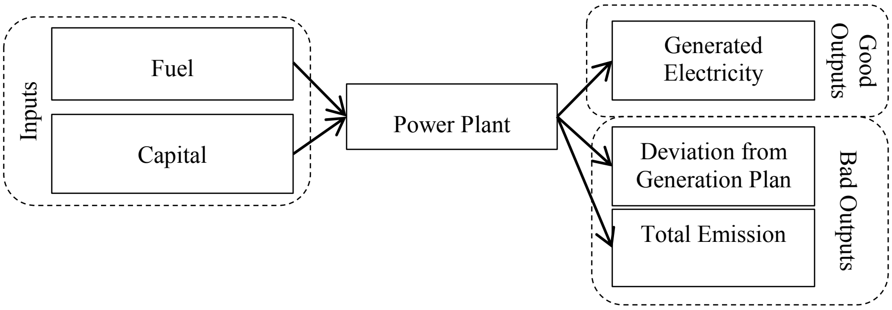

Figure 4-1: Eco-efficiency (Technical Efficiency) Measurement Conceptual Model

Here, we should remind that Model (3-12) is an output-oriented model. Once the models are employed and the indexes are calculated in the results of Equations (3-16) to (3-25), the related graphs were drawn to illustrate the productivity index changes.

Table 4-1: Technology Gap Ratios for Three Different Types of Thermal Power Plants during an Eight- year Period

TGR	2003	2004	2005	2006	2007	2008	2009	2010
Combined Cycle	0.9585	0.9668	0.9746	0.9843	0.9835	0.9596	0.9815	0.9856
Steam	0.9658	0.9831	0.9716	0.9740	0.9776	0.9745	0.9787	0.9788
Gas	0.9373	0.9277	0.9452	0.9539	0.9167	0.9177	0.9219	0.9258

Figure 4-2 depicts Table 4-1 entries.

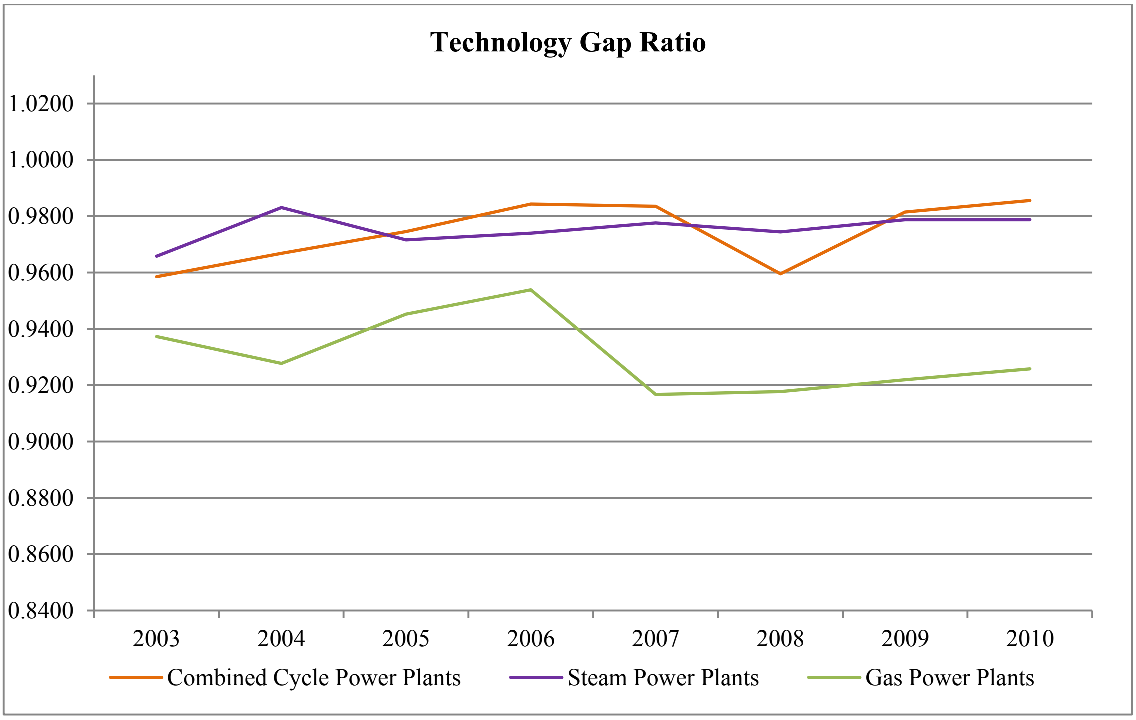

Figure 4-2: Technology Gap Ratios for Three Different Types of Thermal Power Plants during an Eight- year Period

As it can be observed in Figure 4-2, from 2003 onwards, the combined cycle and steam power plants have formed the technology frontier and shown a premier technology. This is a result of the mechanical design of such power plants which normally yields more efficiency in comparison with gas and steam power plants.

Moreover, the results of an eight-year period of power industry restructuring in Iran are given in the Table 4-2, 4-2, and 4-3.

Table 4-2: Malmquist-Luenberger Indices of Combined Cycle Power Plants

Period	2003-2004			2004-2005			2005-2006			2006-2007			2007-2008			2008-2009			2009-2010		
Malmquist-Luenberger Index	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global
CC1	1.004	0.962	0.993	1.007	1.040	1.007	0.985	1.000	1.000	0.906	0.946	0.946	1.014	1.027	1.020	0.978	1.000	1.003	0.973	0.965	0.967
CC2	1.028	1.040	1.052	0.990	0.997	0.999	0.972	0.979	0.978	1.086	0.996	0.996	0.991	0.943	1.000	1.133	1.088	1.016	0.886	0.966	0.978
CC3	1.008	1.015	1.030	0.992	0.941	0.927	1.062	1.056	1.049	0.939	0.945	0.945	1.021	1.001	0.949	1.047	1.032	1.055	1.037	1.022	1.005
CC4	1.033	1.051	1.030	1.071	0.966	0.981	1.026	1.030	1.035	1.045	1.006	1.001	1.037	1.020	1.013	1.009	1.021	1.024	0.997	0.994	0.983
CC5	1.027	1.107	1.010	1.051	1.046	0.992	1.136	0.953	0.999	0.921	0.972	0.971	1.124	0.906	1.009	1.035	1.053	0.999	1.058	1.125	1.033
CC6	0.959	0.979	0.967	0.997	0.926	0.938	1.041	1.021	1.032	0.977	1.016	1.014	1.010	1.014	1.064	1.062	1.047	1.013	0.982	0.946	0.958
CC7	1.056	1.085	1.021	1.118	1.006	0.959	1.196	0.955	0.918	0.859	1.023	1.022	1.098	1.002	1.035	1.058	1.060	1.016	1.065	1.004	1.012
CC8	1.030	1.008	1.002	1.070	0.975	0.963	1.076	1.011	1.008	1.031	0.943	0.943	1.051	1.033	1.073	1.042	1.009	1.012	1.022	0.974	0.973
CC9	1.011	1.014	0.996	0.940	0.942	0.976	1.078	1.061	1.029	0.585	1.050	1.050	1.098	1.029	1.054	1.104	1.093	1.030	0.996	0.969	0.996

The values of Malmquist-Luenberger indices of steam power plants in the period of restructuring are reported in the following tables:

Table 4-3: Malmquist-Luenberger Indices of Steam Power Plants

Period	2003-2004			2004-2005			2005-2006			2006-2007			2007-2008			2008-2009			2009-2010		
Malmquist-Luenberger Index	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global
St1	1.083	1.010	0.914	1.202	1.007	1.064	1.176	1.011	0.987	1.140	0.987	0.977	1.123	0.978	0.954	1.161	0.982	0.925	1.184	0.983	1.108
St2	1.001	0.973	0.969	1.098	1.020	1.001	1.024	0.960	0.962	1.102	1.020	1.028	1.070	1.029	1.043	1.035	0.972	0.957	1.065	0.995	1.011
St3	1.108	1.033	1.014	1.071	1.002	1.007	1.101	1.007	1.018	1.020	0.968	0.957	1.091	0.972	1.008	1.121	1.057	1.019	1.024	0.998	1.001
St4	1.045	1.013	0.999	0.874	0.957	0.991	1.045	0.984	0.970	1.056	1.007	0.990	1.035	1.001	0.997	1.256	1.060	1.056	0.883	0.985	0.996
St5	1.076	1.005	1.031	1.060	1.002	0.964	1.096	1.015	1.011	1.055	0.957	1.016	1.080	1.041	1.002	1.062	0.957	0.937	1.115	1.045	1.033
St6	1.151	1.095	1.000	1.133	0.947	0.890	1.106	0.973	1.011	1.138	0.968	0.969	1.081	1.024	1.128	1.077	1.017	0.973	1.063	1.010	0.986
St7	1.086	0.991	0.992	1.108	0.999	0.984	1.130	1.076	1.094	0.988	0.984	0.968	1.029	0.934	0.927	1.112	0.944	1.064	1.069	1.031	0.926
St8	1.014	0.985	0.945	1.046	1.023	1.058	1.065	0.942	0.976	1.053	1.000	0.956	1.108	0.998	1.072	1.044	1.023	0.991	1.073	0.987	0.954
St9	0.986	0.930	0.969	1.071	0.994	1.006	0.984	1.004	0.977	1.053	1.012	1.040	1.021	0.989	0.971	1.097	1.041	1.024	1.014	0.981	0.962
St10	1.106	0.999	0.961	1.113	1.033	1.066	1.075	0.975	0.967	1.088	1.001	0.971	1.081	1.029	1.069	1.066	0.972	0.957	1.092	1.000	1.014
St11	0.921	0.990	0.856	1.018	0.998	1.166	0.996	0.994	0.988	1.001	1.020	0.985	1.126	1.082	1.089	0.972	0.955	0.975	0.886	0.931	0.932
St12	1.008	1.007	1.004	1.009	0.999	1.003	0.953	0.998	0.993	0.999	0.987	0.996	0.998	0.999	0.975	1.019	0.973	0.981	1.028	1.009	1.003
St13	0.968	0.982	0.786	1.077	0.888	1.256	0.996	1.026	0.936	1.057	1.041	0.998	0.998	0.985	1.014	1.010	1.021	1.020	0.969	0.962	1.051
St14	1.051	1.046	0.998	0.860	0.954	0.974	0.947	0.995	0.984	1.454	1.022	1.029	1.066	1.002	1.015	1.007	0.960	0.907	1.089	1.013	1.070
St15	0.972	0.993	0.987	1.034	1.007	1.020	0.879	0.926	0.953	1.011	0.998	0.979	1.036	1.022	1.019	1.029	1.017	1.023	0.996	0.993	0.985
St16	1.066	1.001	0.984	1.070	0.995	1.016	1.056	0.991	0.993	1.068	0.972	0.967	1.133	1.039	1.004	1.062	1.000	1.034	1.062	0.993	1.005
St17	1.034	1.006	0.992	1.117	0.990	0.986	1.034	0.995	1.009	1.021	0.982	0.968	1.147	1.010	0.951	1.101	1.028	1.054	1.032	0.991	0.975
St18	1.094	1.015	1.027	1.021	0.987	0.973	1.101	1.009	1.011	1.027	0.998	1.013	1.080	1.009	1.022	1.045	1.002	0.975	1.047	0.993	0.991

Like the results of other types of power plant, the results for gas power plants can be seen in Table 6 below:

Table 4-4: Malmquist-Luenberger Indices of Gas Power Plants

Period	2003-2004			2004-2005			2005-2006			2006-2007			2007-2008			2008-2009			2009-2010		
Malmquist-Luenberger Index	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global	Contemporaneous	Intertemporal	Global
G1	1.385	1.000	0.980	0.719	1.000	1.006	2.223	0.985	0.990	0.701	0.951	0.967	1.585	1.068	1.044	0.451	1.000	0.989	0.911	0.954	0.976
G2	0.917	1.028	0.993	1.007	1.019	0.995	1.066	0.985	1.003	0.996	0.997	1.001	0.957	1.043	0.995	1.065	1.063	1.005	0.953	0.954	1.001
G3	0.990	0.992	0.968	1.053	1.040	1.029	0.939	0.965	1.011	0.986	0.973	0.982	1.081	1.066	1.017	1.009	1.013	1.003	0.973	0.973	1.004
G4	0.952	1.032	1.131	1.055	0.946	0.975	0.962	1.065	1.040	0.959	0.959	0.975	1.071	0.988	1.039	1.009	1.093	0.998	0.968	1.000	1.002
G5	0.917	1.026	0.997	1.061	1.003	0.957	1.000	1.001	1.005	1.059	0.965	0.923	0.980	1.014	1.123	0.999	1.073	0.997	0.970	0.969	1.003
G6	1.019	1.018	0.998	0.987	0.987	1.001	1.016	1.017	0.991	0.993	0.991	0.996	1.007	0.992	1.012	0.987	1.003	1.000	1.002	1.000	0.981
G7	0.917	1.027	0.912	0.960	1.025	1.079	1.060	0.944	1.015	0.919	1.039	0.881	0.990	1.002	1.117	0.981	1.037	1.013	0.988	0.989	0.930
G8	0.981	1.000	1.000	0.963	0.934	0.789	0.890	0.864	1.067	1.150	1.113	1.164	1.004	0.940	0.926	1.120	1.085	1.036	0.904	1.002	1.021
G9	0.888	1.041	0.980	1.017	1.014	0.869	1.097	0.973	0.969	0.991	0.979	0.964	0.993	1.062	1.110	0.926	1.021	1.050	0.977	1.060	1.058
G10	0.944	1.016	1.038	1.007	0.986	0.972	1.066	1.134	1.017	0.914	0.893	0.990	0.988	0.985	0.851	1.061	1.057	1.188	1.019	1.031	1.038
G11	0.961	0.996	1.027	0.982	0.982	0.957	1.015	1.017	1.005	0.997	0.995	0.990	0.979	0.980	1.050	1.051	1.049	0.987	1.008	1.008	1.008
G12	0.802	0.940	1.091	0.939	0.929	0.881	1.011	1.041	0.877	0.878	0.882	1.518	0.998	0.996	0.673	1.060	1.050	1.470	1.022	1.020	0.734
G13	0.871	0.756	0.779	0.933	0.938	0.955	0.851	1.018	0.987	1.152	0.952	0.919	1.272	1.132	1.212	1.307	1.253	1.129	0.849	0.789	0.969
G14	0.928	1.004	1.108	1.052	0.947	0.976	1.004	1.074	1.030	0.982	0.959	1.046	1.083	0.993	1.056	1.086	0.975	0.991	0.921	1.021	1.026
G15	0.937	1.003	1.008	0.979	1.037	0.985	0.954	0.956	1.004	1.061	0.995	0.998	1.062	0.990	1.008	1.083	1.008	1.003	1.091	0.987	1.002
G16	0.957	1.026	1.101	0.984	0.983	0.939	1.063	1.032	1.019	1.044	0.983	1.072	1.072	1.026	1.002	0.984	0.984	0.995	0.998	1.000	1.006
G17	0.969	0.971	1.037	1.058	1.057	0.999	0.959	0.959	0.889	0.910	0.907	1.175	1.113	0.968	0.890	1.010	1.011	1.044	1.144	1.166	1.078

Using results above to see a complete picture calculating aggregated value of global and intertemporal Malmquist-Luenberger indices we can compose Table 4-5 below:

Table 4-5: Technology Gap Ratios for Three Different Types of Thermal Power Plants during an Eight-year Period

Technology	2003	2004	2005	2006	2007	2008	2009	2010
Combined Cycle	1.0290	0.9844	1.0067	0.9957	0.9986	1.0397	0.9986	1.0290
Steam	1.0042	0.9889	0.9934	0.9958	1.0080	0.9989	0.9945	1.0042
Gas	0.9928	0.9898	1.0017	0.9726	1.0144	1.0455	0.9955	0.9928

Figure 4-3 depicts Table 4-5 entries.

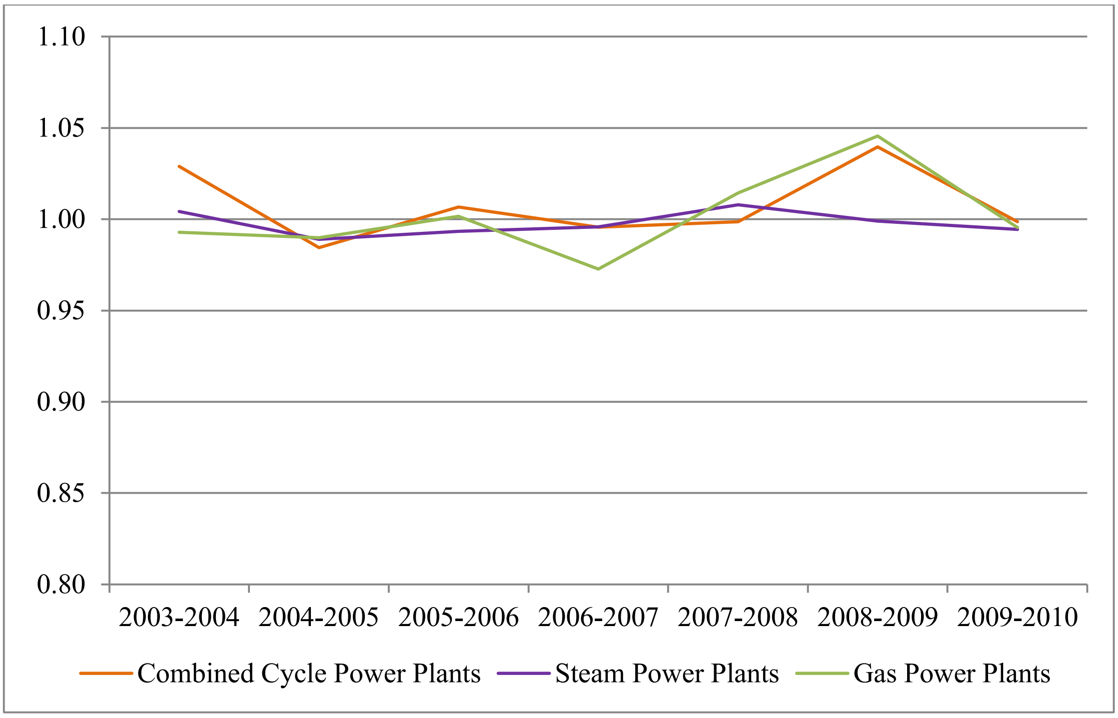

Figure 4-3: Aggregated Inter-temporal Malmquist-Luenberger[1] Indices for Three Types of Thermal Power Plants

Figure 4-3 shows a drop in eco-efficiency during the early years of restructuring, 2003-2004. The drop has continued for all power plants, more significantly for the ones which used gas turbines in 2005-2007 compared against the intertemporal frontier. Although gas and combined cycle power plants managed to increase their eco-efficiency in the following years, the steam power plants spectacularly failed to do so. A similar pattern of the aggregated Global Malmquist-Luenberger can be seen in Table 4-6 and Figure 4-7 below:

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[1] Aggregated Intertemporal Malmquist-Luenberger=$\sum_{n=1}^{C_s} \boldsymbol{ML_S^I}$

Table 4-6: Aggregated Best Practice Change, Technology Gap Change and Global Malmquist-Luenberger Index for Three Different Types of Thermal Power Plants during an Eight-year Period

	Technology	2003	2004	2005	2006	2007	2008	2009	2010
BPC	Combined Cycle	0.99163	1.00144	1.00132	0.98223	0.99019	1.04068	0.98604	0.99163
	Steam	1.00629	1.01226	0.97422	0.99044	1.00488	1.01446	0.98326	1.00629
	Gas	1.02320	0.98839	1.02134	0.97792	1.02193	0.98356	0.98876	1.02320
TGC	Combined Cycle	0.98903	0.99456	0.98944	0.99867	1.03012	0.97567	0.99777	0.98903
	Steam	0.96460	1.03713	0.99815	0.99363	1.00643	0.99445	1.00614	0.96460
	Gas	1.01705	0.97250	0.99731	1.06790	0.99232	1.00859	0.99907	1.01705
MLG	Combined Cycle	1.0165	0.9783	0.9958	0.9935	1.0276	1.0136	0.9952	1.0165
	Steam	0.9683	1.0236	0.9912	0.9893	1.0144	0.9930	1.0001	0.9683
	Gas	1.0087	0.9626	0.9952	1.0330	1.0073	1.0529	0.9905	1.0087

Figure 4-4 below depicts Table 4-6.

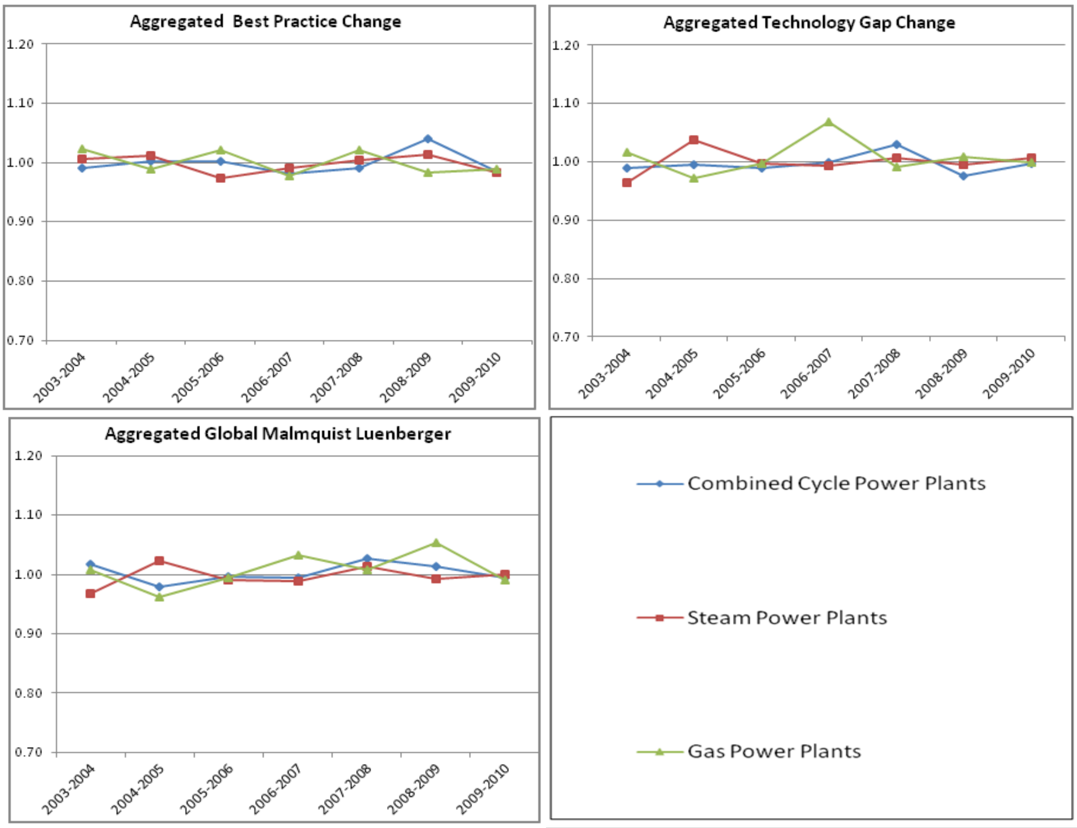

Figure 4-4: Some Aggregated Meta-Frontier Indices[1] for Three Types of Thermal Power Plants

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[1] Aggregated Global Malmquist-Luenberger=$\sum_{n=1}^{N} ML_n^G$

Aggregated Best Practice Change=$\sum_{n=1}^{N} BPC_n$

Aggregated Best Practice Change=$\sum_{n=1}^{N} TGC_n$

In Figure 4-4, one can see that except for the first two years of the period, the combined cycle and gas power plants managed to enhance their eco-efficiency in comparison with the global frontier. In addition, graphs show a similar pattern; however, the technology gap change s has experienced larger fluctuations. Moreover, based on the aggregated global Malmquist graph, power plants, except for gas turbine ones, failed to enhance their eco-efficiency from 2006 to 2007. This pattern will be analyzed and discussed in further detail in the next section.

Toward the end, we calculate the index introduced in Section 3.8. The aggregated rates of change of the three types of power plants during each period, S_{ML}, are summarized in Table 4-7 below:

Table 4-7: S_{ML} Index Aggregate Rate of Change

Periods	S_{ML}			
	Gas	Steam	Combined Cycle	Grand Total
2003-2004	-0.04002	0.01782	0.017883	0.01135
2004-2005	-0.06706	0.03847	0.02892	0.02389
2005-2006	0.194871	0.01317	-0.06794	0.04908
2006-2007	-0.08238	0.09731	0.06090	0.03121
2007-2008	0.125627	0.06566	0.04854	0.06731
2008-2009	-0.03415	0.05546	0.05265	0.04472
2009-2010	-0.0153	0.02666	0.01162	0.01781

Looking at Table 4-7, it is noticed that power plants all in all have managed to enhance their eco-efficiency during an eight years of restructuring. It can also be observed that gas turbines could not improve their eco-efficiency except during 2005-2006 and 2007-2008. All in all, the results suggest that there has been a significant eco-efficiency improvement in the sector. At this point, it is worth mentioning that although Figure 4-4 and Table 4-7 portrays a general improvement in the eco-efficiency of the power plants over the period, it is observed that amongst the individual gas power plants, the largest plants have performed less efficiently than the smaller ones, a fact inferred from the negative values of S_{ML} for 5 out of 7 periods of the study.

4.3. Aspects of Technological Heterogeneity in Iranian Power Generation Sector Illuminated by Changes in Different Productivity Indices

Model (3-27) was used to measure eco-efficiency and cost efficiency. We also customized (3-29) in the following fashion to work out eco-efficiency:

$$D_o(x, y, z) = Max\frac{\sum_{l=1}^{L}\alpha l_l+\sum_{h=1}^{H}\alpha h_h}{L+H} + \sum_{m=1}^{M}\alpha_m + \sum_{k=1}^{K}\gamma_k \tag{4-1}$$

$$st$$

$$\sum\nolimits_{n=1}^{N}\lambda_n xl_{ln} \le xl_{lo} + \alpha l_l.1\,; l = 1,2,\dots,L$$

$$\sum\nolimits_{n=1}^{N}\lambda_n xh_{hn} \le xh_{ho} - \alpha h_h.1\,; h = 1,2,\dots,H$$

$$\sum\nolimits_{n=1}^{N}\lambda_n x_n \le x_{mo} - \alpha_m.1\,; m = 1,2,\dots,M$$

$$\sum_{l=1}^{L}\alpha l_l - \sum_{h=1}^{H}\alpha h_h = 0$$

$$\sum\nolimits_{n=1}^{N}\lambda_n y_{jn} \ge y_{jo} j = 1,2,\dots,J$$

$$\sum\nolimits_{n=1}^{N}\lambda_n z_{kn} = z_{ko} - \gamma_k.1\,; k = 1,2,\dots,K$$

$$\lambda_n \ge 0\,;\ \alpha l_l \ge 0; \alpha h_h \ge 0; \alpha_m \ge 0; \gamma_k \ge 0; n = 1,2,\dots,N;$$

$$l = 1,2,\dots,L;\ h = 1,2,\dots,H; m = 1,2,\dots,M;\ j = 1,2,\dots,J; k = 1,2,\dots,K$$

In Model (4-1), we divided high and low polluting inputs slacks (inefficiencies) by the number of them (here gas, gasoil, fuel oil, making three) in order to leverage the role of fuel inefficiencies in the overall inefficiency. The allocative efficiency of the Iranian power plants over an eight-year period of restructuring in power industry was calculated using eco-efficiency and cost efficiency scores. The reader should remember that the model (3-27) and (4-1) are input-oriented ones in type.

Using Malmquist and Malmquist Luenberger type indices, we also indicated the trends of the aforementioned productivity measures over the same period. AIMMS 3.12, the student version, was employed to use the models. To measure the eco-efficiency and cost-efficiency, we employed the conceptual models illustrated in the Figure 3-1 and Figure 3-2 respectively. Technical efficiency values can be seen in the table below:

Table 4-8: Technical Efficiencies by Model (4-1) for Different Power Plant Technologies

Type	2003	2004	2005	2006	2007	2008	2009	2010
CC1	0.621427	0.894414	0.840722	0.882063	0.89886	0.834591	0.948845	1
CC2	0.752905	1	0.826377	0.774146	1	0.734993	1	0.809629
CC3	0.57112	0.852346	0.60492	0.573576	0.398065	0.758495	0.904408	1
CC4	0.82205	0.867776	0.770873	0.802762	0.731373	0.947557	0.994756	1
CC5	0.511318	0.718708	0.625969	0.55804	0.54509	0.59747	0.781224	1
CC6	0.698326	0.884787	0.671561	0.707499	0.759843	0.882033	0.852732	0.737159
CC7	0.486945	0.846378	0.704464	0.674359	0.476836	0.803235	0.856881	0.380209
CC8	0.87053	1	0.937765	0.912489	0.939843	1	1	1
CC9	0.863335	1	0.9588	1	0.872546	0.925652	0.964174	1
G1	0.813587	0.962072	0.832673	0.853354	1	1	0.901025	0.889523
G2	0.861849	0.901703	0.899429	0.88448	0.873697	0.920867	1	0.923445
G3	0.927825	0.931293	0.958441	0.931267	0.913619	1	1	1
G4	0.893382	0.909122	0.789744	0.931712	0.863636	1	0.909829	0.871969
G5	1	0.96808	1	0.889336	0.878136	1	0.8284	0.904246
G6	0.978302	0.945175	0.921455	1	1	0.930078	0.922623	0.975236

Type	2003	2004	2005	2006	2007	2008	2009	2010
G7	0.86347	0.885485	0.884012	0.838448	0.871184	0.861058	0.916456	0.898826
G8	0.763948	0.875744	0.779653	0.849601	0.891945	0.86115	0.869194	1
G9	0.810065	0.600297	0.513875	0.491459	0.482385	0.516394	0.522805	0.606138
G10	0.816889	0.930398	0.914483	0.944676	0.899808	0.896728	0.930626	0.898801
G11	0.944295	0.940124	0.901708	0.934342	0.931801	0.922628	0.96967	1
G12	0.267953	0	0	0	0	0	0	0
G13	0.701766	0.781644	0.58098	0.660407	0.611954	0.768104	0.774105	0.693878
G14	0.863146	0.862898	0.776577	0.859772	0.844105	0.844858	0.761719	0.814839
G15	0.790343	0.956237	0.884651	0.866996	0.887015	0.930005	0.88655	1
G16	0.88942	0.90882	0.885819	0.887834	0.913773	1	0.900438	0.954097
G17	0.914304	0.734426	0.709999	0.642275	0.458593	0.374392	0.299659	0.24366
H1	1	0.71227	0.67866	0.71224	0.58716	0.37698	0.86314	0.41868
H2	9.54E-01	1	0.94417	0.93165	0.94511	0.9029	1	1
H3	1	1	1	1	1	1	1	1
H4	0.87427	1	1	0.89138	0.89261	1	0.81459	0.9005
H5	1.00E+00	1	1	1	1	1	1	1
H6	1	1	0.91948	0.96327	1	1	1	1
H7	0.82188	0.82264	0.75197	0.75056	0.74596	0.63915	0.6309	0.62511
H8	0.97033	0.99856	0.95639	1	1	1	1	0.89626
St1	0.23728	0.67879	0.32339	0.26486	0.56838	0.41032	0.32461	0.20319
St2	0.86608	0.93724	0.93193	0.86997	0.89707	1	0.90945	0.91014
St3	0.81007	0.90286	0.90207	0.93528	0.90755	0.8678	0.94175	0.96728
St4	0.93786	1	0.85981	0.82441	0.80179	0.84836	1	1
St5	0.81461	0.80671	0.7111	0.73695	0.80919	0.61681	0.58998	0.75022
St6	0.82013	1	0.9927	0.8738	0.91104	1	0.8235	0.92927
St7	0.95114	0.71698	0.63882	0.67734	0.66431	0.64229	0.60636	0.57095
St8	0.91494	0.9897	1	0.93642	0.91103	1	1	0.95359

Type	2003	2004	2005	2006	2007	2008	2009	2010
St9	1	1	1	1	1	1	1	1
St10	0.86176	0.74298	0.76935	0.79589	0.71784	0.75041	0.73002	0.56359
St11	0.72352	0.53355	0.68706	0.47402	0.35067	1	0.70343	0.80346
St12	0.95174	1	0.81937	1	1	1	0.86185	0.7875
St13	0	0.72813	0.62491	0.66915	0.73448	0.81936	1	1
St14	0.39599	1	0.81317	0.91024	0.84779	1	0.87573	1
St15	0.93656	0.67513	0.74929	0.58884	0.60123	0.52884	0.92239	0.78479
St16	0.67784	0.7418	0.7002	0.75886	0.7258	0.77592	0.66414	0.78238
St17	0.76002	1	1	1	0.9385	0.96834	1	1
St18	0.96683	0.91646	0.8846	0.90269	0.89843	0.89724	0.90252	0.88673

Cost efficiency values are seen in the table below:

Table 4-9: Cost Efficiencies by Model (3-27) for Different Power Plant Technologies

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
CC1	0.159462107	0.1706038	0.1747113	0.1827955	0.2049611	0.1899393	0.1877961
CC2	0.158297666	0.143719	0.1644248	0.1581956	0.1850883	0.1717767	0.1862856
CC3	0.176122417	0.1833206	0.1848773	0.1905106	0.2146302	0.2235283	0.209847
CC4	0.171754563	0.2402826	0.2220816	0.285649	0.3339051	0.4049086	0.3695058
CC5	0.860613087	0.1808997	0.1853089	0.1945102	0.2374031	0.2298643	0.2077322
CC6	0.212161479	0.143879	0.1591873	0.1627355	0.2127247	0.1980483	0.1862408
CC7	0.159764069	0.1990861	0.1498361	0.1712575	0.2108119	0.2211433	0.1706563
CC8	0.260561399	0.2364478	0.2009002	0.2109878	0.2778196	0.1541923	0.1468491
CC9	0.296402502	0.241363	0.2227583	0.2283275	0.2223238	0.2466459	0.2326684
G1	0.097349921	0.2022424	0.211516	0.2412799	0.2500308	0.2924577	0.2315606
G2	0.391105587	0.1377256	0.1106201	0.3683635	0.4034655	0.4190264	0.4302733
G3	0.529610369	0.5402448	0.4290483	0.4556145	0.3809205	0.5485349	0.4374031
G4	0.343216094	0.1731806	0.0804697	0.2803534	0.2451299	0.2869924	0.2557966

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
G5	0.111796828	0.1950404	0.0892284	0.3890227	0.2947664	0.3935863	0.3475363
G6	0.278628772	0.3676728	0.3598453	0.3585559	0.3829562	0.4166186	0.3391666
G7	0.043411695	0.077258	0.0975617	0.0362647	0.1081352	0.1494344	0.1668839
G8	0.336996386	0.349002	0.3427426	0.3545359	0.3864123	0.4165483	0.3482598
G9	0.241003244	0.2722977	0.2820291	0.2808563	0.2980839	0.344736	0.2474134
G10	0.401454697	0.4447693	0.4478108	0.4046821	0.4137333	0.4279082	0.3482208
G11	0.35299533	0.3467319	0.2544736	0.3678505	0.3771377	0.377702	0.3193728
G12	0.720671473	0.4415997	0.3667383	0.6040178	0.6109998	0.6409439	0.5157144
G13	0.441133305	0.4375733	0.3292874	0.4439336	0.4449973	0.5080717	0.3788773
G14	0.2810847	0.3119483	0.2226752	0.3034523	0.2790642	0.3152996	0.2219761
G15	0.275783149	0.2308159	0.1504081	0.2900639	0.3076803	0.2955787	0.2458527
G16	0.094388695	0.2085237	0.1959503	0.1834606	0.2108544	0.271535	0.2097632
G17	0.19735383	0.2007534	0.2432879	0.2155604	0.2915049	0.3142368	0.2670772
H1	0.38952177	0.1485158	0.0778282	0.2435225	0.2307777	0.1441352	0.1930008
H2	0.155345701	0.2122819	0.163864	0.1370977	0.1670059	0.1576492	0.2232098
H3	0.399237644	0.1593784	0.0968007	0.3437647	0.3614228	0.3571744	0.3244221
H4	0.141568635	0.1647589	0.1416615	0.1234663	0.1168892	0.0590175	0.0528611
H5	0.095783824	0.1068108	0.1087754	0.1113622	0.1164838	0.1188583	0.130459
H6	0.140170501	0.1288845	0.1558239	0.1487396	0.1625545	0.1636356	0.1401196
H7	0.192678983	0.1772205	0.1802309	0.1734446	0.1737871	0.1606828	0.1834431
H8	0.293085488	0.3283173	0.3041113	0.3381106	0.3355626	0.3390807	0.3538679
St1	0.217012499	0.2368573	0.2397118	0.2391287	0.2694478	0.2721939	0.2443253
St2	0.371287217	0.3743879	0.3962634	0.3580239	0.4155477	0.4560666	0.3524662
St3	0.363599848	0.408403	0.3677981	0.4274671	0.4256463	0.4047358	0.3726436
St4	0.16828024	0.1955153	0.1879117	0.1772489	0.2149473	0.2121576	0.2277787
St5	0.312834198	0.3366167	0.3180533	0.3171543	0.3353113	0.3499219	0.285734
St6	0.161723002	0.1668953	0.1671903	0.1763016	0.2042944	0.2327944	0.2278238

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
St7	0.096304773	0.178147	0.1362132	0.1526604	0.1735146	0.1720414	0.133636
St8	0.294598631	0.2982438	0.3327687	0.2882435	0.3356297	0.369398	0.3177469
St9	0.16770592	0.2141296	0.190919	0.1886459	0.2180077	0.2410023	0.2056166
St10	1	0.4486158	0.4741159	0.4553616	0.4747749	0.5049895	0.4006085
St11	0.347766534	0.3078003	0.2796216	0.2489732	0.2570003	0.2971722	0.2369998
St12	0.152795039	0.1784052	0.1834525	0.180229	0.2104139	0.2193561	0.1986638
St13	0.098644378	0.1160914	0.1068452	0.1075178	0.131679	0.1266901	0.1233548
St14	0.256886927	0.2749931	0.2770526	0.2637002	0.3097661	0.3500273	0.295665
St15	0.159458129	0.1824577	0.1912652	0.1931412	0.2201744	0.2234809	0.2079886
St16	0.15730667	0.2005257	0.1950069	0.1872913	0.1816999	0.2495767	0.2179433
St17	0.168394189	0.190707	0.1908966	0.1922356	0.2133379	0.2244659	0.2091982
St18	0.464820736	0.3671156	0.3355179	0.3485749	0.368931	0.3906429	0.3319754

Furthermore, allocative efficiency values are presented in the table below:

Table 4-10: Allocative Efficiencies for Different Power Plant Technologies

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
CC1	0.12212	0.21268	0.25092	0.28415	0.25003	0.29246	0.25320
CC2	0.38952	0.20664	0.10567	0.32842	0.33944	0.23488	0.21794
CC3	0.16517	0.21228	0.17405	0.14845	0.17746	0.17312	0.22321
CC4	0.44298	0.34035	0.42027	0.45210	0.40208	0.43440	0.40013
CC5	0.46487	0.15614	0.12300	0.41992	0.46158	0.45254	0.43027
CC6	0.43917	0.40635	0.42629	0.41442	0.46433	0.45607	0.38260
CC7	0.58179	0.59074	0.44890	0.49355	0.41845	0.54853	0.43740
CC8	0.45788	0.46237	0.40789	0.46098	0.47052	0.45881	0.39314
CC9	0.18256	0.19552	0.21724	0.21495	0.26354	0.24467	0.22778
G1	0.39317	0.19459	0.09930	0.30355	0.28325	0.28699	0.27757
G2	0.39924	0.15938	0.09680	0.34376	0.36142	0.35717	0.32442

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
G3	0.11180	0.20351	0.08923	0.44118	0.33573	0.39359	0.40384
G4	0.16587	0.16476	0.14166	0.13971	0.13121	0.05902	0.06211
G5	0.39201	0.42512	0.42034	0.41822	0.40828	0.48543	0.39635
G6	0.24188	0.19511	0.20569	0.20891	0.22860	0.22169	0.19687
G7	0.20144	0.16690	0.16855	0.20326	0.22502	0.23279	0.26579
G8	0.28688	0.39509	0.39131	0.35856	0.38296	0.44606	0.36395
G9	0.21170	0.14372	0.19621	0.20148	0.18509	0.21778	0.18629
G10	0.27924	0.22014	0.26619	0.28893	0.36197	0.27808	0.22879
G11	0.05150	0.08929	0.11016	0.04336	0.12402	0.17042	0.18005
G12	0.10273	0.24673	0.19098	0.21233	0.23994	0.23423	0.18330
G13	0.44560	0.40799	0.42682	0.41913	0.43403	0.47500	0.39127
G14	0.09578	0.10681	0.10878	0.11136	0.11648	0.11886	0.13046
G15	0.21348	0.28350	0.27873	0.35390	0.43620	0.42637	0.37134
G16	0.30350	0.42035	0.43465	0.45389	0.47405	0.51322	0.35889
G17	0.32881	0.30242	0.33277	0.31045	0.36968	0.36940	0.31775
H1	0.50181	0.48688	0.49044	0.43181	0.46101	0.47257	0.37103
H2	0.14017	0.12888	0.16979	0.15536	0.16255	0.16364	0.14012
H3	0.16771	0.21413	0.19092	0.18865	0.21801	0.24100	0.20562
H4	1.18873	0.60546	0.59585	0.56796	0.62755	0.63236	0.50273
H5	1.43478	0.25012	0.26247	0.29866	0.36057	0.32337	0.25064
H6	0.47903	0.50310	0.37704	0.40762	0.44732	0.29717	0.30336
H7	0.29954	0.16643	0.21739	0.22040	0.27099	0.22166	0.21214
H8	0.37984	0.37497	0.28232	0.39711	0.40647	0.40724	0.32852
St1	0.16286	0.17841	0.22034	0.18023	0.21041	0.21936	0.22458
St2	0.27167	0.24069	0.19913	0.23882	0.33659	0.26512	0.19372
St3	0.23332	0.15902	0.15146	0.15061	0.17155	0.14982	0.12335
St4	1.44091	1.04230	0.77500	1.33577	1.30782	1.28868	1.00264

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
St5	0.46871	0.27499	0.33468	0.29237	0.36354	0.35003	0.33036
St6	0.30662	0.23645	0.21482	0.23336	0.29688	0.15419	0.14685
St7	0.23953	0.21998	0.23000	0.22586	0.22414	0.21928	0.24737
St8	0.35170	0.24136	0.23297	0.22833	0.25464	0.26518	0.24054
St9	0.17327	0.26309	0.24465	0.28935	0.32030	0.32989	0.22323
St10	0.62074	0.56754	0.48289	0.62657	0.64193	0.62714	0.45969
St11	0.33360	0.37013	0.27806	0.35500	0.32868	0.36473	0.27192
St12	0.22649	0.27095	0.26009	0.24201	0.23852	0.30609	0.28706
St13	0.35472	0.24456	0.16972	0.33680	0.34733	0.31649	0.27219
St14	0.22357	0.19071	0.19090	0.19224	0.22830	0.23165	0.20920
St15	0.10864	0.23439	0.22086	0.20839	0.23159	0.27153	0.22948
St16	0.22044	0.27328	0.32183	0.30898	0.47150	0.51291	0.44368
St17	0.48587	0.40883	0.37862	0.38967	0.41167	0.43121	0.36253
St18	0.30496	0.32896	0.31888	0.33811	0.33556	0.33908	0.35387

The following table has been compiled using the mean values within different types of power plants:

Table 4-11: Mean Technical, Cost and Allocative Efficiency Values for Different Types of Power Plants during an Eight-year Period

	Technology	2003	2004	2005	2006	2007	2008	2009	2010
TE	Combined Cycle	0.70196	0.89088	0.72831	0.70924	0.56893	0.68664	0.85860	0.82076
	Steam	0.75702	0.85391	0.80043	0.78993	0.79362	0.84032	0.82532	0.82739
	Gas	0.87053	0.85078	0.77628	0.81076	0.79972	0.77895	0.78213	0.83251
	Hydro	0.95252	0.94168	0.90633	0.90614	0.89635	0.86488	0.91358	0.85507
CE	Combined Cycle	0.27695	0.19828	0.18949	0.20264	0.23925	0.23205	0.21624	0.27620
	Steam	0.28321	0.26669	0.26005	0.25518	0.28197	0.30148	0.26125	0.28260
	Gas	0.30667	0.29758	0.25365	0.33498	0.34261	0.38624	0.32001	0.28492
	Hydro	0.20733	0.18219	0.15702	0.20689	0.21264	0.19166	0.20458	0.21239
AE	Combined Cycle	0.36067	0.30923	0.28603	0.35744	0.36082	0.36616	0.32952	0.30296
	Steam	0.36265	0.31920	0.29027	0.34291	0.37339	0.36902	0.31235	0.32824
	Gas	0.24851	0.24267	0.23283	0.28306	0.29988	0.31095	0.27288	0.28421
	Hydro	0.57395	0.34125	0.32328	0.33344	0.36931	0.34488	0.28927	0.29254

Using the mean values in Table 4-11, the average values of technical, cost, and allocative efficiency of different types of power plants are delineated here in Figure 4-5.

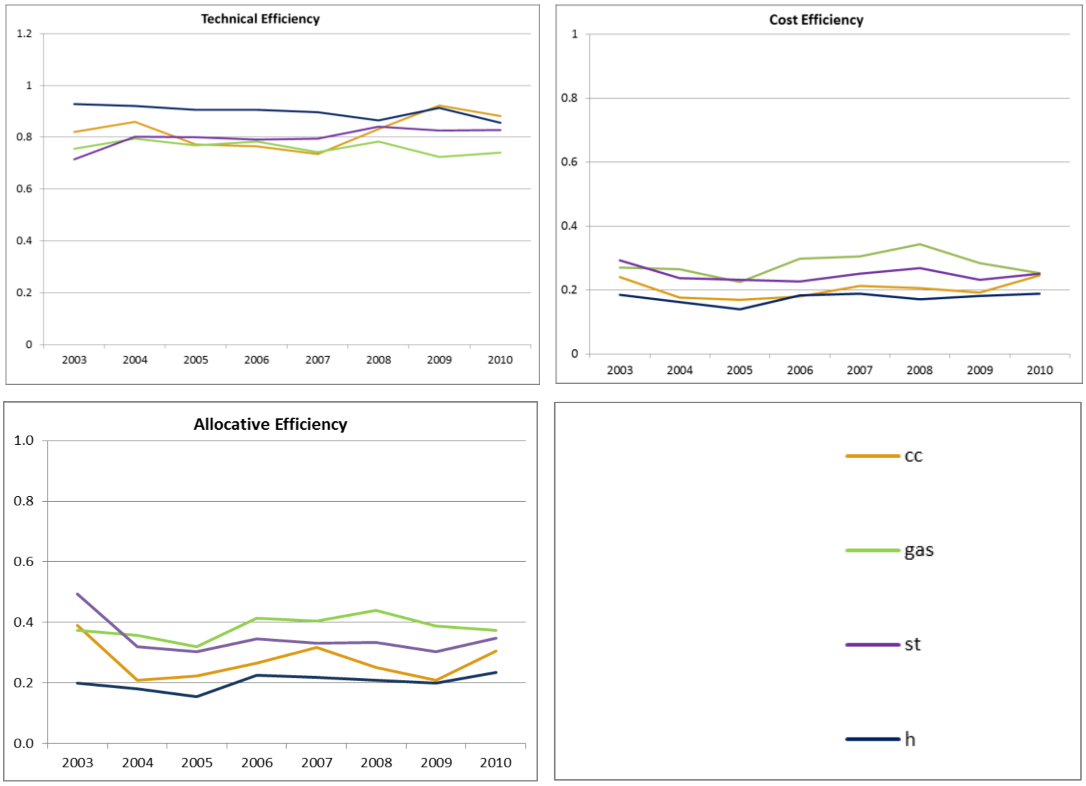

Figure 4-5: Average Technical, Cost and Allocative Efficiency of Different Types of Power Plants

As expected, it can be observed that, hydro power plants, on average, have been more eco-efficient because in this type of power plants no fuel is used, so no emissions are produced obviously. It is true that hydro power plants have been less cost-efficient as a result of not use any fuel and producing no emissions; however, enormous investments are required for supplying their electricity generation equipment as well as hydroelectric dam facilities and installations. During the same period, except for the first year, gas technology has proven more cost efficient as it employs smaller and cheaper electricity generation facilities and mostly consumes gas as the main fuel which contains much lower amounts of sulfur than the other types of fuels do and carries almost zero social costs caused by emissions. Moreover, gas technology has shown a more allocative efficiency, while hydro power plants have been less allocatively efficient. A drop in allocative efficiency can be observed from 2003 to 2004. This is due to a growth in the technical efficiency which has been accompanied by a drop in the cost efficiency in the same period.

To observe the trend of eco-efficiency changes, we calculated ML and compiled Table 4-15 below.

Table 4-12: ML Index for Different Power Plant Technologies

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
CC1	1.45390	0.98625	1.00582	0.95791	0.89560	1.15778	1.03116
CC2	1.43610	0.95401	0.91494	1.21420	0.86188	1.20784	0.82780
CC3	1.45125	0.86650	0.91966	0.72890	1.28784	1.05197	1.12905
CC4	1.07229	0.95211	1.00436	0.92668	1.23298	1.01581	0.91899
CC5	1.22782	1.07700	0.88122	0.98375	0.97704	1.19011	1.24934
CC6	1.35424	0.91335	0.95431	1.01261	1.10155	0.99581	0.84406
CC7	1.42977	0.99518	0.90805	0.84937	1.22370	1.04813	0.75196
CC8	1.21854	0.94504	0.95734	1.02122	1.05064	1.01125	0.93986
CC9	1.29710	0.95450	1.02494	0.85650	1.05552	1.07641	1.00558
G1	1.05012	0.90082	0.99490	1.08380	0.99872	0.90541	0.99788
G2	1.04962	1.02004	0.97537	0.99613	1.05847	1.08134	0.93634
G3	1.01395	1.04569	0.96062	0.98406	1.09278	1.02268	0.99562
G4	1.02131	0.91185	1.13784	0.93586	1.14939	0.92115	0.97726
G5	0.95546	1.05095	0.85864	0.99511	1.13944	0.85961	1.07237
G6	0.95986	0.98903	1.08658	0.95718	0.97740	1.00075	1.04588
G7	1.02575	1.02487	0.94356	1.04241	1.00431	1.06752	0.99056
G8	1.14592	0.94209	1.05310	1.05021	0.92936	1.01755	1.11438
G9	0.81874	1.00364	0.95134	1.01362	1.06543	1.03077	1.07398
G10	1.15950	1.01349	1.01317	0.95078	1.00415	1.04149	0.96943
G11	1.00093	0.97831	1.02412	0.99945	0.99792	1.05422	1.00086
G12	0.87377	1.15916	0.92561	1.01549	1.04972	1.05666	1.01332
G13	1.11408	0.88631	1.03239	0.97449	1.16443	1.02795	0.94905
G14	1.01323	0.95169	1.06300	0.99051	1.01156	0.95086	1.04543
G15	1.32180	0.95043	0.97116	1.02755	1.04797	0.96344	1.11889

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
G16	1.03110	1.00032	0.98846	1.03154	1.09588	0.93646	1.07041
G17	0.82702	1.03991	0.91539	0.88318	0.98430	0.98832	0.99331
H1	0.68722	1.08554	1.00297	0.89240	0.00069	1.38077	0.87603
H2	1.06370	0.94098	0.98086	1.01869	0.93430	1.09622	1.01523
H3	0.99469	0.96893	1.02924	0.96886	0.60405	0.98296	1.19837
H4	1.21974	1.00584	0.86491	1.00753	1.02350	0.87042	1.12708
H5	0.95415	1.13639	1.00100	0.99296	0.68810	0.89666	1.30934
H6	0.98722	1.02057	1.03767	0.89722	0.00073	0.91448	1.28263
H7	0.98966	0.98484	0.98046	1.00912	0.91853	0.99444	1.04480
H8	1.00730	0.99295	1.04900	0.98934	0.92686	1.00933	0.96987
St1	1.52215	0.81098	0.91055	1.24017	0.92349	0.96588	0.97649
St2	1.14971	1.01272	0.92032	1.03147	1.13836	0.91250	1.00117
St3	1.13770	1.01975	1.01927	0.96488	0.97096	1.07663	1.02656
St4	0.95868	0.85006	0.88629	0.98095	1.04490	1.11570	0.97266
St5	1.10286	0.93028	0.98237	1.05311	0.87178	0.96336	1.10255
St6	1.33999	0.97113	0.85515	1.04624	1.06753	0.87386	1.09891
St7	0.77134	0.98981	1.00241	0.99604	1.01345	0.98787	1.00045
St8	1.13291	1.02838	0.91640	0.93454	1.10314	1.00070	0.95575
St9	0.86879	1.09020	0.92625	1.02112	0.98111	0.97818	0.97450
St10	0.94179	1.08061	0.97784	0.91707	1.04137	0.98634	0.89782
St11	0.55059	1.25235	0.77464	0.89487	1.32411	1.04568	0.98017
St12	0.92088	0.91123	0.94541	1.13426	0.83569	0.77824	1.00124
St13	1.84941	0.96969	0.97893	1.01866	0.99180	0.98608	0.99609
St14	2.15169	0.83624	0.92480	1.04291	1.01892	0.77420	1.12877
St15	0.64700	1.21732	0.73780	0.99176	0.95395	1.14979	0.87369
St16	1.07341	1.00283	1.03131	0.98351	1.06333	0.93102	1.10955
St17	1.63996	0.98551	0.99538	0.88886	1.01842	1.01437	1.02701
St18	0.94337	0.98772	1.00920	0.99988	1.00916	1.00800	0.98801

We also calculated MCP to observe the trend of cost efficiency changes in Table 4-13 below:

Table 4-13: Cost Efficiency Changes (MCP) for Different Power Plant Technologies

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
CC1	1.0501414	1.0157556	1.0542431	1.1155105	0.9034793	1.0064299	1.4012769
CC2	0.8900123	1.1348117	0.9694319	1.1643015	0.90474	1.105866	1.3546901
CC3	1.0178772	1.0027791	1.0391228	1.1214608	1.0153634	0.957565	1.2586174
CC4	1.3686045	0.9178921	1.2953739	1.1636459	1.1827358	0.9306051	0.7772145
CC5	0.208113	1.0231176	1.0595407	1.2132776	0.9435762	0.9098225	1.2857117
CC6	0.6657051	1.0972915	1.029202	1.3004541	0.9075853	0.9593852	1.3883764
CC7	1.2103215	0.7498031	1.1526326	1.2246112	1.0228218	0.7870339	1.532742
CC8	0.8967208	0.8378948	1.0572089	1.3115961	0.5408164	0.9708461	1.6392039
CC9	0.8074428	0.9131588	1.0325553	0.9698422	1.0809129	0.9616791	1.1811514
G1	2.0505475	1.0320641	1.1478639	1.0310318	1.1413984	0.8063852	0.9454874
G2	0.3514786	0.7913652	3.3503747	1.0901659	1.0124403	1.0459848	0.6690141
G3	1.0034498	0.7898077	1.068925	0.8262156	1.3600944	0.817014	0.7025943
G4	0.487898	0.4725107	3.5449646	0.8674713	1.1306108	0.913561	1.0691237
G5	1.6976558	0.467443	4.462312	0.7524739	1.306566	0.8993043	0.8245581
G6	1.2878415	1.0010972	1.0309249	1.0425586	0.9639572	0.8435295	0.8640306
G7	1.7353189	1.2906707	0.3772059	2.8942422	1.3212692	1.1451893	1.3931391
G8	1.0441192	0.97003	1.0400775	1.0869836	1.0588982	0.8465973	0.8033634
G9	1.1086945	1.0217158	1.0012139	1.0592774	1.1332439	0.7305072	1.0682206
G10	1.1115584	0.9915273	0.9093011	1.0187437	1.0118162	0.8268279	0.805997
G11	0.9638496	0.733947	1.458965	1.0209776	0.9782155	0.8607083	0.882422
G12	0.6128465	0.8183826	1.6560137	1.005471	1.0243224	0.8205528	0.5630401
G13	1.0052445	0.7420098	1.3563309	1.0001783	1.1216933	0.7554232	0.752384
G14	1.0830817	0.7094725	1.3708815	0.9170808	1.100567	0.7172148	1.2180506

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
G15	0.8282931	0.6566	1.95521	1.0574121	0.9388432	0.847011	1.0970474
G16	2.1378869	0.9329216	0.9414309	1.1396414	1.2480524	0.7875832	1.2837335
G17	0.9918678	1.1990399	0.8913002	1.3454262	1.0524084	0.8659293	1.022909
H1	0.661022	0.5492511	3.3540539	0.8896015	0.4471776	1.409226	1.110287
H2	1.3595385	0.8135477	0.8712222	1.142249	0.6716698	1.4466796	1.1874786
H3	0.3962215	0.6365838	3.806719	0.9869497	0.6922152	0.9559205	1.3337251
H4	1.1596748	0.9011753	0.9342536	0.8887236	0.4179254	0.8250963	1.0605314
H5	1.092362	1.1685147	1.0123085	0.9916934	0.8944083	1.0281847	1.3170285
H6	1.050933	1.2671839	1.0232008	1.0259189	0.7051076	0.901182	1.1357831
H7	0.8753948	1.0962586	0.9625028	0.9710469	0.8879332	1.0082663	1.1045563
H8	1.1177986	0.9708342	1.1822241	0.9328391	0.7275774	1.0820818	0.9795733
St1	1.0813145	0.9941685	1.0023171	1.1262366	0.9864964	0.913321	1.0558919
St2	1.0083337	1.0423196	0.9091792	1.1565208	1.0717242	0.7857615	0.7975525
St3	1.1158666	0.888856	1.1687032	0.9937369	0.9321421	0.9353241	0.76179
St4	1.1356279	0.9477974	0.9507221	1.20096	0.9549588	1.0780525	1.1748838
St5	1.0610565	0.9301346	1.002658	1.0544285	1.0172379	0.8318656	0.9696077
St6	1.0274363	1.026021	1.0663485	1.1400609	1.0975247	0.9740428	1.1724424
St7	1.8153953	0.7660785	1.1259666	1.1335311	0.971086	0.7807364	1.8858422
St8	1.010288	1.0990663	0.8719411	1.1600866	1.0772356	0.8732859	0.8915206
St9	1.2352369	0.8911423	1.0002419	1.1431819	1.0790579	0.8666564	1.2655962
St10	0.4493602	1.0412512	0.96727	1.0369722	1.0387509	0.8095225	0.7189062
St11	0.8745018	0.8957046	0.8952509	1.0282987	1.129692	0.8123178	1.1390812
St12	1.1393218	1.0283609	0.989453	1.1571714	1.0096461	0.9033441	1.3163648
St13	1.1567581	0.9059872	1.0126214	1.2204795	0.9373961	0.9858661	2.229927
St14	1.0601281	0.9909985	0.9582478	1.1696885	1.1024763	0.8593109	0.9458368

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
St15	1.1113423	1.0392119	1.0163495	1.1326402	0.9864122	0.9414959	1.2667663
St16	1.2443176	0.9572162	0.9673648	0.9646552	1.3321755	0.8880302	1.2245644
St17	1.1164647	0.9848599	1.0133684	1.1051497	1.0271697	0.948915	1.2955088
St18	0.7640304	0.9043494	1.0440211	1.0589494	1.0386905	0.8642212	0.8464427

ALEFFCH index values which show the allocative efficiency change can be seen in the following table:

Table 4-14: Allocative Efficiency Changes for Different Power Plant Technologies

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
CC1	0.80851	0.95426	0.98046	0.70134	1.05137	0.98732	0.97428
CC2	0.67965	0.90889	1.04192	0.78660	0.93910	1.01094	0.92864
CC3	0.78944	1.36973	0.87855	0.80868	1.04599	0.77567	1.18390
CC4	1.32940	1.61864	1.40372	0.77982	1.04632	1.09802	1.03587
CC5	0.17820	1.18366	1.71762	0.73424	0.99238	0.89051	0.97500
CC6	0.55780	0.79153	1.29559	0.74688	0.99246	0.98359	0.99677
CC7	0.88677	1.08839	1.27390	0.86201	0.69199	0.74920	1.10523
CC8	0.77601	1.53917	1.98135	0.84669	0.97554	1.23502	1.00515
CC9	0.69276	2.13820	0.94188	0.86691	0.98825	0.95142	0.66284
G1	1.05327	1.67239	0.95674	0.96521	0.44981	1.21445	1.04214
G2	1.36399	1.16511	0.88302	0.72568	1.02038	0.92973	0.87188
G3	1.20768	1.74851	1.10325	0.70071	1.00665	0.95851	0.96020
G4	0.98251	0.34079	0.84953	1.10007	0.97833	0.99931	1.02783
G5	1.04796	1.02655	0.93618	0.78499	1.01048	0.92684	1.28073
G6	1.30558	0.49245	0.76274	0.82377	0.92786	1.07125	1.01258
G7	0.82653	1.81384	1.06958	1.40903	1.28934	0.96936	1.04517
G8	0.90742	1.37279	2.86622	0.72365	0.90830	1.12693	0.92248

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
G9	0.96427	1.73637	1.03883	1.00787	1.05248	0.98645	0.84070
G10	1.01256	0.93363	1.04892	0.83609	1.09760	0.99115	0.85819
G11	1.02372	1.37601	1.07128	0.87349	0.85629	1.20348	0.92897
G12	1.08241	0.98726	1.02783	0.55816	1.12812	1.10740	0.81892
G13	1.26537	0.99518	0.98240	0.79750	1.04361	0.93117	1.14063
G14	1.13525	0.73529	1.02823	1.19187	1.35075	0.98590	0.78440
G15	1.01033	0.93753	0.93065	1.01165	1.09214	0.95103	0.86174
G16	1.19604	1.11387	1.03557	1.24338	1.21036	1.07727	0.85387
G17	1.08311	0.70025	1.11375	1.04379	0.83341	0.81461	0.79884
H1	0.97699	2.15076	1.53228	0.92501	1.12414	0.99117	1.02341
H2	1.09797	1.23281	1.16807	1.28630	1.03073	0.87117	1.02244
H3	0.92194	1.17888	0.97846	0.39922	0.87360	1.17783	0.82432
H4	1.25761	0.78660	1.31115	0.99323	1.01995	0.92847	0.94497
H5	1.23726	0.75995	1.01248	1.11514	0.77223	1.00386	0.67773
H6	1.21102	0.51017	1.17097	1.05610	0.93861	1.02651	0.93867
H7	1.23366	0.43824	1.16485	0.91855	1.01768	0.89566	0.90448
H8	1.41409	0.98956	1.37329	1.07900	1.06923	1.12522	0.84436
St1	1.27775	1.23251	1.09192	0.51136	1.08709	1.02564	1.11594
St2	1.12004	1.04441	1.08063	0.81989	0.83359	1.23099	0.80481
St3	0.96848	1.03226	1.02279	0.60736	2.38873	0.98125	0.75382
St4	1.17446	1.00539	0.99962	0.85981	0.93079	1.10887	1.19533
St5	0.76693	0.75180	0.98482	1.01839	1.27425	1.13491	0.86685
St6	0.97574	0.74293	0.97491	1.31738	0.51886	1.19518	1.07313
St7	0.89664	0.84863	1.10700	1.04555	1.05451	1.15818	1.91271
St8	0.81674	0.75034	0.90878	0.96934	1.09260	1.10740	0.94108

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
St9	0.78645	0.69295	1.17215	3.10796	0.68197	1.10140	1.30662
St10	0.51799	0.94092	1.08544	0.85293	0.59004	1.17238	0.80673
St11	1.03859	1.17673	0.86727	3.55126	1.51471	1.14397	1.06096
St12	0.88961	1.12814	0.95252	0.98625	1.19281	1.24803	1.39754
St13	0.85705	3.40450	0.79587	1.02378	0.85611	1.11194	2.26685
St14	0.82420	1.09573	0.96744	0.91500	0.82788	0.98977	0.86071
St15	0.87271	3.04468	1.02803	0.98201	1.22965	1.19201	1.43069
St16	0.77576	4.93866	0.81554	1.06032	1.04744	1.06357	1.12563
St17	0.95890	0.91515	1.05591	1.03355	0.88200	1.07757	1.31674
St18	0.73207	0.39325	0.82501	1.19542	1.11044	0.97938	0.86373

Mean values of the different efficiency measures are calculated and presented in Table 4-15 below:

Table 4-15: Mean ML, MCP and ALLEFFCH for Different Types of Power Plants during an Eight- year Period

	Technology	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	Grand Total
ML	All Power Plants	1.11402	0.99222	0.96551	0.98844	0.97935	1.00721	1.01918	1.00942
	Combined Cycle	1.32678	0.96044	0.95229	0.95013	1.07630	1.08390	0.96642	1.04518
	Steam	1.15012	0.99704	0.93302	1.00780	1.02064	0.97491	1.00619	1.01282
	Gas	1.02248	0.99227	0.99384	0.99596	1.04537	0.99566	1.02147	1.00958
	Hydro	0.98796	1.01700	0.99326	0.97202	0.63709	1.01816	1.10292	0.96120
MCP	All Power Plants	1.05262	0.92404	1.31464	1.10677	0.99308	0.91976	1.11484	1.06082
	Combined Cycle	0.90166	0.96583	1.07659	1.17608	0.94467	0.95436	1.31322	1.04749
	Steam	1.07815	0.96297	0.99789	1.11015	1.04388	0.89178	1.16436	1.03560
	Gas	1.14715	0.86004	1.62137	1.12679	1.11202	0.85467	0.93912	1.09445
	Hydro	0.96412	0.92542	1.64331	0.97863	0.68050	1.08208	1.15362	1.06110
ALLEFFCH	All Power Plants	0.97629	1.22935	1.10898	1.01077	1.01806	1.03786	1.02302	1.05776
	Combined Cycle	0.74428	1.28805	1.27944	0.79258	0.96927	0.96463	0.98530	1.00336
	Steam	0.90278	1.39661	0.98531	1.21431	1.06186	1.11236	1.17222	1.12078
	Gas	1.08635	1.12634	1.10028	0.92923	1.01505	1.01440	0.94408	1.03082
	Hydro	1.16882	1.00587	1.21394	0.97157	0.98077	1.00249	0.89755	1.03443

Figure 4-6 portrays Table 4-15.

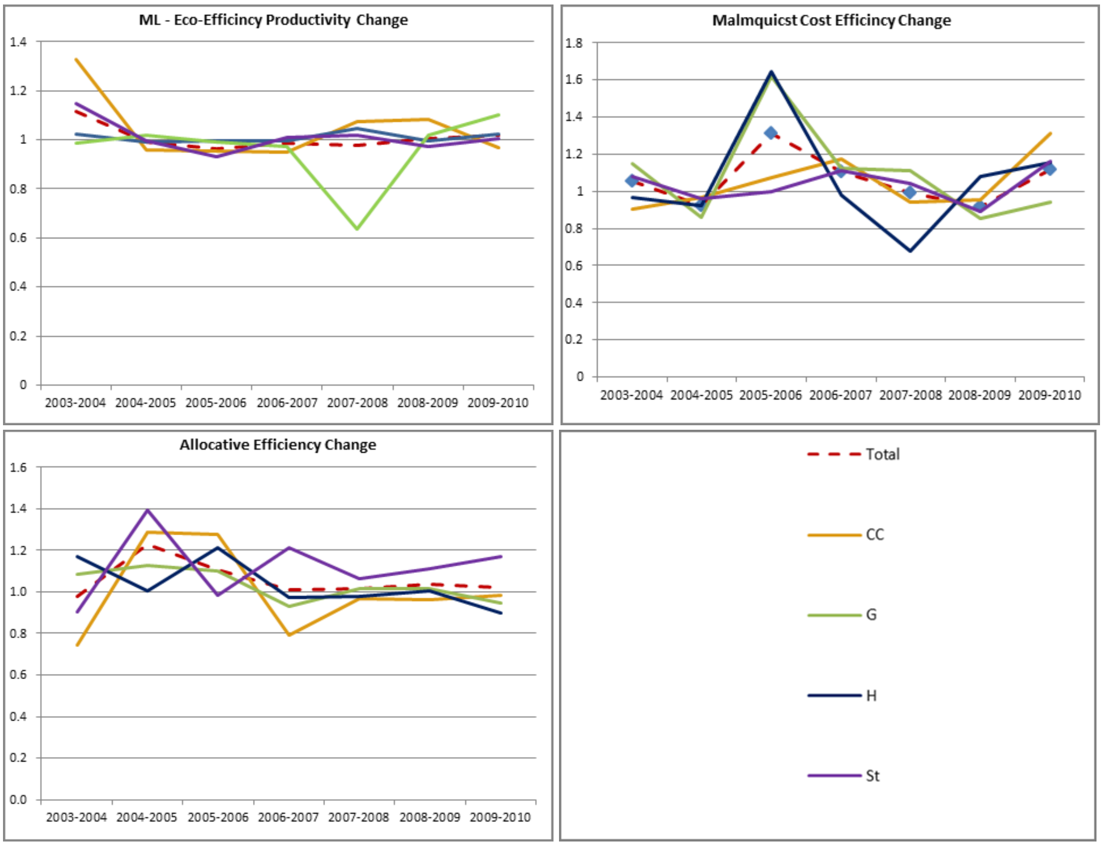

Figure 4-6: Aggregated ML, MCP and ALLEFFCH indices for Observing Productivity Changes during the Restructuring Period

As seen in Figure 4-6, during the period of restructuring, technical efficiency dropped from 2005 to 2008, while it was controlled afterwards. The allocative efficiency and Malmquist cost efficiency have shown a positive trend in general, except for the cost efficiency in the second and sixth periods and for the allocative efficiency in the first period.

It should be reminded here that as addressed in Section 3.3.8, all the models were developed from a national point of view as well as that of the Ministry of Energy, but as both views (national point of view and that of the Ministry of Energy) showed similar result patterns due to the marginality of the social costs of SO_2 in comparison with the other costs mentioned in cost efficiency measurement models we just presented the results obtained from a national point of view incorporating social costs of SO_2.

Finally, to observe the trends, we also devised formula (3-44). After calculating each index, we obtained:

Table 4-16: S_p[1] Index Values

	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	Grand Total
MLI	0.00354	0.000030	-0.00112	-0.00032	-0.001582	0.00056	0.000168	0.001277
MCP	-0.00042	-0.00122	0.00531	0.00202	-0.000697	-0.001125	0.004232	0.008096
$AEFFCH$	-0.001944	0.0092081	0.0018365	0.0017875	0.0003104	0.0008455	0.002378	0.014422

As it can be observed in Table 4-16, although productivity indices show drops in certain periods, all the indices have sustained an overall growth. *MLI* has dropped during 2005 to 2008, and cost efficiency has shown a downfall in two periods: 2003 to 2005 and 2007 to 2009. However, the allocative efficiency has decreased just in 2004.

4.4. An MBP-enabled Slack-Based Model to Illustrate Eco-efficiency Change

Here, the conceptual model in Figure 3-1 is taken into account. Then by customizing the objective function of Model (3-42) we obtain:

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[1] $P = \{MLI, MCP, AEFFCH\}$

$$D_o(x,y,z) = Max \frac{\sum_{l=1}^{L} \alpha l_l + \sum_{h=1}^{H} \alpha h_h}{L+H} + \sum_{m=1}^{M} \alpha_m + \sum_{j=1}^{J} \beta_j + \sum_{k=1}^{K} \gamma_k \qquad (4\text{-}2)$$

st

$$\sum_{n=1}^{N} \lambda_n x l_{ln} \leq x l_{lo} + \alpha l_l . 1 \, ; l = 1,2,\dots,L$$

$$\sum_{n=1}^{N} \lambda_n x h_{hn} \leq x h_{ho} - \alpha h_h . 1 \, ; h = 1,2,\dots,H$$

$$\sum_{n=1}^{N} \lambda_n x_n \leq x_{mo} - \alpha_m . 1 \, ; m = 1,2,\dots,M$$

$$\sum_{n=1}^{N} \lambda_n y_{jn} \geq y_{jo} + \beta_j . 1 \, ; j = 1,2,\dots,J$$

$$\sum_{n=1}^{N} \lambda_n z_{kn} = z_{ko} - \gamma_k . 1 \, ; k = 1,2,\dots,K$$

$$\sum_{l=1}^{L} \alpha l_l - \sum_{h=1}^{H} \alpha h_h = 0$$

$$\gamma_k - \sum_{j=1}^{J} b_{jk} \beta_l = \sum_{h=1}^{H} a h_{hk} \alpha h_h - \sum_{l=1}^{L} a l_{lk} \alpha l_l \, ; k = 1,2,\dots,K$$

$$\lambda_n \geq 0 \, ; \; \alpha l_l \geq 0; \alpha h_h \geq 0; \alpha_m \geq 0; \beta_j \geq 0; \gamma_k \geq 0; n = 1,2,\dots,N;$$

$$l = 1,2,\dots,L; \; h = 1,2,\dots,H; m = 1,2,\dots,M; \; j = 1,2,\dots,J; k = 1,2,\dots,K$$

In Model (4-2), we have divided high and low polluting input slacks (inefficiencies) by the number of them (here gas, gasoil, fuel oil, making 3) in order to leverage the role of fuel inefficiencies in the overall inefficiency. Once the models were adopted, the following results were achieved:

Table 4-17: Power Plant Eco-Efficiencies Using an MBP-enabled Model

Type	2003-2004	2003-2005	2003-2006	2003-2007	2003-2008	2003-2009	2003-2010
CC1	0.768853	0.810043	0.619973	0.487593	0.529937	0.792444	0.942061
CC2	0.755446	1	1	0.607668	1	0.785163	1
CC3	1	0.85499	0.648669	0.350097	0.301459	0.834608	0.947409
CC4	0.780908	1	0.911088	0.787711	0.784254	0.964359	0.995447
CC5	0.413386	0.69665	0.891444	0.429493	0.659859	0.73866	0.917681
CC6	0.734036	0.844688	0.62814	0.409166	0.596622	0.924688	0.919321
CC7	0.60189	0.784556	0.670708	0.44033	0.443542	0.850365	0.945159
CC8	0.85202	1	1	0.738464	0.769344	1	1
CC9	0.901102	1	0.88786	1	0.802046	0.914425	0.972429
G1	0.821085	0.940136	0.796156	1	1	1	0.87693
G2	1	0.894353	0.964762	0.939591	0.943189	0.961193	1
G3	0.88867	0.895426	0.95879	0.914554	0.91819	1	1
G4	1	1	0.602336	0.951548	1	1	1
G5	1	1	1	0.932764	0.944554	1	0.837176
G6	1	1	1	1	1	0.964093	0.975401
G7	0.868859	0.877989	0.935003	0.91173	0.932176	0.909874	0.893714
G8	1	0.870512	1	0.875504	0.901982	0.935835	0.877727
G9	0.749706	1	1	0.798137	0.82139	0.797775	1
G10	0.889926	0.868981	0.888228	0.882387	0.883207	0.893115	0.869621
G11	0.949875	0.956609	0.95847	0.950291	0.954585	0.954866	0.977039
G12	0	0.334856	0.363327	0.187674	0.265066	0.359346	0
G13	1	0.770155	0.847088	0.787557	0.799851	0.846433	0.777344
G14	0.856574	0.882804	0.906235	0.910351	0.914968	0.92776	0.758646
G15	0.813527	0.913836	1	0.926301	0.946806	0.969933	0.89898

Type	2003-2004	2003-2005	2003-2006	2003-2007	2003-2008	2003-2009	2003-2010
G16	0.926688	0.928833	0.946996	0.924745	0.939969	1	0.887647
G17	0.887033	0.982343	1	0.853972	0.787683	0.731368	0.899229
H1	1	0	0	0	0	0	0.734367
H2	0.949444	1	0.97666	0.97136	0.978903	0.956481	1
H3	1	1	1	1	1	1	1
H4	0.846608	1	1	0.932441	0.953494	1	0.824587
H5	1	1	1	1	1	1	1
H6	1	1	0.609606	0.588698	1	1	1
H7	0.830169	0.848837	0.903349	0.896941	0.910771	0.821697	0.636643
H8	0.973992	0.998957	0.970555	1	1	1	1
St1	1	0.558537	0.784467	0.676117	0.621247	0.644083	0.22893
St2	1	0.864647	0.934835	0.82238	0.84737	1	0.91285
St3	0.893033	0.930842	0.954192	0.967252	0.895984	0.887047	0.934686
St4	0.985893	1	1	0.853071	1	0.909021	1
St5	0.642114	0.805978	0.779398	0.848755	1	1	0.572015
St6	0.846687	1	0.986325	0.9267	0.953383	1	0.83265
St7	0.749378	1	1	1	1	0.922955	0.717865
St8	1	0.968194	1	0.937975	0.926407	1	1
St9	1	1	1	1	1	1	1
St10	0.657821	0.749858	0.870569	0.706526	0.818408	0.867726	0.65812
St11	1	0.696076	1	0.751445	1	1	0.789846
St12	0.913795	1	1	1	1	1	1
St13	1	0.492978	0.092683	0.149084	0.43632	0.908909	1
St14	1	1	1	0.811808	1	1	0.618711
St15	0.767668	0.890691	1	0.795762	0.813421	0.87031	0.930941

Type	2003-2004	2003-2005	2003-2006	2003-2007	2003-2008	2003-2009	2003-2010
St16	1	0.879985	1	1	1	1	1
St17	1	1	1	1	0.835214	0.965835	1
St18	0.926659	1	1	0.983922	1	0.971178	1

By calculating the mean values, we can compile Table 4-19 below:

Table 4-18: Malmquist Luenberger Index Using an MBP-enabled Model

Typp	2003-2004	2003-2005	2003-2006	2003-2007	2003-2008	2003-2009	2003-2010
CC1	0.842198	0.744	0.869488	0.161118	1.136643	1.394388	1.078656
CC2	1.16673	0.831097	0.466042	1.963504	0.756529	1.439201	0.757576
CC3	0.753295	0.614281	0.838468	0.473513	1.900511	1.217452	1.128861
CC4	1.104949	0.788431	0.862665	0.797511	1.329806	1.029109	0.926157
CC5	1.025711	1.344219	0.654545	1.135105	0.811889	1.239032	1.234739
CC6	0.78009	0.799159	0.851242	1.087032	1.00165	1.117935	0.707099
CC7	0.82277	1.062808	0.827008	0.931102	1.124598	1.127438	0.752202
CC8	1.107203	0.876718	0.651834	1.40669	1.080253	1.00971	0.926313
CC9	1.107412	0.790152	1.272922	0.54347	1.075818	1.171372	0.992647
G1	1.011429	0.730647	1.819598	0.998712	0.998715	0.869974	0.934947
G2	0.80016	1.048605	0.948746	0.990308	1.115989	1.090917	0.909124
G3	0.963263	1.073876	0.885453	0.983245	1.264063	1.02406	0.990592
G4	1.093287	0.413014	2.047309	1.179302	1.098136	1.00012	0.877849
G5	0.997961	1.007784	0.782511	1.015546	1.193923	0.882317	0.441838
G6	1.004507	0.954661	1.092841	0.944585	0.963143	0.992842	0.99325
G7	1.006373	1.008538	0.938621	1.035573	1.037801	1.081268	0.933528
G8	0.88921	0.916868	0.83656	1.229846	1.005399	1.090005	1.142408
G9	1.150612	0.99996	0.741196	1.00497	1.091464	1.049428	0.83729

Typp	2003-2004	2003-2005	2003-2006	2003-2007	2003-2008	2003-2009	2003-2010
G10	0.795824	0.998786	0.995591	0.967999	0.976143	1.059077	0.963267
G11	0.967582	0.969264	0.996994	0.996804	0.992873	1.073831	0.999143
G12	0.908952	0.838745	0.924041	0.992117	1.031358	1.125151	0.91506
G13	0.673082	0.965468	0.922785	0.977071	1.160024	1.074109	0.936227
G14	0.976964	0.93932	1.031653	0.985293	1.032573	0.927359	1.074853
G15	1.216064	1.178436	0.987753	1.037697	1.300578	0.963427	1.127058
G16	1.015035	0.991912	0.976287	1.024139	1.179838	0.910802	1.133259
G17	0.971005	1.0406	0.909102	0.821237	1.034349	0.933915	1.104502
H1	0.329132	0.807423	0.985135	0.914934	0.600186	2.025258	0.541462
H2	1.079847	0.922518	0.980403	1.017031	0.941161	1.102152	1.015231
H3	0.980436	0.867879	1.533149	0.794814	0.710987	0.984702	1.3893
H4	1.27863	0.932682	0.787194	1.047952	1.052049	0.863893	1.139604
H5	0.967563	1.185265	1.001553	0.996527	0.917735	0.974567	1.247115
H6	3.638492	1.008783	0.968864	0.828856	0.36559	0.812618	1.974829
H7	0.988708	0.983702	0.978007	1.008841	0.905358	0.992726	1.054919
H8	1.00798	0.992604	1.107194	0.972138	0.915254	1.009109	0.957256
St1	0.360046	1.221512	0.937336	0.832731	1.129052	0.966989	0.838586
St2	0.760478	1.076083	0.838027	1.015728	1.639234	0.893487	0.985344
St3	0.95783	1.025736	1.049257	0.791772	1.0194	1.157445	1.011017
St4	0.990477	0.982731	0.639419	1.369923	0.885972	1.140656	0.972943
St5	0.968651	0.762693	1.235398	1.377575	1.339392	0.788574	1.051684
St6	1.135786	0.818836	0.657952	1.064869	1.116479	0.944253	0.928565
St7	1.356723	1.060534	1.14077	0.990085	0.806842	0.887592	1.008954
St8	0.947489	1.034595	0.80755	0.825382	1.213837	0.999254	0.925449
St9	0.868786	1.040415	1.195146	0.867858	0.981108	0.978199	0.9745

Typp	2003-2004	2003-2005	2003-2006	2003-2007	2003-2008	2003-2009	2003-2010
St10	0.764067	1.111878	0.797457	1.107026	1.153262	0.939102	1.017349
St11	0.518227	1.671987	0.812762	1.977711	1.268655	0.969823	0.792138
St12	0.954775	1.000763	1.002944	1.022903	0.96461	0.99582	0.831291
St13	0.363883	0.868572	1.093707	2.125792	0.92362	1.101924	0.996092
St14	0.757434	0.821221	0.336372	6.424335	0.777813	0.850925	1.826899
St15	0.769163	0.942123	0.611831	1.044054	0.964696	1.161355	0.889876
St16	0.677528	1.138135	0.973946	1.001517	1.276115	0.961606	1.010849
St17	1.065343	0.985509	0.903508	0.476354	1.013711	1.027582	1.060292
St18	1.112098	1.01304	1.031443	1.00115	1.008966	1.044707	0.979641

By calculating the mean values of the results in Table 4-17 within each technology class, the following table can be compiled:

Table 4-19: Mean Technical Efficiency Values for Different Types of Power Plants during an Eight year Period Using the MBP-enabled Model

Technology	2003	2004	2005	2006	2007	2008	2009	2010
Combined Cycle	0.68866	0.89604	0.77127	0.76499	0.73582	0.83155	0.92255	0.88077
Steam	0.75702	0.85391	0.80043	0.78993	0.79362	0.84032	0.82532	0.82739
Gas	0.83180	0.84881	0.76761	0.78346	0.74309	0.78347	0.72449	0.74129
Hydro	0.95252	0.94168	0.90633	0.90614	0.89635	0.86488	0.91358	0.85507

Using Table 4-19 entries, we can draw the following graph.

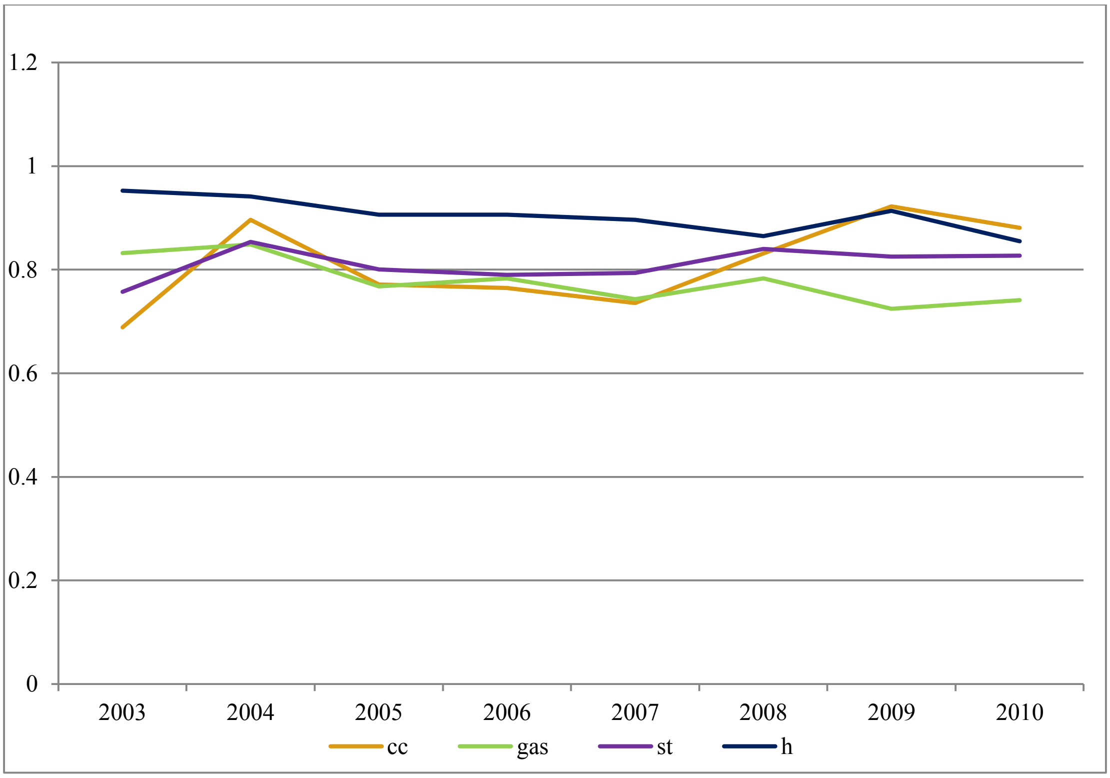

Figure 4-7: Different Power Plants Eco-efficiencies using an MBP-enabled Slack Based Model

The Eco-efficiency graphs in Figure 4-6 and Figure 4-7 show a similar pattern except that in Table 4-19 and Figure 4-7 hydro power plants do not demonstrate dominance in eco-efficiency; rather, it is the combine cycle power plants which have outperformed the other power plant types in terms of eco-efficiency during 2009 and 2010.

To observe the changes of eco-efficiency, we ought to calculate ML Index. The following table can be consulted for the results obtained:

Table 4-20: Aggregated ML Index for Different Types of Power Plants during an Eight- year Period Using the MBP-enabled Model

Technology	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	Grand Total
Combined Cycle	0.97599	0.96547	0.95265	1.12656	1.04971	1.04747	1.00461	1.01749
Steam	0.96782	0.87232	0.81047	0.94434	1.13530	1.19396	0.94492	0.98130
Gas	0.85160	1.03202	0.89249	1.40649	1.08238	0.98941	1.00564	1.03714
Hydro	0.96714	0.94568	1.04924	1.01085	1.08685	1.00874	0.95966	1.00402

Using Table 4-20, the Malmquist Leunberger Index graph can also be produced as below:

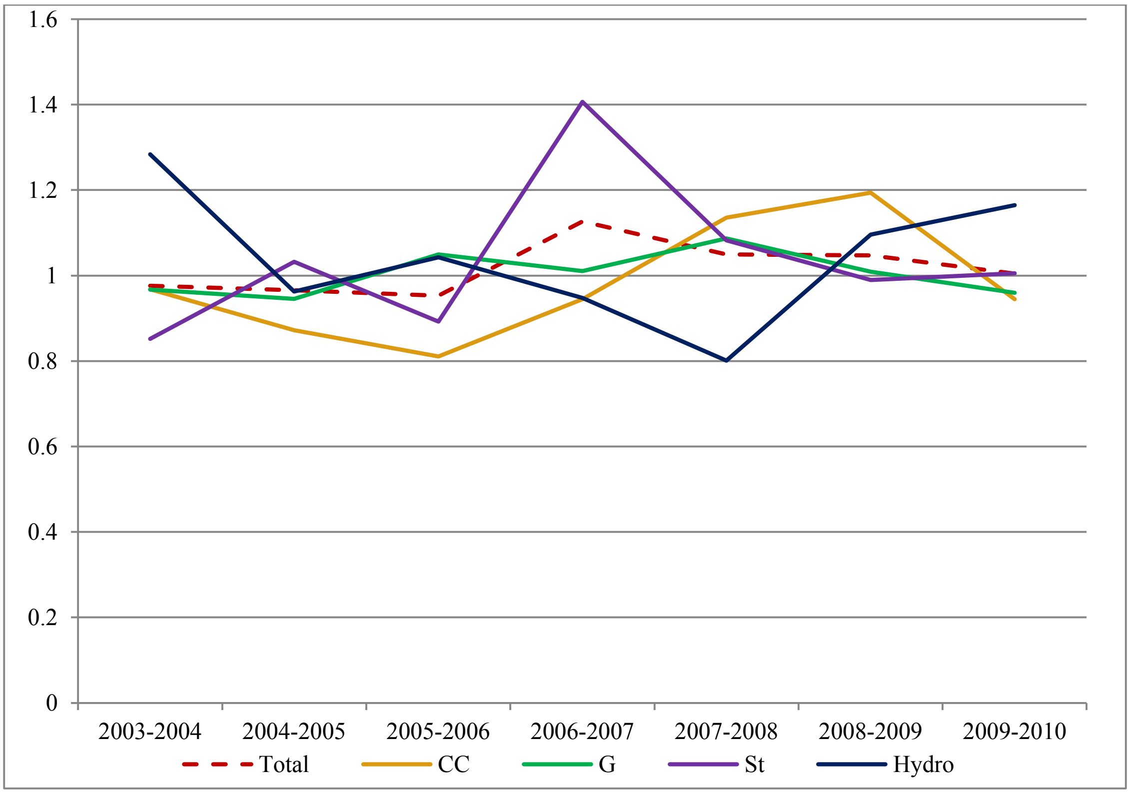

Figure 4-8: Malmquist Leuenberger Index Using a MBP-enabled Model

As observed in Figure 4-8, although the eco-efficiency dropped during the first three periods, a growth (the red dotted line) is observed in the following years. Then, taking *S* Factor into account, the relevant values are tabulated as in the following:

Table 4-21: S_{ML} Index Aggregate Rate of Change Using an MBP-enabled Model

Periods	S_{ML}				
	Hydro	Gas	Steam	Combined Cycle	Grand Total
2003-2004	0.03901	-0.00361	-0.01577	-0.01018	-0.00242
2004-2005	-0.01146	-0.00664	0.00293	-0.01360	-0.00058
2005-2006	0.00667	0.00495	-0.00758	-0.02277	-0.00195
2006-2007	-0.01372	0.00017	0.05154	-0.01300	0.00800
2007-2008	-0.04980	0.00319	0.00241	0.01956	0.00028
2008-2009	0.05636	0.00207	-0.00050	0.02458	0.00228
2009-2010	0.01108	-0.00295	0.00250	-0.00471	0.00036

Table 4-21 corroborates the results in Figure 4-8 although the size of power plants has been incorporated to calculate S_{ML}.

4.5. Gas Power Plants

In this section, we present comparative results related to Gas power plants. The following table contains the eco-efficiency values in addition to the cost and allocative efficiencies values measured by different models employed in this study:

Table 4-22: Efficiency Measures for Gas Power Plants by Different Models

Model	2003	2004	2005	2006	2007	2008	2009	2010
Simple SB	0.93537	0.95819	0.93977	0.94792	0.93802	0.95344	0.97246	0.95624
SB-MBP	0.83719	0.82369	0.78615	0.80825	0.78628	0.87053	0.84751	0.83974
SB-IO	0.75586	0.79433	0.76761	0.78346	0.74309	0.78347	0.72449	0.74129
CE	0.27006	0.26500	0.22588	0.29831	0.30510	0.34395	0.28497	0.25372
AE	0.37297	0.35654	0.31953	0.41420	0.40449	0.43912	0.38793	0.37319

Figure 4-9 depicts Table 4-22.

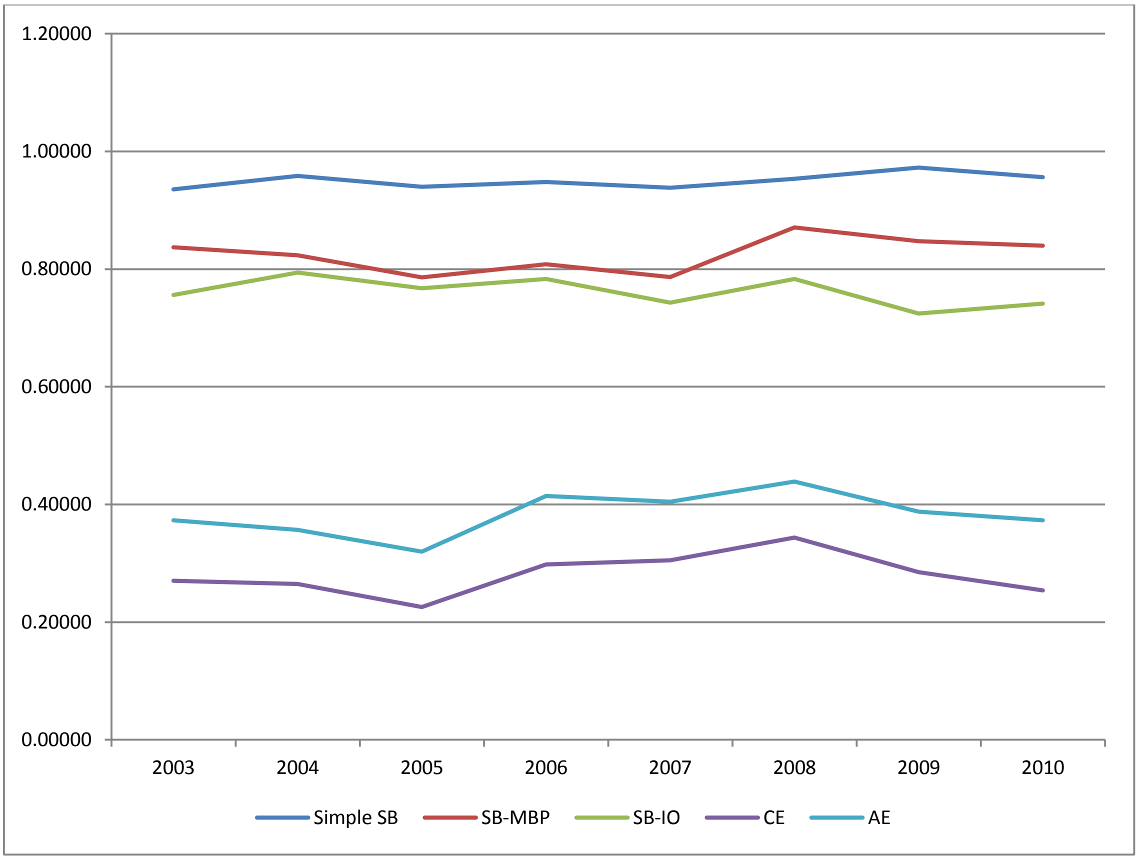

Figure 4-9: Comparative Graph for Gas Power Plants

As it can be seen in Figure 4-9, the values of allocative and cost efficiencies for gas power plant are very low, much lower than the eco-efficiency values for different models. In addition, Simple Slack-Based measure of eco-efficiency has yielded higher values, with a significant margin in comparison with the slack-based input-oriented model and the MBP-enabled slack-based model since there are extra MBP and fuel control constraints imposed on the models. The reader may have noted that Figure 4-9 and similar graphs do not indicate the trend. In this research, the trend is evaluated and indicated by MLI.

4.6. Steam Power Plants

In this section, we present comparative results related to the steam power plants. The following table contains the eco-efficiency values as well as those of the cost and allocative efficiencies, all measured by various models employed in this study:

Table 4-23: Efficiency Measures for Steam Power Plants by Different Models

Model	2003	2004	2005	2006	2007	2008	2009	2010
Simple SB	0.97111	0.93011	0.92083	0.89957	0.92140	0.92443	0.94730	0.94396
SB-MBP	0.76708	0.86986	0.75570	0.79005	0.74674	0.84493	0.82975	0.83677
SB-IO	0.71381	0.80127	0.80043	0.78993	0.79362	0.84032	0.82532	0.82739
CE	0.29354	0.23749	0.23158	0.22725	0.25110	0.26847	0.23265	0.25166
AE	0.49446	0.32020	0.30337	0.34564	0.33188	0.33401	0.30211	0.34869

Figure 4-10 below depicts Table 4-23:

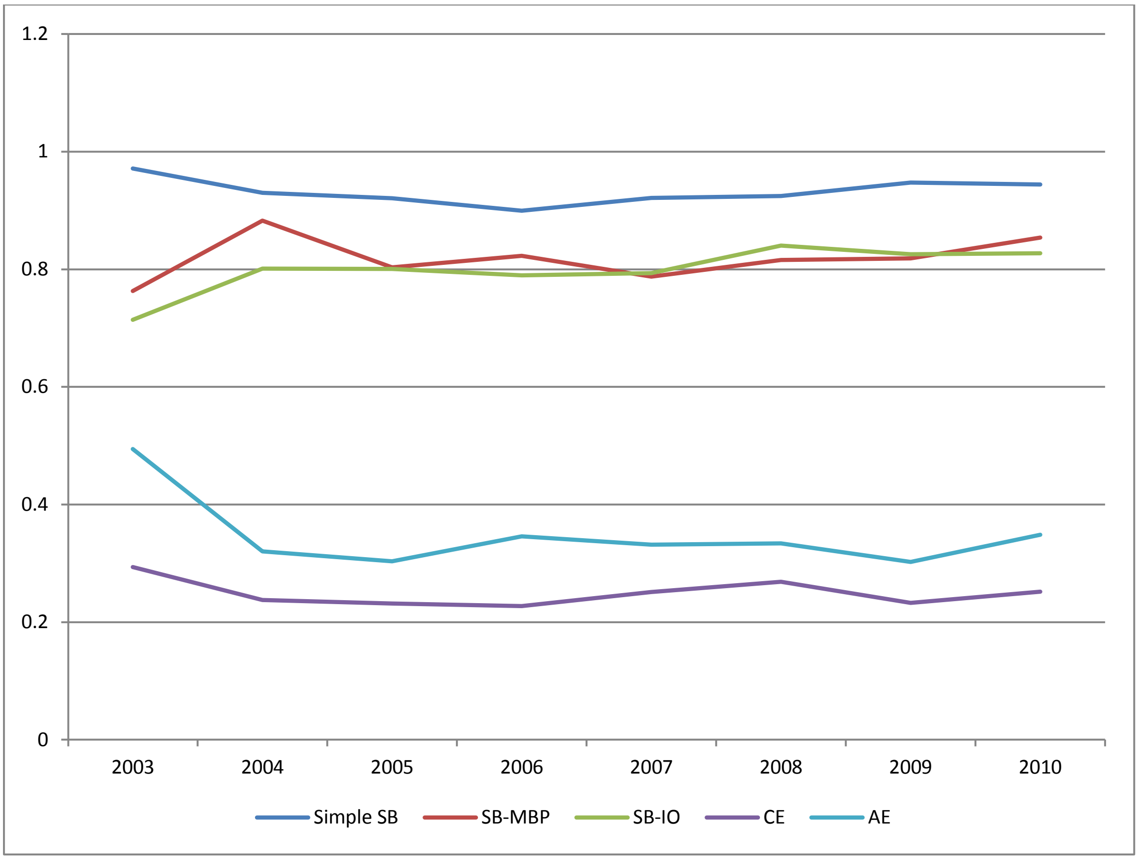

Figure 4-10: Comparative Graph for Steam Power Plants

As observed in Figure 4-10, the allocative and cost efficiency values for the steam power plants are very low value, much lower than those obtained using different models. Similar to the gas power plants, the allocative efficiency of the steam power plants has been higher than their cost efficiency. In addition, simple Slack-Based measure of eco-efficiency shows higher values, with a significant margin, in comparison with the slack-based input-oriented model and the MBP-enabled slack-based model since there are extra MBP and fuel control constraints imposed on the models. Furthermore, the MBP-enabled model and the simple input-oriented model have shown very similar results for the steam power plants.

4.7. Hydro Power Plants

In this section, we present comparative results related to hydro power plants. The following table contains the eco-efficiency values as well as the values of cost and allocative efficiencies measured, using various models in this study:

Table 4-24: Efficiency Measures for Hydro Power Plants by Different Models

Model	2003	2004	2005	2006	2007	2008	2009	2010
SB-MBP	0.97362	0.97039	0.94138	0.95006	0.93198	0.89868	0.94205	0.92011
SB-IO	0.92877	0.92067	0.90633	0.90614	0.89635	0.86488	0.91358	0.85507
CE	0.18460	0.16225	0.13983	0.18425	0.18936	0.17068	0.18218	0.18914
AE	0.19920	0.17960	0.15502	0.22579	0.21726	0.21002	0.19924	0.23588

Figure 4-11 below depicts Table 4-24:

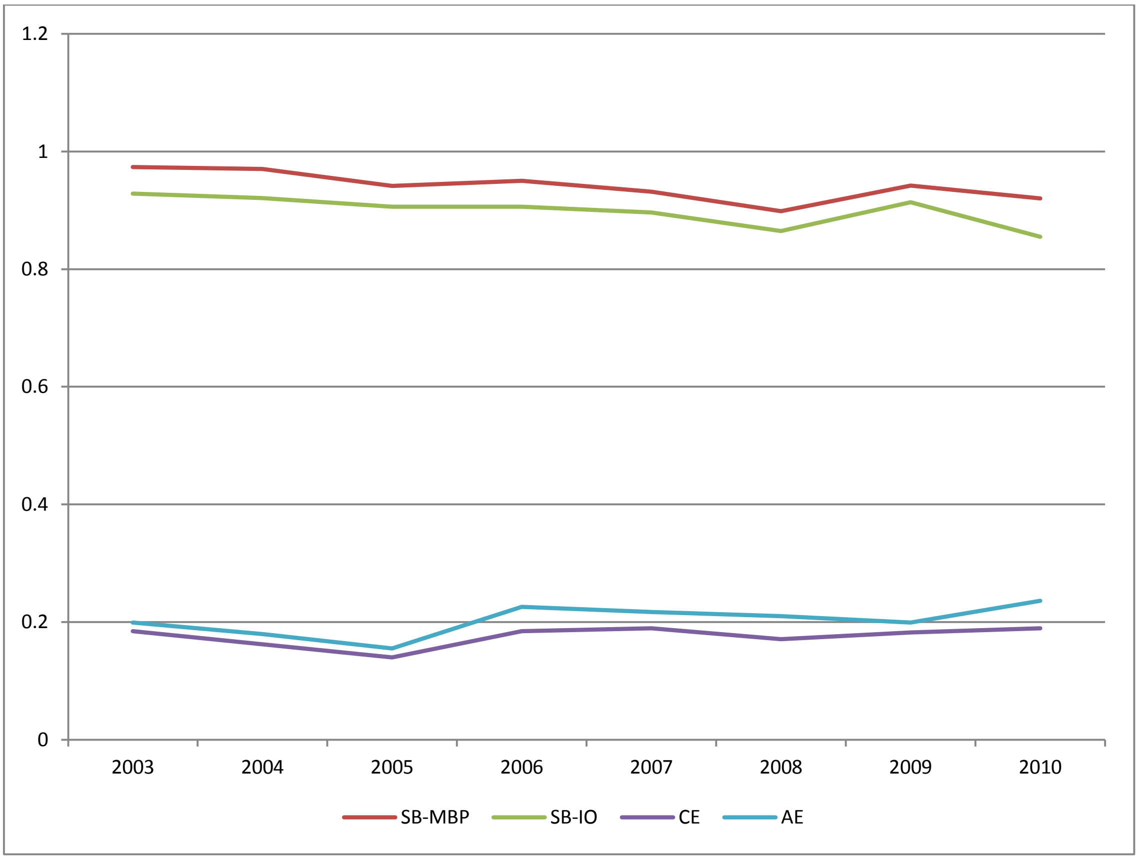

Figure 4-11: Comparative Graph for Steam Power Plants

As seen in Figure 4-11, allocative and cost efficiency values for the Hydro power plants are very low, much lower than the eco-efficiency values obtained using different models.

Similar to the gas and steam power plants, the allocative efficiency values for hydro power plants have been higher than their cost efficiency values. Furthermore, like the steam power plants, MBP-enabled model and simple slack-based model with fuel control have formed similar patterns.

4.8. Combined Cycle Power Plants

In this section, we present comparative results related to combined cycle power plants. The following table contains the eco-efficiency values as well as the cost and allocative efficiency values measured by various models used in this study:

Table 4-25: Efficiency Measures for Combined Cycle Power Plants by Different Models

Model	2003	2004	2005	2006	2007	2008	2009	2010
Simple SB	0.97248	0.96129	0.96291	0.96124	0.93975	0.96234	0.95763	0.96635
SB-MBP	0.68866	0.89605	0.77148	0.76302	0.73235	0.82292	0.92383	0.87126
SB-IO	0.81958	0.85859	0.77127	0.76499	0.73583	0.83156	0.92256	0.88078
CE	0.24095	0.17657	0.16874	0.18046	0.21306	0.20665	0.19257	0.24596
AE	0.36067	0.30923	0.28603	0.35744	0.36082	0.36616	0.32952	0.30296

Figure 4-12 below depicts Table 4-25:

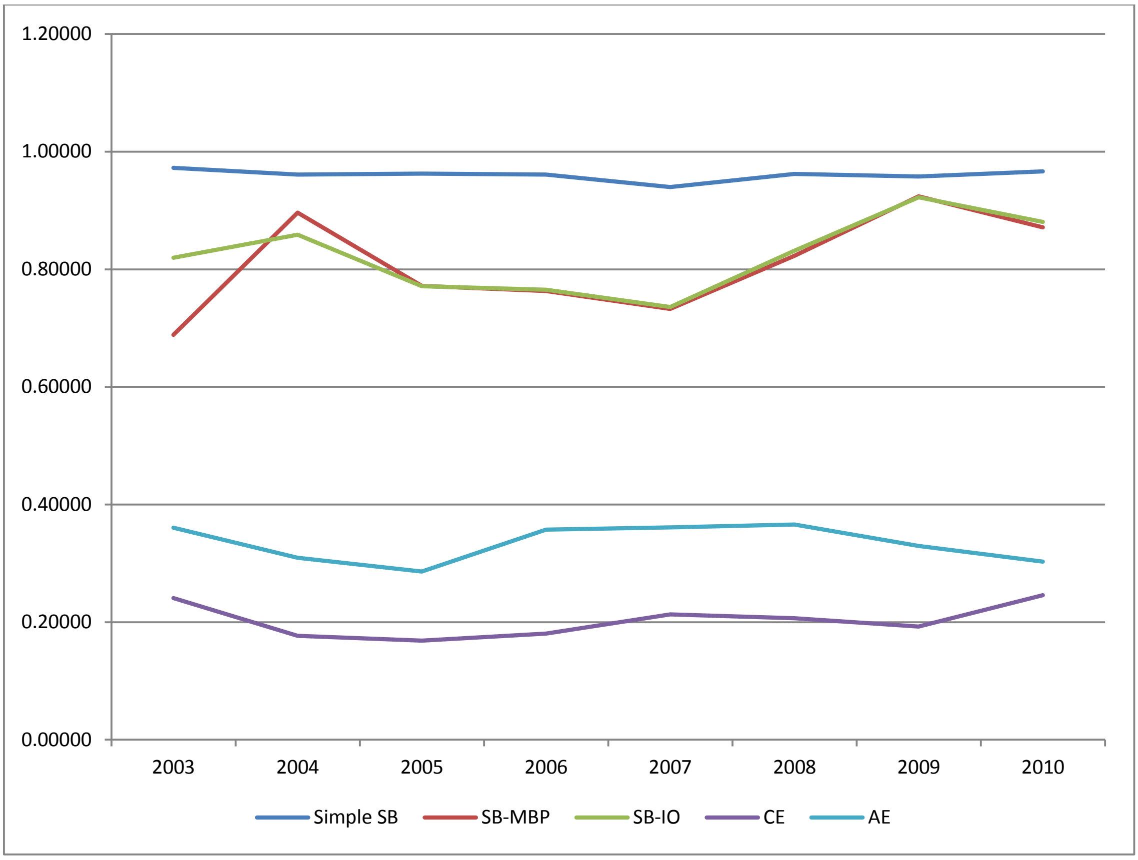

Figure 4-12: Comparative Graph for Combined Cycle Power Plants

As observed in Figure 4-12, the allocative and cost efficiency values for the gas power plants are very low, much lower than the eco-efficiency values obtained using different models. Similar to other types of power plants, the allocative efficiency values of combined cycle power plants have been more than their cost efficiency values. Furthermore, like in the other power plants, MBP-enabled model and simple slack-based model with fuel control have formed similar patterns. Again, the simple Slack-Based measure of eco-efficiency yields higher values, with a significant margin, in comparison with the slack-based input- oriented model and the MBP-enabled slack-based model since there are extra MBP and fuel control constraints imposed on the models.

4.9. Summary

In this chapter, the results of the models introduced and adopted in Chapter 3 were presented and briefly discussed. In addition, in order to operationalize the models introduced in Chapter 3, the models were customized to fit our problem. In Chapter 5, the results presented in the present chapter are going to be elaborated in further detail.

Chapter 5.

Discussions

5.1. Introduction

In this chapter, we are going to discuss more about the results and findings given in Chapter 4. These elaborations are meant to pave the way for the researchers to come up with new decision supporting ideas to offer to the policy makers and authorities so that they can design more effective strategies for the future. In addition, these discussions highlight the strengths and weaknesses of restructuring with a focus on the environmental issues for the restructuring leaders and directors hence enabling them to see whether the restructuring has been successful or not.

5.2. A Meta-frontier Malmquist Luenberger Approach

5.2.1. Theoretical Issues

A newly adopted model, Model (3-12), was used and reasonable results were achieved by observing the results given Table 4-2, Table 4-3, Table 4-4, and Table 4-7. According to Färe and Grosskopf (2010a; 2010b), where Model (3-12) was adopted from, this model has major advantages as it does not use an arbitrary direction. The model also allows the unit to determine the direction in a way that it is projected to the frontier via the longest distance while the good outputs are expanded and bad ones are contracted simultaneously.

This will clarify everything for the unit and specifies targets which are easier for the unit to achieve in the short run. From this perspective, this new model can be employed for eco-efficiency and ML Index evaluation henceforth.

The meta-frontier approach enables a researcher to measure contemporaneous as well as Intertemporal and global eco-efficiency changes. The indices such as *BPG*, *TGR,* and *BPC* can shed light on the dark angles of eco-efficiency changes in a particular context.

5.2.2. Empirical Issues

On the other hand, when observing the results, one can see a drop in eco-efficiency for base load combined cycle power plants during 2005-2006; however, the gas power plants succeeded in improving their eco-efficiency during the same period. In that period, the gas power plants which would normally generate electricity in peak hours, were used as base load power plant in the summer of 2006 and showed a reliable rate of eco-efficiency.

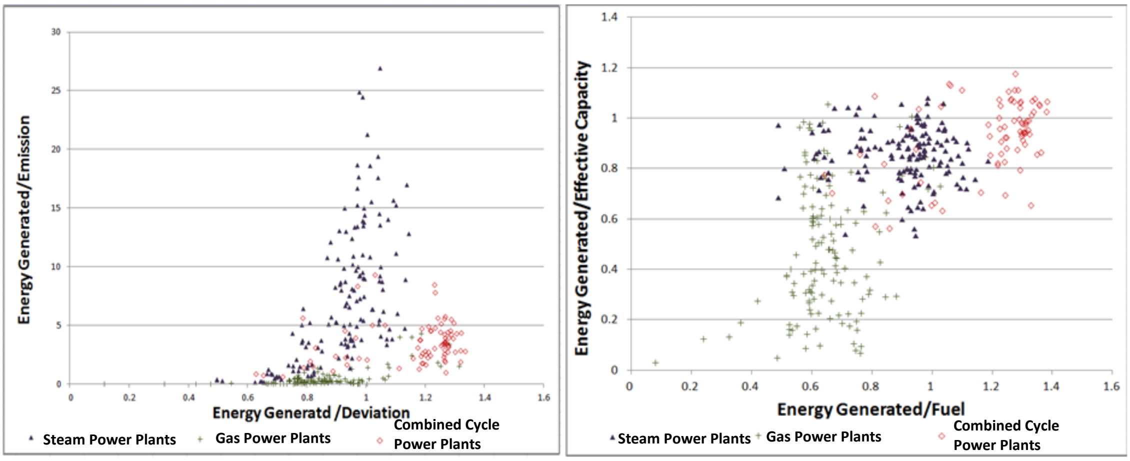

Figure 5-1: Some Productivity Indices of Three Categories of Thermal Power Plants

In addition, Table 4-7 contains a critical implication for Iran's power industry restructuring project. Although in 5 out of the 7 periods ML Index shows drops for the gas power plants, it shows a clear overall growth. This drop in the gas power plant eco-efficiency could be due to several reasons. First, the gas power plants are only employed temporarily in the peak hours since their minimum up and down times are very short. Actually, their operation is sometimes much harder than that of the other types of power plants because operators have to act promptly/ immediately to execute the orders issued by the dispatching units. Thus, as according to Figure 5-1, energy generated per deviation rate is very small for the majority of these power plants during this period in comparison with the same rate for other types of power plants. Second, fuel quality and supply has not been steady and in many cases the power plants have had to use their second or third fuel types; that is, gasoil and fuel oil. Finally, taking into account the results displayed in Table 4-7 as well as in Figure 4-3, it can be concluded that in the eight-year period of restructuring in Iran power industry, the thermal power plants have improved their eco-efficiently in general.

5.3. Eco-efficiency, Cost Efficiency and Allocative Efficiency of Heterogeneous Power Plants

5.3.1. Theoretical Issues

Models (3-29) and its customized version (4-1) which are introduced in this study have been successfully adopted to measure the eco-efficiency and its changes. The constraint $\sum_{l=1}^{L} \alpha l_l - \sum_{h=1}^{H} \alpha h_h = 0$, which guarantees supply of the required amount of fuel for generation of a constant level of electricity to the power plants is a critical constraint. While in the absence of this constraint and in the presence of at least one nonpolluting input, the peer efficient DMU can be a DMU of a nonzero output and a zero level of fuels, which is of course practically impossible. In Model (4-1), it is also important to leverage the role of fuel in the eco-efficiency measurement. Since Fuel is just one of the inputs in technical efficiency measurement, if it is broken down to more different fuel type inputs, its role in the technical efficiency measurement will be multiplied by three, which can lead to inaccuracy of technical efficiency values. To avoid this pitfall here in Model (4-1), we divided the polluting inputs (inefficiency values) by their number.

Model (3-27) was also successfully employed to measure the cost efficiency and thereby the allocative efficiency. Cost efficiency values and changes in addition to the eco-efficiency and the allocative efficiency values and changes provide the researchers with the opportunity to observe the heterogeneous technologies under evaluation from different angles. Thus, researchers will be able to pass a more reasonable judgment about different technologies and provide a more realistic report about different technologies.

5.3.2. Empirical Issues

It is obviously inferred from the laws and regulations governing the Iranian power industry restructuring and the environmental protection that they have all been codified and enforced in order to lower the level of fuel consumed, promote consumption of a cleaner fuel (natural gas), curb the emission level, enhance the operational availability of the plants, and decrease the rate of deviations from the generation plan. Therefore, all the relevant laws and regulations have aim for eco-efficiency and cost efficiency, and allocative efficiency thereby.

Looking at Figure 3-3 and Figure 3-6, we can see that the ratio of SO_2 emissions to the electricity generated began to increase, and the policies and mechanism have not been strict enough to curb this growth till 2007. From 2007 onwards ratio of SO2 emission to the generated electricity began to drop. This has probably had to main reasons: first, the emission charges bylaws have not been enforced; second, there have been no fuel price signals sent to the power plants and they are reimbursed for the marginal price differences between gas and gasoil/ fuel oil in the end of each fiscal year. However, based on the discussion in Sections 3.3.1, 3.3.2, 3.3.7 and 3.3.8 rate of emission production in comparison to the generated electricity began to drop.

Figure 3-7 shows that although the mechanisms used to restrain the deviations have not effective enough as of 2008, the deviations have begun to shrink from 2009. In addition, Figure 3-5 shows the trend of the major index introduced in Section 3.3.5; that is, the ratio of the generated electricity to the operational availability, which has been clearly enhanced as a result of restructuring. This shows that power plants not only have been available more but also could generate as much as they had declared to the dispatching unit. On the other hand, the same figure shows that after 2005, the ratio of the generated electricity to the installed capacity has decreased considerably. This implies that the capacity reserve margin has increased. In addition, according to Figure 3-4, the installed and effective capacities of the power plants both have experienced a steady growth during the same period.

By looking at Figure 4-5, one can understand that amongst all types of power plants, the hydro ones were the most eco-efficient. This is because hydro power plants neither use fuel nor produce emissions. However, amongst the thermal ones, contrary to the expectations, gas and steam power plants outperformed the combined cycle ones during 2005 through 2008. Going through the data, one can see the ratio of the operational availability to the effective capacity of the combined cycle power plants has been dropped dramatically during the same period. This was mainly due to the severe winter of 2005 when the majority of fuel was supplied to the household sector for warming purposes, and the base-load power plants which are basically combined cycle ones, remained out fuel. In the same winter, the hydro power plants were used to generate the energy while they were in their water impoundment period. That winter was followed by a hot summer when the hydro power plants could not generate energy because there was not water behind the dams. As a result, the combined cycle power plants had to postpone their maintenance programs so that they could generate electricity. Consequently, the deviation rate and the fuel consumption in proportion to the generated electricity both increased dramatically. This paradigm continued till 2008, when the Ministry of Energy managed to alleviate the crises.

On the other hand, Figure 4-5 exhibits that the gas power plant technology has been the most cost efficient one while hydro technology has been the least cost efficient one. This can be because of the magnitude of the depreciation cost which impacts the cost efficiency more significantly compared with the other factors. In fact, although hydro electricity generation can be the most eco-efficient technology, it seems to be less cost efficient. On the contrary, gas power plants which enjoy a cheaper technology with the least depreciation cost are the most cost efficient ones.

From the allocative efficiency point of view, the gas power plants stood in the first place while, unlike in 2003, the three other types of power plants acted almost similarly. It is clearly shows that the thermal power plants managed to compete with the steam power plants in terms of allocative efficiency.

Moreover, by looking at Figure 4-6 and Table 4-16, one can see that from 2004 to 2007, power plant eco-efficiency dropped, but an enhancement in eco-efficiency can be observed in the other periods. Based on the contents of Table 4-16, eco-efficiency of the power plants has generally increased during the eight years of restructuring. The same holds true for the cost-efficiency and the allocative efficiency. Therefore, it is safe to claim that the power industry restructuring succeeded in enhancement of the efficiency in power generation industry from different perspectives.

Finally, although Figure 4-5 exhibits that Hydro electricity generation is less cost efficient than the thermal power plants, they are more eco-efficient (technically efficient) than thermal power plants. It can also be said that, if the emission charges are imposed, fuel prices are liberated and the marginal price differences between gas and gasoil/ fuel oil are not paid back to Ministry of Energy, the cost efficiency gap will become narrower than it currently is. In view of the foregoing arguments and pieces of evidence, green technologies will be more cost attractive for investing.

5.4. An MBP-enabled Model

5.4.1. Theoretical Issues

Model (3-42) and its customized version (4-2) can be called ‘matured' models. Since these models, in addition to accommodating MBP conditions, are able to draw DMU the under assessment to its peer on the frontier with an optimal use of inputs and producing less pollutants while they increase the outputs simultaneously. These models also prevent the amounts of required inputs (fuel) from becoming zero. Otherwise, models can assign a zero to these types of inputs and take them as substitute ingredients. Finally, Model (4-2), in certain cases when a polluting input is broken down, offsets the role of that inputs in the eco-efficiency measurement through dividing its corresponding slacks (inefficiencies) by the number of the sub-polluting inputs.

5.4.2. Empirical Issues

Figure 4-7 illustrates a pattern of eco-efficiencies which is similar to that in Figure 4-5. As observed in Figure 4-7, in the last period (2010), the combined cycle power plants managed to perform better than hydro power plants even though hydro technology did not consume fuel and produced no emission. Looking at the data, one can discern that it was due to low operational availability rate of the hydro power plants. Lower operational availability was because of the drought in the same year and the insufficiency of water reserves behind the damns. The growth in eco-efficiency during the second period was because of the switching from the heavier fuels to gas culminating in much lower emissions. The drop in eco-efficiency during the following three years, as already dwelled on in Section 5.3.2, was due to the very cold winter in 2006 and its repercussions throughout the following three years.

Figure 4-8 also shows that after a three-year downfall of eco-efficiency, power industry managed to increase its eco-efficiency in the following years. This trend can be observed in Table 4-21, too.

5.5. Comparisons across Models

As argued in Sections 4.5, 4.6, 4.7, and 4.8 and shown in Figure 4-9, Figure 4-10, Figure 4-11, and Figure 4-12, a simple Slack-Based measure of eco-efficiency shows more values, with a significant margin, in comparison with the slack-based input-oriented model and the MBP-enabled slack-based model for every power plant technology since there are extra MBP and fuel control constraints imposed on the models.

From the aforementioned sections and Figures, it can be also inferred that similar patterns in simple input-oriented slack-based model and MBP-model signifies robustness of the models adopted. Moreover, it proves that the models are well-constructed and compatible with the requirements of the real world as they deliver similar patterns with and without MBP requirement.

5.6. Summary

In this chapter, the results and finding of the study were elaborated and discussed in detail from two different aspects: theoretical and empirical. These discussions underpin the conclusions presented in Chapter 6.

Chapter 6.

Conclusions

6.1. Introduction

In this chapter, the findings of the research are summarized and some suggestions for future planning and amendment of rules and regulation are made. Limitations of the research are also discussed in the present chapter. Moreover, using theoretical findings, further studies are suggested.

6.2. A Summary of the Research

As its first objective, this research aims at measuring the eco-efficiency change of power plants using current methods. However, toward this aim, the researcher should cope with an infeasibility problem which occurs when DDF is chosen as the main model for ML measurement. In Section 3.4, an algorithm together with a slack-based model was introduced to tackle this problem. It was also shown that the previous approaches for handling this problem can be seriously questionable since in some cases they fail to measure the eco-efficiency change correctly. Then in Section 3.5, using a newly adopted model and employing a meta-frontier approach, the eco-efficiency changes of different types of power plants in Iran during an eight-year period of restructuring were calculated and the results were exhibited in Section 4.2.

The second objective of the present thesis is to introduce a new models to measure the eco-efficiency change of heterogeneous power plants as well as incorporating the materials balance principle. In Section 3.6, sources of heterogeneity amongst power plants have been elaborated, and by introducing a new fuel control constraint to the models, we obtained more rigorous models which were more appropriate for the power plants' eco-efficiency, cost-efficiency and allocative efficiency change measurement. These different productivity indices can show the reasons for inefficiencies of different types of the power plant.

However, as the accuracy of the recent eco-efficiency measurement models were had been seriously questioned by Coelli et al. (2007) in terms of the compatibility with Materials Balance Principle or MBP, in Section 3.7, this MBP requirement has been elaborated. Moreover, in the same section, the deficiencies of the models introduced by Coelli et al. (2007) were discussed. Next, in Section 3.7.1 the compatibility of a number of existing models with MBP conditions have been tested and discussed. Finally, in Section 3.7.2 a comprehensive MBP-enabled model was introduced for measuring the eco-efficiency change, and the results obtained after running this model were reported in Section 4.4.

These new models for the eco-efficiency, cost-efficiency and allocative efficiency change measurement have been employed and run over an eight-year period of restructuring in the Iranian power industry (2003-2010) to fulfill the requirements of the third objective of the research. The empirical results are summarized in the next section below.

In the next section, the empirical contributions and implications of the research are briefly addressed.

6.3. Empirical Contributions and Implications

By reviewing the findings of Chapter 4 and discussions of Chapter 5, it can be concluded that restructuring of the Iranian power industry has marginally succeeded in achieving the first and foremost objective which is improving power generation facility performance. Simultaneously, emissions have been controlled and the eco-efficiency improved. Inauguration of power market, price liberation, separation of financial and accounting units followed by separation of their managements, and establishment of power plants as independent power producers have made them be more conservative about their costs, prices and consumption. These all have led to a series of changes in performance via regular and careful maintenance programs, and in some cases, upgrading the existing technology. Thus, the road to sustainable development will be illuminated before the restructuring leaders and they will be able to continue their efforts. In addition, the results of this study not only will provide a general view of the power plants, which are owned and managed by the government, but also t will be useful for the private sector in selecting a proper power plant to purchase, as the power industry reform involves privatization of the power plants, too.

Furthermore, in Section 3.6, we introduced two new models for measurement of eco-efficiency and cost efficiency. These models have been employed to measure the eco-efficiency, cost efficiency and allocative efficiency trends of heterogeneous types of power plants in Iran meant to evaluate the achievements of power industry restructuring in enhancement of the efficiency of power generation industry. The results reveal that although the hydro power plants have been more eco-efficient, they are less cost efficient. This is while the gas power plants have been more cost and allocative efficient, than other technologies. It has been also shown that during the period of restructuring, in spite of incidents such as severe winters, the different indices of efficiency have been relatively enhanced. There is also a requirement for imposing the emission charges and assigning a budget for abatement technologies to control the emissions produced by the power plants; however, determination of gas as the main fuel for the power plants has significantly controlled the emissions produced by the power plants.

6.4. Theoretical Contributions and Implications

Using an evolutionary paradigm in this study, we introduced a number of new beneficial models and approaches for calculation of various productivity indices and their changes.

As the first step, a very common infeasibility problem in Malmquist Leunbegr Index calculation was tackled by introducing a slack based model and an algorithm. This approach paved the way for the researcher to introduce new models and solve them without encountering the infeasibility problem.

Then, to observe the change in productivity indices in a heterogeneous set of DMU’s, we implemented a meta-frontier approach to adopt the aforementioned slack-based model for thermal power plants.

Moreover, a new slack-based model with fuel control capability was introduced. This newly introduced model prevents the efficient peer of the DUM under assessment from becoming zero in all types of fuels with nonzero outputs. In the final step, this slack-based model was refined to be compatible with MBP requirement.

Nevertheless, the present study introduces a series of MBP-enabled slack-based and DDF models with fuel control capability, accompanied by an algorithm, which enables researches to carry out Malamquist Luenbeger Analysis without any concerns about infeasibility problems. The fuel type constraints incorporated in the model enables it to project the DMU’s under assessment toward their peers on the frontier with at least the same level of good output and at most the same level of bad outputs (emissions) hence minimizing the emissions.

6.5. Managerial Implications

Findings of this research can help power plant and power generation management companies obtain a more accurate picture of their firms vis-à-vis other firms active in the same market. The results provide them with complete information concerning their target setting. This research can also serve them as a comprehensive report on their performance during the restructuring period as well as a model for preparation of reports to be submitted to for the Ministry of Energy.

Using the software developed for the purposes of this research, managers can easily run sensitivity analyses to prepare different scenarios for the future. The software also has the capability of obtaining the data online from power market databases and provides the management with online and up-to-date performance measures.

The research also helps power plants with budgeting and cost allocation as well. By liberating the prices and implementing the bylaw mandating emission charges, using the finding of the research and the software applied, managements will be able to develop scenarios for replacing less polluting yet cheaper fuels such as gas in order to spend less and be more cost efficient.

6.6. Future Studies

As stated in Section 3.4.1, slack-based models can be used to find indigenous directions of DDF models. These slack-based models can also be customized to find the optimal direction for different strategies of a firm; for example, when they plan to increase their output for the next period keep the same level of outputs and decrease inputs in order to boost efficiency.

In addition, once inefficiency impacts of different fuel types are leveraged through replacing the summation of corresponding slacks by the average values given in Section 4.3 and 4.4., these impacts can be improved in a better way by applying the Range Adjusted approach used in our slack-based models.

Furthermore, a two-stage DEA approach can be adopted to identify the relationship between the trends of different efficiency measures and those of the power generation industry long term plans (long-term and strategic restructuring planning).

Moreover, adding other types of pollutions such as sound and water pollution into the account, other aspects of the problem can be analyzed.

Finally, emission markets and their implications can also be simulated by another two stage study in the countries where this type of markets has not been introduced yet.

6.7. Limitations of the Research

The main software used to run the program and perform the DEA analysis in this research was AIMMS. AIMMS is well-known as the best operation research software which employs the best solvers to solve mathematical problems. The professional version of this software is too expensive for students so the researcher had to use the free student version with some limitations on the number of variables. Hence it was inevitable for the researcher to set up a different AIMMS project for each single model developed rather than implementing one integrated AIMMS project for all models. This would have wasted the research time and sometimes become painstaking and confusing.

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Appendix 1: Supporting Data Tables

Table 6-1: Required Coefficient to Calculate Fuel and SO2 Costs and Deviation Charges, in Rials

Year	Mean Yield Factor (Percent)	Liberated Gas Price (Rials)	Gas Price (Rials)	Gasoil Price (Rials)	Fuel Oil Price (Rials)	Basic Rate for Capacity Payment (Rials)	SO2 Social Costs (Rials)
2003	37.2	27	27	27	27	72000	14600
2004	36	29	29	29	29	72000	14600
2005	37.6	29	29	29	29	72000	14600
2006	35.5	29	29	29	29	72000	14600
2007	35.8	690	49	49	49	77000	14600
2008	36	690	49	49	49	77000	14600
2009	36	49.3	49.3	49.3	49.3	89000	14600
2010	36.6	950	793	793	793	89000	14600

Table 6-2: Gasoil and Fuel Oil Heating Values, Btu/Littre

Year	Gasoil	Fuel Oil
2003	9232	9790
2004	9232	9790
2005	9232	9790
2006	9232	9790
2007	9232	9790
2008	8600	9200
2009	8600	9200
2010	8600	9200

Table 6-3: Gas Heating Value by Different Resources, Btu/M^3

Pipe Line	2003	2004	2005	2006	2007	2008	2009	2010
1	8210	8614	8614	8614	8614	8486	8486	8486
2	8590	8664	8664	8664	8664	8541	8541	8541
3	9355	8779	8779	8779	8779	8642	8642	8642
4	n/a	8793	8793	8793	8793	8763	8763	8763
5	n/a	9099	9099	9099	9099	n/a	n/a	n/a

Here n/a means the pipeline has not been used for gas delivery to the power plants

Table 6-4: Different Fuel Type Emission Factors (*gr/Gj*)

Sector	Fuel	SOx	NOx	CO	HC	SPM
1. Industry	**Gasoline**	43	165	7,744	298	41
	Kerosene	64	165	15	9	64
	Gas Oil	447	164	13	9	65
	Heavy Oil	1,404	175	12	9	67
	LPG	61	52	7	2	8
	Natural Gas	1	73	7	1	6
	Solid Fuel*	590	250	170	0	74
2. Household & Commercial	**Kerosene**	64	62	15	11	22
	Gas Oil	447	71	15	4	55
	Heavy Oil	1,404	70	15	4	71
	LPG	61	36	9	3	8
	Natural Gas	1	50	8	3	7
	Solid Fuel*	590	215	800	1	74
3. Transport	**Gasoline**	43	376	12,730	1850	575
	Jet Fuel	129	280	120	63	23
	Gas Oil	447	1037	1040	1298	9,190
	LPG	61	165	15	3	112
4. Power Plant & Refinery	**Gas Oil**	447	284	15	15	66
	Heavy Oil	1,637	325	16	16	70
	Natural Gas	1	234	7	16	6

According to the Result of the *Comprehensive Plan on Tehran Air Pollution Control,* 1997, *by JICA and Municipality of Tehran*

Appendix 2: Table of Formula

No	Index	Formula
1.	Excessive Fuel Use	$EC=GE.((1/PYF)-(1/NGYF))/(RGHV)$
2.	Excessive Consumption Charge	$EFCH=EC.(GLP-RPGP)$
3.	Regional Power Plant Gas Price	$RPGP=PGP.RGHV/AVGHV$
4.	Deviation from the Generation Plan	$Dev_d^t = (DAC - GE).BRCP.CHM$
5.	Aggregated Rate of productivity index change index by Effective Capacity	$S = \sum_{n=1}^{N}(ML_n.PEFFCAP_n - PEFFCAP_n) / \sum_{n=1}^{N} PEFFCAP_n$
6.	Cost Efficiency	$\frac{\text{Minimum Possible Cost}}{\text{Actual Cost}}$
7.	Allocative Efficiency	$\frac{\text{Cost Efficiency}}{\text{Input Oriented Measure of Technical Efficiency}}$

All the variables in the table have been defined in Table of Abbreviations as well as the text.

Appendix 3: Result Tables

Table 6-5: A Sample of *D* Values Which Are Calculated by Model (3-29) for Different Power Plant Technologies

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
CC1	1.3177316	0.9909742	0.9617736	0.9577687	0.9697686	1.0618639	1.0142858
CC2	1.2696093	0.957545	0.9045468	1.2098565	0.8781784	1.1589373	0.8410942
CC3	1.2541701	0.9027954	0.841793	0.7315033	1.263512	1.0385094	1.129982
CC4	0.9786975	0.9762469	0.9554269	0.9292537	1.2228283	1.0152503	0.9140509
CC5	1.0533714	1.0105069	0.89679	0.9188275	1.0047165	1.1605315	1.2193902
CC6	1.2180134	0.9304672	0.9193866	0.9747539	1.1046293	0.9786041	0.880428
CC7	1.2431121	0.9687942	0.9283066	0.788859	1.2240198	1.0310607	0.734654
CC8	1.1328068	0.9784762	0.9815528	1.0070212	1.0180994	1.0041174	0.9785546
CC9	1.1796815	0.9748331	1.0139824	0.909468	1.0265003	1.0460852	1.008585
G1	1.035903	0.9280854	0.9222833	1.090188	0.9965214	0.9386983	1.003098
G2	1.0212642	1.0056277	0.9881078	0.9960262	1.0203643	1.0288748	0.9752685
G3	1.0083187	1.0138688	0.986699	0.9978932	1.0357415	1.0131022	0.9962075
G4	0.9676464	0.9304039	1.1153202	0.9777773	1.0533051	0.9689024	0.9893577
G5	0.9830184	1.0181918	0.9410299	0.975086	1.0737208	0.9425933	1.0255026
G6	0.9544236	0.9897304	1.0643798	0.9551105	0.9826457	1.0006927	1.0454614
G7	1.00065	1.0082025	0.9763371	1.0085425	0.9943313	1.0358959	0.9963923
G8	1.1205726	0.9723892	1.0177625	1.0170377	0.9717849	1.0044951	1.0409426
G9	0.7603651	0.9806878	0.9460179	1.0172345	1.0091973	1.0077256	1.0456027
G10	1.1084418	1.0040384	1.0023495	0.9488276	1.0290225	1.0168845	0.9870438
G11	0.9912679	0.987057	1.0045376	1.0028907	1.0074403	1.0203294	0.9980887
G12	0.7625271	1.199089	0.8689224	1.1548964	1.0147969	1.0234547	1.0170164
G13	1.1110322	0.8956226	1.0224435	0.9977873	1.0664593	1.0092433	0.9773052

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
G14	0.9891451	0.9788317	1.0049324	1.025789	1.0039636	0.9687583	1.0220663
G15	1.1728353	0.9987254	0.9872396	1.0009409	1.0236112	0.9841946	1.9
G16	0.9883949	0.9995695	1.0029927	1.014747	1.0371931	0.9741091	1.0250173
G17	0.816576	0.9885428	0.9297125	0.9033095	0.9702523	0.9713663	0.9368183
H1	0.8598508	1.02987	0.9957097	0.9454927	0.6846423	1.1446339	0.9362693
H2	1.0226267	0.9771529	0.9914037	1.0057832	0.9741253	1.0342126	1.005164
H3	0.9981479	0.9882642	1.0099582	0.9884276	0.8533742	0.993864	1.067679
H4	1.0765704	1.0026162	0.9463998	0.9851813	1.0173225	0.9459304	1.045314
H5	0.9850307	1.0458881	1.0004215	0.9977349	0.907801	0.9666717	1.092541
H6	0.9967304	1.0059997	1.0129634	0.9573199	0.7040027	0.9691495	1.0934119
H7	0.9917917	0.9892184	0.986934	0.9990032	0.9596169	0.9920225	1.0133812
H8	1.0025631	0.9965358	1.0174067	0.9960243	0.9723754	1.0031932	0.9872792
St1	1.4205563	0.8352159	0.9097954	1.1621886	0.9436365	0.967767	1.0003544
St2	1.1000167	0.9982662	0.9399675	0.9949858	1.1134651	0.9316588	0.9902556
St3	1.0815313	1.0057015	1.009692	0.9785151	0.9923326	1.0290969	1.0161496
St4	0.9829412	0.9046277	0.9298002	0.9797959	1.0339081	1.0540976	0.985545
St5	1.0669335	0.9496387	0.9749689	1.0331487	0.8985186	0.9654825	1.0630683
St6	1.2002056	0.9769957	0.9418994	1.0081112	1.0310748	0.9476614	1.0353329
St7	0.8312322	0.9802005	0.9798571	0.9893184	1.0098984	1.0012965	0.9842197
St8	1.0872468	1.0118649	0.966376	0.9448261	1.0661321	1.0003954	0.9830345
St9	0.9246406	1.0427499	0.9598293	1.0077825	0.9937262	1.0042428	0.983132
St10	0.9690585	1.0295944	0.988625	0.9292389	1.0213977	0.989225	0.9181588
St11	0.7059453	1.1594434	0.8262235	0.9040053	1.2051592	1.0230156	0.9873489
St12	0.9613468	0.939404	0.9642686	1.0747025	0.890566	0.8452193	0.9990767
St13	1.6723377	0.997292	0.961097	1.0019947	1.0041732	0.994217	0.9960516

Type	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010
St14	1.7269744	0.8964323	0.9641274	1.0064219	1.0128705	0.8654087	1.0615286
St15	0.745542	1.1296218	0.8193097	0.980914	0.9569405	1.0837235	0.9205036
St16	0.9978783	1.0539925	1.0225885	0.9827403	1.0268584	0.9504263	1.0562276
St17	1.3430305	0.9950495	0.997823	0.9349669	1.0094436	1.006981	1.0125121
St18	0.9540326	0.9966605	0.997604	0.9968312	1.0001886	1.0033833	0.9919391