RECONCILING ENERGY AND CARBON EMISSION PERFORMANCE FOR SUSTAINABILITY

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I hereby certify that this thesis meets all the requirements of the Graduate School of Social Sciences for a Master's degree.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I have therefore fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

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The concepts of energy and environmental efficiency, with creating less or no pollution in production processes, help to redefine efficiency in general and serve to attain a sustainable future. The relevant literature is underprovided in analyzing environmental efficiency and thus performance measures for countries over time.

This study models energy and CO_2 emission performance in electricity generation from the production efficiency point of view. It uses a non-radial directional distance function and constructs energy, environmental and energy-environmental performance indices for 112 countries over the period of 1988-2011. The models are run in GAMS 23.5 with IEA data 2013. The countries are grouped firstly with respect to their use of combined heat and power (CHP) technology to construct best practice frontier. The second group is G20 countries, which allows investigation of the tradeoffs amongst energy and environmental performances of top 20 countries in the world. The last group is UNFCCC Annex I countries, consisting of Turkey. The study shows that the majority of the countries still have room for improvement for energy and the environment. For the most current year in the dataset, 2011, for all the indices, the following countries are the best performers; Switzerland and Sweden in the group of countries with CHP technology, Brazil for the non-CHP countries, Brazil and United Kingdom among G20 countries, and Belarus and Slovak Republic in Annex I. Consistent with the literature, Turkey has better energy and environmental performance compared to the major polluters as it performs around the medians of sample countries in UNFCCC Annex I.

Keywords: Energy efficiency, Environmental efficiency, CO_2 emission performance, Electricity Generation, Directional distance function, Data envelopment analysis.

ÖZET

SÜRDÜRÜLEBİLİRLİK İÇİN ENERJİ VE KARBON EMİSYON PERFORMANSININ DEĞERLENDİRİLMESİ

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Enerji ve çevresel verimlilik kavramları üretim süreci esnasında çok az ya da hiç kirlilik açığa çıkmamasını sağlayarak verimliliği yeniden tanımlar ve sürdürülebilir bir geleceğe erişimi sağlar. Konuyla ilgili literatür ülkelerin çevresel verimlilik ve performans ölçümlerinin sağlanması konusunda yeterli değildir.

Bu çalışma, elektrik enerjisi üretiminde enerji ve CO_2 salımı performansını üretim verimliliği açısından modeller. Bu çalışmada radyal olmayan mesafe fonksiyonu kullanılmış; enerji, çevre ve enerji-çevre performans indisleri 112 ülke için ve 1988-2011 periyotlarını kapsayacak şekilde oluşturulmuştur. Model IEA 2013 datasını kullanarak GAMS 23.5 programında çözülmüştür. Ülkeler, ilk etapta birleşik ısı ve güç üretim (CHP) teknolojisini kullanımlarına göre gruplanmış ve en iyi üretim sınır eğrisi oluşturulmuştur. İkinci grup ise G20 ülkelerinden oluşmakta olup, bu gruplama dünyadaki 20 majör ülkenin enerji, çevre ve enerji-çevre performanslarının karşılaştırılmasını sağlamaktadır. Son grup ise Türkiye'nin de içinde bulunduğu Birleşmiş Milletler İklim Değişikliği Çerçeve Sözleşmesi (UNFCCC) Ek I ülkelerinden oluşmaktadır. Data setteki en son yıl olan 2011 yılı için tüm performans indislerinde en iyi performans gösteren ülkeler şunlardır: CHP teknolojisini kullanan ülkeler arasında İsviçre ve İsveç; CHP teknolojisini kullanmayan ülkeler arasında Brezilya; G20 ülkeleri arasında Brezilya ve İngiltere; Ek I ülkeleri arasında ise Beyaz Rusya ve Slovak Cumhuriyeti. Literatürle uyumlu olarak Türkiye, kirliliğe sebep olan ana ülkelere göre daha iyi enerji ve çevresel performans sergilemiş olup, Ek I örneklem ülkeleri arasında ise medyanda yer almaktadır.

Anahtar Kelimeler: Enerji Verimliliği, Çevresel Verimlilik, CO_2 Salım Performansı, Elektrik Üretimi, Yönsel Mesafe Fonksiyonu, Veri Zarflama Analizi

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LIST OF ABBREVIATIONS

BRICS	:	Brazil, Russian Federation, India, China and South Africa
CHP	:	Combine Heat and Power
CPI	:	Carbon Performance Index
CO_2	:	Carbon Dioxide
CRS	:	Constant Returns to Scale
DDF	:	Directional Distance Function
DEA	:	Data Envelopment Analysis
DMU	:	Decision Making Units
ECPI	:	Energy - Carbon Performance Index
EIT	:	Economies in Transition
EPI	:	Energy Performance Index
EU	:	European Union
EU ETS	:	European Union's CO_2 Emissions Trading Scheme
G20	:	Group of Twenty
GAMS	:	General Algebraic Modeling System
GDP	:	Gross Domestic Product
GEM	:	Global Efficiency Measures
GHG	:	Greenhouse Gas

GWh	:	Gigawatt hour
$GtCO_2$	:	Giga tone of CO_2 equivalent
IEA	:	International Energy Agency
LP	:	Linear programming
MCDA	:	Multiple Criteria Decision Analysis
MCPI	:	Malmquist CO_2 emission Performance Index
ML	:	Malmquist–Luenberger
Mt	:	Metric ton
NGL	:	Natural Gas Liquids (NGL)
OECD	:	Organisation for Economic Cooperation and Development
ppmv	:	Parts Per Million by Volume
SBM	:	Slacks-Based Measure
TJ	:	Terajoule
UNFCCC	:	United Nations Framework Convention on Climate Change
WBCSD	:	World Business Council for Sustainable Development
WEO	:	World Economic Outlook

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CHAPTER ONE

INTRODUCTION

Sustainability, the collection of policies and strategies employed by various institutions at micro and macro levels to minimize their environmental impact on future generations, is a great concern in economics. More recently, sustainability regained importance and has been becoming the focus of attention not only in policy design but also in theory building. Efficient use of all resources, specifically natural resources, with creating less or no pollution and environmental damage in production processes helps to attain a sustainable future. Traditional efficiency measures and approaches in economics could not capture fully the efficient use of natural resources, ecological services and the environment. Traditional efficiency measures treat desirable and undesirable outputs asymmetrically, by valuing desirables and ignoring undesirables (Fare et al., 1989). However, the concepts of environmental efficiency and eco-efficiency help to redefine efficiency in general and serve to attain sustainability on the supply side. Because of this, economic - ecological efficiency is a matter of concern since 1990s as an approach to sustainability among politicians, researchers and decision makers in business world.

For the monetary gains, firm managers must minimize costs, maximize revenues, or maximize profits. If market structures are not pareto efficient, then these monetary objectives may drive firm managers to produce products with detrimental impact on environment. The relationship between environmental goals and monetary objectives has a tradeoff between social benefits and monetary costs. Social equilibrium is different than the market equilibrium due to the failure of markets and other institutions to take into account the effect of supply and demand decision on the environment and the ecosystem. The balancing of society's desire and economic goals is important issue (Porter and Linde, 1995). For this reason, measuring environmental and ecological efficiency in addition to economic and technical efficiency is required to develop sustainability. Therefore, researchers should provide methodology to measure and improve environmental and ecological efficiencies and facilitate the design of environmental policies.

Industrialization, high population growth, and urbanization cause the misuse and overuse (not use optimally) of natural resources in the long run and thus raise numerous environmental problems. As a depletion of natural resources, fossil fuel consumption results in the increase of greenhouse gas (GHG) emissions in the atmosphere. Climate scientists have observed that the concentration of atmospheric CO_2, which is the major GHG, have been increasing significantly. The 2012 CO_2 concentration (394 ppmv) was about 40% higher than the concentration in the mid-1800. The average growth is 2 ppmv/year in last ten years (CO_2 Emissions Overview, IEA 2013). Thus, stabilizing CO_2 concentrations is very important. Even after stabilization of the atmospheric concentration of $CO_{2,}$ global warming and sea level rise would continue due to the time scales related with climate processes and feedbacks. Large reductions of global CO_2 emissions are required for stabilizing concentrations of GHG or CO_2 in the atmosphere. For this purpose, the United Nations Framework Convention on Climate Change (UNFCCC) is negotiated (CO_2 Emissions Overview, IEA 2013). The major aim of the convention is to stabilize GHG concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC, 1992).

The use of energy represents obviously the largest share of GHG emissions, which is 83% for UNFCCC Annex I countries. CO_2 emissions from energy represent 60% global emissions (CO_2 Emissions Overview, IEA 2013). CO_2 emissions from combustions dominate the total GHG emissions in the energy sector. Because of growing world energy demand from fossil fuels, CO_2 emissions has upward trend, annual CO_2 emissions from fuel combustion increased from near zero to over 31 $GtCO_2$ in 2011 (CO_2 Emissions Overview, IEA 2013). This trend is the most obvious for the electricity generation industry. Two-thirds of global CO_2 emissions in 2011 are produced because of electricity and heat generation. Electricity and heat generation that relies on coal is the most carbon – intensive fossil fuel. According to World Economic Outlook (WEO) 2013 projects, by 2035, the demand for electricity will be 70% higher than current demand because of the rapid growth in population and income in developing countries, by the continuing increase in the number of electrical devices used, and by growth in the electrically driven industrial processes (CO_2 Emissions Overview, IEA 2013). Therefore, it is important to analyze environmental and ecological performance in addition to energy performance in electricity generation.

Many recent approaches for developing energy and environmental performance have been using especially nonparametric data envelopment analysis (DEA) from a production point of view (Sueyoshi and Goto, 2012). DEA is a linear programming

(LP) based technique for evaluating the relative efficiency of decision making units (DMUs) with observed quantities of the inputs and outputs (Ramanathan, 2003). It is a non-parametric method: we don't need an explicit speciation of the functional relationship between inputs and outputs. The literature that applies DEA to measure environmental performance, first defines undesirable outputs, and then calculates the environmental efficiencies. DEA uses linear programming to construct the technology and best practice frontier from the data sample. Simultaneously, it estimates the distance to the best practice frontier for each observation. One of the most popular approaches for estimating the distance is directional distance function (DDF) approach.

The directional distance function is developed by Chambers et al. (1996). This approach is seeking to expand the desirable outputs and reduce the undesirable outputs and inputs directionally. Electricity production from fossil fuel combustions inevitably produces undesirable outputs also, such as CO_2 emissions. As there has been growing importance of CO_2 emissions reduction, in the literature, there are most current studies using DDF approaches for evaluating the impact of CO_2 emissions on the environment.

Previous studies presented a non-radial directional distance function approach to modeling of the performance of electricity generation within a joint – production framework. For instance, Zhou et al. (2012) proposes the use of non-radial directional distance function and several performance indexes are developed to model energy and CO_2 emission performance in electricity generation. Similarly, this study also contributes to the modeling of the performance of electricity with several standardized indexes. Nevertheless, this study differs from previous studies in the following aspects. First, this study demonstrates performance changes over time for over one hundred countries while previous studies in the literature are based only the data for a single year. In the case of energy sectors, there is continuously changing demand and supply conditions. Thus, for this sector, there is generally an increasing concern in investigating their productivity change over time. This study measures relative efficiency over time. Second, this study contributes to modelling Group of Twenty (G20) countries' energy and environmental performances to investigate differences in preferences over energy and environmental tradeoffs among top 20 countries in the world. G20 countries represent close to 80% of this energy related CO_2 emissions. The G20 group is therefore presented with an important opportunity to make collective progress towards the objective of developing energy and environmental efficiency (G20 Clean Energy, And Energy Efficiency Deployment and Policy Progress, 2011). This study measures how far each member country might be from their potential objective as a group. Third, this study also investigates Turkey's energy and environmental performances in electricity generation among UNFCCC Annex-I countries. It is important to investigate Turkey's performance as Turkey has been tracking of its GHG emissions as a member of UNFCCC and Kyoto Protocol. As a member of UNFCCC Annex-I countries, Turkey plans to limit future GHG emissions. Given Turkey's environmental goals, Turkey's energy and environmental performance comparison with Annex-I members is significant to evaluate its performance in comparison to its peers.

In this study, CO_2 emission performance is used to represent the environmental performance. Thus, in this thesis, the term "environmental performance" is used and it captures "CO_2 emission performance". Environmental performance is a broader measure that includes not only CO_2 emissions but also performances related to other emissions as well as performances related to water and solid and hazardous waste.

Due to restrictions on data availability, in this thesis, the term “environmental performance” captures solely CO_2 emissions. The organization of this study as follows. In the next chapter, the literature on the directional distance functions is reviewed. In chapter 3, methods for measuring energy and ecological performances are explained. Results are provided and discussed in chapter 4. In the last chapter, the study is concluded.

CHAPTER TWO

LITERATURE REVIEW

Environmental performance is a matter of concern since beginning of the UNFCCC negotiation in the early 1990s as an approach to sustainability among policy analysts and decision makers due to the fact that global warming and climate change is the major policy issue in the world. OECD defines eco- efficiency as the efficiency with ecological resources that are used to meet human needs at the end of the 1990s (OECD, 1998). Then, the notion was popularized by the World Business Council for Sustainable Development as a practical approach to encourage companies to become more environmentally responsible and more competitive (WBCSD, 2000). As a result of this concern, a growing literature has arisen to relate to environmental issues into traditional production theory. Figure 1 shows the general structure of literature on energy and environmental issues as well as types of DEA which will be discussed in the next sections.

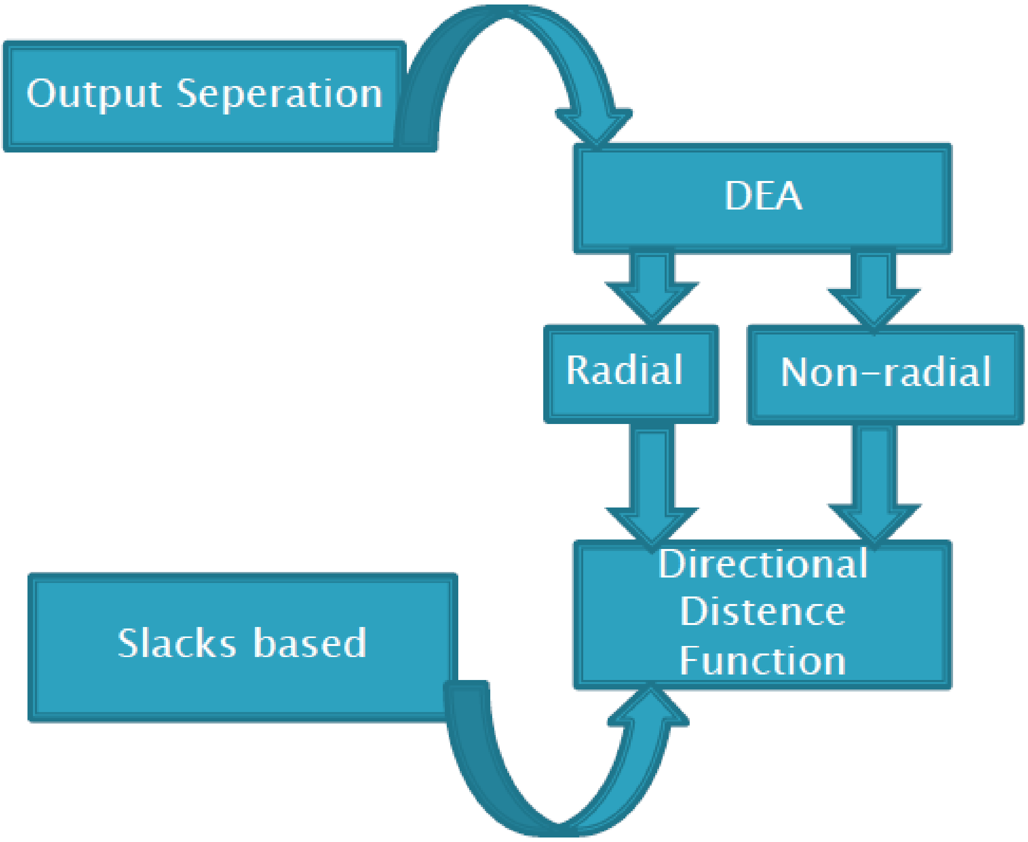

Figure 1 General Structure of Literature

2.1. Data Envelopment Analysis and Directional Distance Functions

Production of desirable outputs often produced jointly by–products that have harmful effects on the environment. When evaluating the environmental performance, it makes sense to implement a performance measure of production technology which has some outputs that are desirable and some others that are not, and the undesirable outputs may not be freely disposable. Three categories, which are inputs, desirable outputs and undesirable output, are taken into account in the scope of the theory of productive efficiency. Traditional efficiency measures and production theory treat desirable and undesirable outputs asymmetrically, by valuing desirable and ignoring undesirable.

A pioneer paper, Fare et al. (1989) developed and implemented a new performance measure by modifying Farrell (1957) measure of technical efficiency which has permitted an asymmetric treatment of inputs, desirable outputs and undesirable outputs. Farrell (1957) estimated a radial measure of technical efficiency by constructing a piece-wise linear technology representing the best practice methods of production and using linear programming (LP). Then, Data Envelopment Analysis (DEA) is named by Charnes et al. (1978) and Banker et al. (1984) who extended a popularized Farrell's method. In economic literature, model developed by Charnes et al. (1978) has relation with the activity analysis model introduced by Von Neumann (1945) and Koopmans (1951) and the input distance function introduced by Shephard (1970).

DEA has been a well-established nonparametric methodology to evaluate the relative performance of decision making units (DMUs) with multiple inputs and outputs. Seiford and Thrall (1990) mentioned advantages of DEA and main advantage is that it is a nonparametric approach not needing to functional relationships between inputs and outputs. Considering these methodological advantages, DEA has rapidly grown in operations research and management science (Forsund and Sarafoglou, 2002, 2005). Among the current studies, presentation of introductory materials can be found in Ramanathan (2003), Cooper et al. (2006) documented more comprehensive study about DEA.

There are mainly two methods which incorporates undesirable outputs into DEA models. One is based on the original data with the concept of weak disposability proposed by Fare et al. (1989). The other is based on data translation and the utilization of traditional DEA models such as the one in Seiford and Zhu (2002).

The optimal solution called radial efficiency of DMU that reveals existence of excessive uses of inputs and shortfalls in production of outputs (slacks). There are two types of efficiency measure in DEA, namely radial and non-radial. Some studies used radial measures which adjust inputs or outputs proportionally, e.g. Tyteca (1996, 1997) and Fare et al. (2004). Radial measures overestimate technical efficiency when there exist non-zero slacks. Fare and Lovell (1978) constructed alternative efficiency measures that minimize input slacks while allowing slack in output constraints. In the scope of defining inefficiency based on the slacks, Fare et al. (1985), Torgersen et al. (1996), Cooper and Tone (1997), Pastor et al. (1999), and Tone (1999) proposed several methods.

Fare et al. (1985) used DEA on electricity generation plants by assuming both strong and weak disposability of inputs to measure the performance. Torgersen et al. (1996) developed the radial measures of Farrell type to include slacks and applied to a typical multidimensional small-sample data set for Norwegian employment offices. Cooper and Tone (1997) detailed the studies in developing scalar measures of inefficiency including non-zero slacks. Pastor et al. (1999) proposed a new Global Efficiency Measures (GEM) inspired by the Russell Graph Measure of Technical Efficiency to avoid the computational and explanatory difficulties. Tone (1999) proposed a slack-based measure (SBM) of efficiency which deals with the input excesses and the outputs shortfalls of DMU concerned in DEA model.

Generalized measure of technical inefficiency with accounting for all slacks in input and output constraints is related to directional distance function of Chambers et al.

(1996). The concept of directional distance function, dual of profit function, was developed by Luenberger (1992, 1995) as a shortage function in production theory and as a benefit function in consumer theory. The directional distance function seeks increase in desirable outputs and decrease in inputs and undesirable outputs for a given directional vector.

Several studies have introduced the directional distance function technology by incorporating slacks into the measurement of efficiency. Chung et al. (1997) and Ball et al. (2001) used directional distance functions for modeling production in the existence of undesirable outputs. Picazo-Tadeo et al. (2005) used directional distance functions to measure of efficiency while increasing desirable outputs and decreasing inputs with no change in the undesirable outputs. These measures permit free disposal of residuals.

Recently, Fukuyama and Weber (2009) developed a generalized measure of technical inefficiency which also accounts for all slacks in input and output constraints. However, Färe and Grosskopf (2010) also proposed a generalization of the slack based measure of efficiency on the directional distance function. This measure of efficiency could tell level of excess inputs and outputs short of an efficient level regarding the sum of directional distance function. Some studies such as Barros et al. (2012) developed directional slacks based inefficiency measures by incorporating undesirable outputs. Barros et al. (2012) analyzed technical efficiency of the Japanese banks from 2000 to 2007. Based on the Russell directional distance function which considers desirable and undesirable outputs simultaneously, the model used non-performing loans (NPLs) in form of undesirable outputs.

2.2. DEA and DDF Methods Literature on Environmental Issues

In recent years, DEA techniques have been used to address environmental issues by finding importance of desirable and undesirable output separation. After separating outputs, DEA can measure both economic efficiency on desirable outputs and environmental efficiency on undesirable outputs. Considering both economic and environmental goals, DEA is one of the multiple criteria decision analysis (MCDA) methods (Stewart, 1996). Thus, the studies on MCDA about energy and environment are DEA-related studies such as Huang et al. (1995) and Zhou et al. (2006a, 2006b).

DEA research with environmental dimension included are Cooper et al. (1996), Bevilacqua and Braglia (2002), Korhonen and Luptacik (2004), Triantis and Otis (2004), Zaim (2004), Kousmanen (2005), Pasurka (2006).

Cooper et al. (1996) surveyed the literature by employing mathematical programming approaches to air pollution management. Bevilacqua and Braglia (2002) described a DEA model to measure the environmental performance of seven oil refineries in Italy from 1993 to 1996 relatively. Korhonen and Luptacik (2004) measured technical and ecological efficiency of 24 power plants in European country. Triantis and Otis (2004) defined dominance-based DEA with data from manufacturing facility to consider environmental performance. Zaim (2004) used a variant of Malmquist quantity index to measure the aggregate pollution intensity and defined pollution intensity as pollution per unit of manufacturing output. This index provides method for comparing performance of DMUs over time by solving several DEA type models. Kousmanen (2005) identified confusion about weak disposability in nonparametric production analysis. This study has provided new directions for future research. Pasurka (2006) established a linkage between DEA and index decomposition analysis.

DEA is widely used to model regional/national carbon dioxide emissions result of the growing concern on climate change due to CO_2 emissions in recent years such as Zaim and Taskin (2000a, 2000b), Zofio and Prieto (2001), Ramanathan (2002, 2005), Fare et al. (2004) and Zhou et al. (2006b, 2008, 2010). Ramanathan (2005) applied DEA to forecast energy consumption and CO_2 emissions. Zhou et al. (2010) introduced a Malmquist CO_2 emission performance index (MCPI) by solving several DEA models to measure changes in total factor carbon emission performance over time. The index is used for the emission performance of world's 18 top CO_2 emitters from 1997 to 2004.

Directional distance function (DDF) is alternative approach to estimate distance from best practice frontier for each observation. The concept of this approach is expanding desirable outputs and reducing undesirable outputs simultaneously for a given direction vector (Chung et al. 1997). Since most environmental problems arise from undesirable outputs when desirable outputs are produced, there are many studies using DDF approach while evaluating environmental performance such as Picazo-Tadeo et al. (2005), Kumar (2006), Färe et al. (2007). Some studies such as Fukuyama and Weber (2009, 2010), Färe and Grosskopf (2010), and Mahlberg and Sahoo (2011), expanded directional distance function into a more general form that is non-radial DEA models for identifying and incorporate slacks as much as possible.

Picazo-Tadeo et al. (2005) used DDF as a nonparametric approach to evaluate the impact of environmental regulations on the performance of Spanish producers of ceramic pavements when some outputs are undesirable.

Kumar (2006) examined total factor productivity in 41 countries over the period of 1971 to 1992 according to environmental performance. The study used directional distance function to derive Malmquist–Luenberger (ML) productivity index.

Fukuyama and Weber (2009) proposed a directional slacks-based measure of technical inefficiency to examine the financial services provided by Japanese cooperative Shinkin banks during the period 2002–2005. Fukuyama and Weber (2010) also modeled the performance of Japanese banks using a two-stage network model allowing non-radial scaling of outputs and inputs.

Färe and Grosskopf (2010) constructed Environmental Performance Index (EPI) to measure the electric power plants performance that produce both desirable and undesirable outputs. In this study, Malmquist Quantity Index is also derived by extending EPI to include an index of multiple bad outputs. Then, the data is assembled for the period 1998 to 2005.

Mahlberg and Sahoo (2011) developed the non-radial Luenberger indicator used on the directional Russell measure of inefficiency to analyze the eco-productivity performance behavior of the 22 OECD countries during the period 1995–2004.

2.3. DEA and DDF Methods on Energy Efficiency

Energy efficiency is considered to be indispensable solutions to control GHG emissions (Özbuğday and Erbaş, 2015). DEA plays an important role in energy efficiency studies by considering the ability of DEA in combining multiple factors. Recently, there are several studies investigated energy efficiency by using DEA approach in the literature. Ramanathan (2000) used DEA to measure energy efficiencies of alternative transport modes. Boyd and Pang (2000) examined the relationship between energy intensity and productivity while more recent studies, Hu and Wang (2006) and Hu and Kao (2007) applied DEA to develop total - factor energy efficiency index which provides a useful alternative to aggregated energy intensity measure.

Zhou and Ang (2008) presented several DEA-type linear programming models for energy efficiency performance. The model considered a joint production framework of both desirable and undesirable outputs and different inputs with different energy sources. Thus, changes in energy mix accounted to measure energy performances of 21 OECD countries.

Barros and Peypoch (2008) estimated technical efficiency of Portuguese thermoelectric power generating plants with DEA for period 1996-2004. Zhou et al. (2008) summarized the main features of 100 publications on the application of DEA to environmental and energy studies in a literature survey.

Liu et al. (2010) analyzed carbon emissions changes during 1997-2007 based on the index decomposition analysis method in 582 base-load Chinese coal-fired power plants in 2002. Yang and Pollitt (2010) proposed a model that distinguishes weak and strong disposability assumptions among various undesirable outputs based on their respective technical features.

Sueyoshi and Goto (2011) proposed a new approach which incorporates energy and non-energy input separation in addition to desirable and undesirable output separation for Japanese fossil fuel power generation within a computational framework of DEA non-radial measurement.

Jaraite and Maria (2012) investigated environmental efficiency and productivity enhancing performance of the European Union's CO_2 Emissions Trading Scheme (EU ETS) in EU public power generating sector over the 1996–2007 period.

2.4. DEA and DDF Methods on Electricity Generation Sector

Energy is important for economic and social development and improved quality of life in all countries. World primary energy demand is increasing rapidly and fossil fuels will continue to dominate (77% of global primary energy comes from fossil fuels) global energy use. However, fossil fuel energy consumption cause ecosystem disruptions and climate change. Climate change can be prevented by stabilization of the concentration of green-house gases (GHGs). The greenhouse gas emissions that cause climate change are emitted mainly from burning fossil fuels such as coal, oil and natural gas. The natural greenhouse gas, carbon dioxide (CO_2), is the biggest human supplied gas to the greenhouse effect (about 70%). The largest global sources of CO_2 are electricity and heat generation (32%) (Bilen et al, 2008).

Electricity production from fossil fuel combustions produces CO_2 emissions as undesirable output. Directional distance function is recent approach to measure of energy and environmental performance that can increase desirable outputs (e.g. electricity) and reduce undesirable outputs (e.g. CO_2 emissions). Many studies have used DEA to measure the energy performance of DMUs electricity generation. Färe et al. (1996) were the first to include a pollution variable in their DEA methodology for the electrical energy industry. In their paper, environmental performance indicator is introduced by the use of data from U.S. fossil-fuel-fired electric utilities.

The indicator is based on the decomposition of overall factor productivity into a pollution index and an input-output efficiency index.

More recent DEA studies of energy efficiency that address pollution include. Chang and Hu (2010) and Mukherjee (2010). Chang and Hu (2010) used non-radial directional distance function to evaluate the energy productivity change of Chinese provinces. Mukherjee (2010) aimed to achieve joint goals of energy conservation and economic growth with the use of directional distance function. However, these studies did not consider undesirable outputs in their modeling framework. Sozen et al. (2010) conducted DEA for efficiency analyses of the eleven lignite-fired, one hard coal fired and three natural gas-fired state-owned thermal power plants used for electricity generation in Turkey. Operational and environmental performances were defined and the relationship between efficiency scores and input/output factors was investigated. Sueyoshi and Goto (2012) reviewed weak and strong disposability and compared weak/strong disposability to natural/managerial disposability in terms of conceptual and methodological implications. The study is applied Japanese electric power firms and manufacturing firms.

Only few studies have used to directional distance function to measure performance of electricity generation. Färe et al. (2007) employs the directional distance function to measure the environmental efficiency of coal-fired plants in the U.S. Choi et al. (2012) presented a slacks-based measure of efficiency incorporating CO_2 emissions.

Recently, non-radial directional distance function approach described in Zhou et al. (2012) defines total-factor energy efficiency and energy productivity indexes by considering CO_2 emissions, The conventional non-radial measures asses the level of efficiency by slacks. Zhou et al. (2012) assesses energy and CO_2 emission performance in electricity generation with non-radial directional distance function and DEA models. However, Zhou et al. (2012) and this study is different that the amount of slack is replaced by an efficiency score related to each production factor (i.e., inputs, desirable and undesirable outputs). Thus, these researches document a new type of non-radial measure.

CHAPTER THREE

METHODOLOGY

In this study, non-radial directional distance function approach is used to investigate the energy, environmental and economic performance of countries in electricity generation. The possible environmental pressure indicator data is associated with emissions in general and CO_2 in particular. To compare countries' performance, environmental production technologies for countries are constructed with production efficiency point of view. The environmental production technology in this study is the production technology which takes into account undesirable output in addition to desirable output. The model construction is customized for countries with and without combined heat and power (CHP) plants and the countries in the analysis are grouped accordingly.

3.1. Combine Heat and Power (CHP) Technologies

Combined heat and power (CHP) is an efficient and clean approach to generating electric power and useful thermal energy from a single fuel source as a series of proven, reliable and cost-effective technologies. These technologies have been making an important contribution to meeting global heat and increasing electricity demand. Since these technologies provide utilization of waste heat and low-carbon renewable energy resources, CHP is a strategy for national and regional GHG emissions reduction strategies (IEA 2008, Combined Heat and Power Report).

CHP plants have been using the heat output from the electricity generation for heating or other industrial applications. By doing these, CHP plants generally convert 75-80% of the fuel source into useful energy, while conventional generation processes' (separate heat and power generation) efficiency ratio are 40-50%. (IPCC, 2007). Figure 2 shows efficiency gains of CHP with one example (IEA 2008, Combined Heat and Power Report).

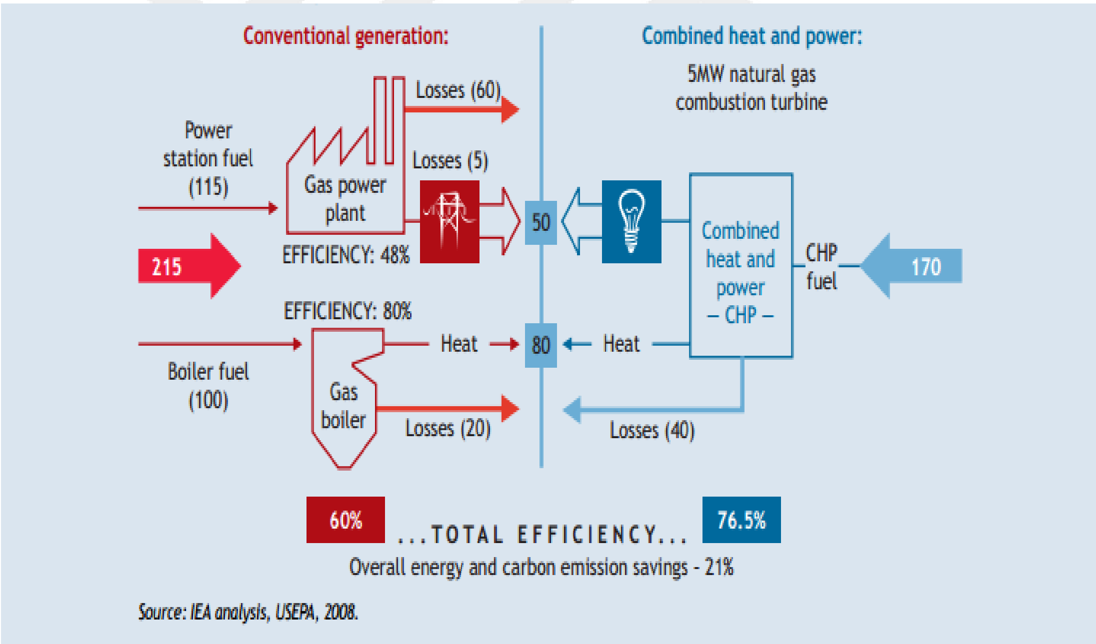

Figure 2 Efficiency Gains of CHP

Considering this efficiency gains, some countries have been able to achieve constructing these technologies to electricity generation plants. However, most countries have not been successful. This study analyzes performance of countries with different technologies separately to discriminate CHP technologies environmental benefits.

3.2. Dataset

The data set is obtained from International Energy Agency 2013 (IEA) Energy and Energy Balance Statistics. These statistics includes CO_2 emissions from fuel combustions, Energy Balance Statistics of non-OECD and OECD countries (fossil fuel consumption because of electricity generation statistics), Energy Statistics of non-OECD and non-OECD countries (electricity and heat generation from fossil fuel consumption statistics). Table 1 shows CHP and non-CHP counties used in the dataset. Excluding countries with incomplete data, the final dataset consist of 72 non-CHP countries (Albania, Congo, Democratic Republic of Congo, Georgia, Nepal, Paraguay are excluded from the dataset because of incomplete data in selected years). Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates (the six Gulf Cooperation Council (GCC) member countries) are excluded because it is not possible to give reasonable estimates of the electricity generation efficiencies of these countries. Some of them operated combined water and power (CWP) plants where desalination and electricity are generated simultaneously using fossil fuels (Ang et al., 2011). Armenia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Tajikistan, Turkmenistan are excluded from dataset because of incomplete data. Poland is excluded because it hasn't reported any CO_2 emission data in selected countries. Final dataset includes 40 CHP countries. Non-CHP countries have single input which is fossil fuel consumption for electricity generation. The input of the model is fossil fuel (coal and coal products, peat, crude, natural gas liquids (NGL) and feedstocks, oil products, natural gas) consumption in generation of electricity and it is denoted by F (unit:ktoe). The other energy sources (nuclear, hydro, geothermal, solar, wind, biofuels, etc.) are not included consumption data because this study used the model which only includes fossil fuel consumption because of electricity generation. The undesirable output is CO_2 emissions from electricity generation processes and presented by C (unit: Mt). The desirable output is electricity generation from fossil combustions and it is denoted by E (unit: GWh). For the countries with CHP plants, there is one more desirable output that is heat generation and it is represented by H (unit: TJ). Therefore, two different production functions should be described, one is for countries without CHP plants, and other is for countries with CHP plants.

The yearly data is available from 1970 to 2011. However, this study covers 5 year periods between 1988 and 2011. This time period is chosen to be consistent with Kyoto Protocol's time frame and to understand how countries evolve in regard to energy and environmental performance during this time frame. The start year 1988 captures performance of countries before Kyoto Protocol base year (1990). In order to capture the most recent year in the data set, the last period has the length of three years instead of five and thus the end year represent the performances of countries in 2011.

Table 1 CHP and non-CHP Countries in the Dataset

Country	Technology	Country	Technology
Albania	non-CHP	Armenia	CHP
Algeria	non-CHP	Azerbaijan	CHP
Angola	non-CHP	Belarus	CHP
Argentina	non-CHP	Bosnia and Herzegovina	CHP
Bahrain	non-CHP	Bulgaria	CHP
Bangladesh	non-CHP	People's Republic of China	CHP
Benin	non-CHP	Croatia	CHP
Bolivia	non-CHP	Kazakhstan	CHP
Botswana	non-CHP	Kosovo	CHP
Brazil	non-CHP	Kyrgyzstan	CHP
Brunei Darussalam	non-CHP	Latvia	CHP
Cambodia	non-CHP	Lithuania	CHP
Cameroon	non-CHP	Former Yugoslav Republic of Macedonia	CHP
Chinese Taipei	non-CHP	Republic of Moldova	CHP
Colombia	non-CHP	Mongolia	CHP
Congo	non-CHP	Romania	CHP
Democratic Republic of Congo	non-CHP	Russian Federation	CHP
Costa Rica	non-CHP	Serbia	CHP
Côte d'Ivoire	non-CHP	Tajikistan	CHP
Cuba	non-CHP	Turkmenistan	CHP
Cyprus	non-CHP	Ukraine	CHP
Dominican Republic	non-CHP	Uzbekistan	CHP
Ecuador	non-CHP	Austria	CHP
Egypt	non-CHP	Belgium	CHP
El Salvador	non-CHP	Canada	CHP
Eritrea	non-CHP	Czech Republic	CHP
Ethiopia	non-CHP	Denmark	CHP
Gabon	non-CHP	Estonia	CHP
Georgia	non-CHP	Finland	CHP
Ghana	non-CHP	France	CHP
Gibraltar	non-CHP	Germany	CHP
Guatemala	non-CHP	Greece	CHP
Haiti	non-CHP	Hungary	CHP
Honduras	non-CHP	Italy	CHP
Hong Kong, China	non-CHP	Japan	CHP
India	non-CHP	Korea	CHP
Indonesia	non-CHP	Luxembourg	CHP
Islamic Republic of Iran	non-CHP	Netherlands	CHP

Country	Technology	Country	Technology
Iraq	non-CHP	Norway	CHP
Jamaica	non-CHP	Poland	CHP
Jordan	non-CHP	Portugal	CHP
Kenya	non-CHP	Slovak Republic	CHP
Dem. People's Rep. of Korea	non-CHP	Slovenia	CHP
Kuwait	non-CHP	Sweden	CHP
Lebanon	non-CHP	Switzerland	CHP
Libya	non-CHP	Turkey	CHP
Malaysia	non-CHP	United Kingdom	CHP
Malta	non-CHP	United States	CHP
Montenegro	non-CHP	Singapore	non-CHP
Morocco	non-CHP	South Africa	non-CHP
Mozambique	non-CHP	Sri Lanka	non-CHP
Myanmar	non-CHP	Sudan	non-CHP
Namibia	non-CHP	Syrian Arab Republic	non-CHP
Nepal	non-CHP	United Republic of Tanzania	non-CHP
Netherlands Antilles	non-CHP	Thailand	non-CHP
Nicaragua	non-CHP	Togo	non-CHP
Nigeria	non-CHP	Trinidad and Tobago	non-CHP
Oman	non-CHP	Tunisia	non-CHP
Pakistan	non-CHP	United Arab Emirates	non-CHP
Panama	non-CHP	Uruguay	non-CHP
Paraguay	non-CHP	Venezuela	non-CHP
Peru	non-CHP	Vietnam	non-CHP
Philippines	non-CHP	Yemen	non-CHP
Qatar	non-CHP	Zambia	non-CHP
Saudi Arabia	non-CHP	Zimbabwe	non-CHP
Senegal	non-CHP	Australia	non-CHP

3.3. Modeling Environmental Production Technology with Desirable and Undesirable Outputs

The concept of joint production is known as one of the conceptual foundations of ecological economics. The theory of multiple-input and multiple-output production technologies are established also in mainstream economics. Most of the production process of ecological problems generates undesirable and desirable outputs. For instance, CO_2 emissions are inevitable when electricity is generated by fossil fuel consumption. Joint production framework allows analyzing both energy and CO_2 emission performance simultaneously.

In relatively recent literature, the energy and environmental performance of countries are modeled with data envelopment analysis (DEA) (Zhou et al., 2008). DEA is a linear programming based technique for evaluating the relative efficiency of Decision Making Units (DMU's). DEA facilitates the construction of a non-parametric piece-wise frontier over the existing data by using linear programming. There is a separate linear programming problem for each observation. Simultaneously, it estimates the distance to the best practice frontier for each observation. All points on the frontier represent technically efficient combinations of inputs and outputs, and all points to the interior of the frontier represent inefficient combinations of inputs and outputs. Figure 3 provides a simple graphical illustration of the best practice frontier and the directional distance technology. In this figure, for simplicity, only desirable and undesirable output is considered (two dimensional graph). The desirable output is electricity generation from fossil combustions and it is denoted by E. The undesirable output is CO_2 emissions from electricity generation processes and presented by C. Point A in the figure represent inefficient input-output combination. Efficiency measures have been determined by examining distances between observed input and output combinations and frontier input and output combinations. The method seeks to determine the maximal radial contraction or expansion of inputs or outputs, while still remaining with the feasible input or output set (Coelli et al., 2005).

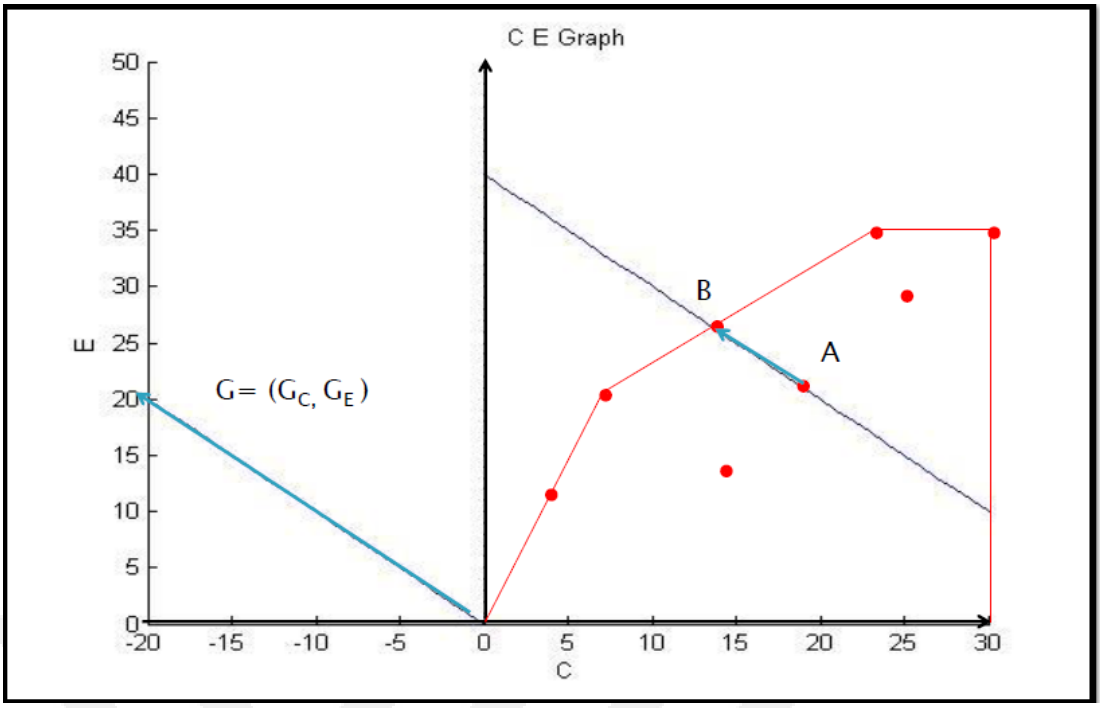

Figure 3 Graphical Illustration of Directional Distance Technology

This study employs the model developed by Zhou et al. (2012). Figure 4 shows general structure and flow chart of methodology used in this study. First, environmental DEA technology is constructed. Second, non – radial directional distance function is defined and the model is developed in GAMS Program. After finding optimum values, EPI, CPI and ECPI are calculated.

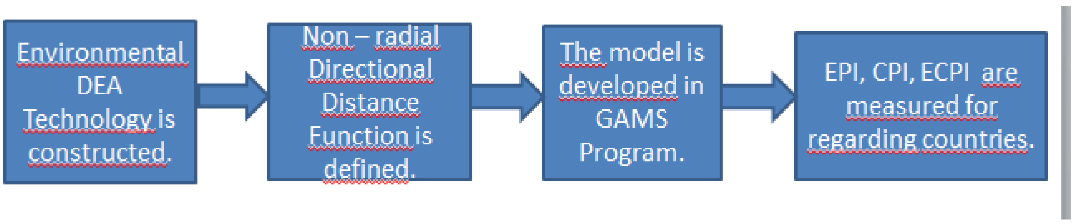

Figure 4 Flow Chart of Methodology

In this study, only energy related input is considered which is similar to the earlier researches by Zhou and Ang (2008) and Zhou et al. (2012) as this study aims to assess the energy and CO_2 emission performance of electricity generation at the economy level. Modeling energy inputs only are adequate to assess environmental performance when there is pollution as an undesirable output For the simplicity, similar to Zhou et al. (2012), this study only the fossil fuels used in the model as an input. Figure 5 shows three dimensional graph which also includes fossil fuel consumption in the form of input. In this figure, a simple graphical illustration of the best practice frontier and the directional distance technology is illustrated.

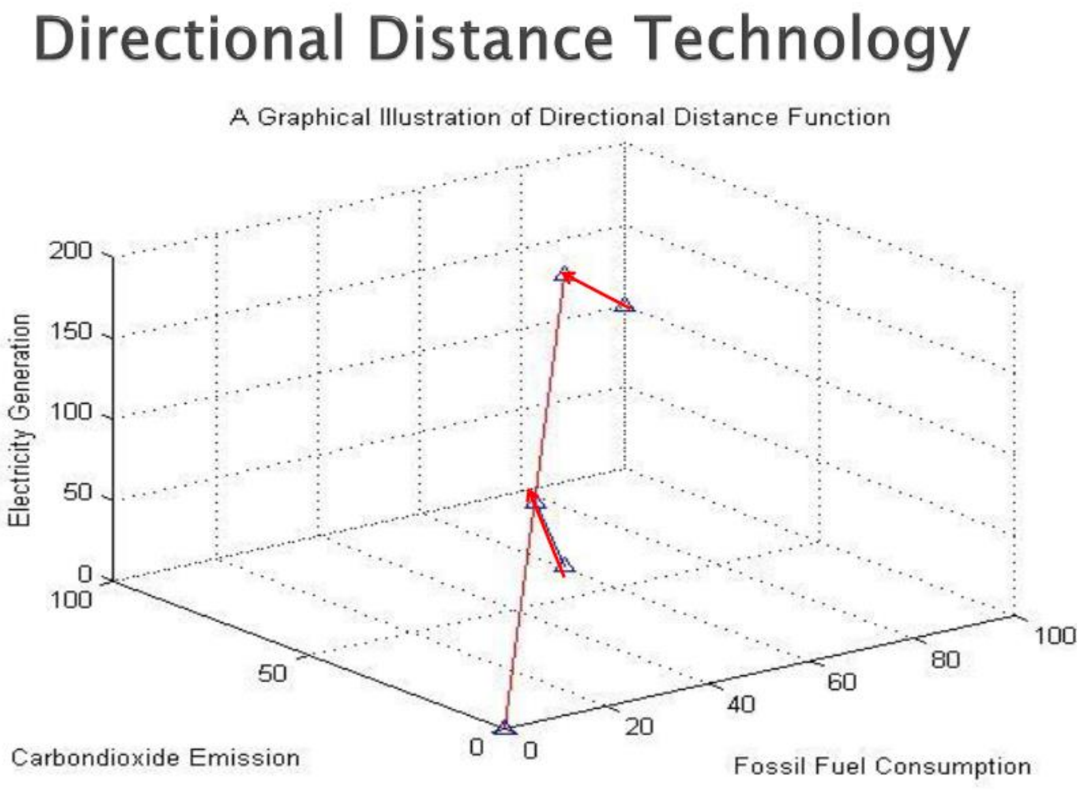

Figure 5 Graphical Illustration of Directional Distance Function of Model

3.3.1. Environmental Production Technology without CHP Plants

The production technology for the countries without CHP plants can be characterized as

$$T_1 = \{(F, E, C): F \text{ can produce } (E, C)\} \tag{3.1}$$

The production technology can be described via the environmental output set

$$P_1(F) = \{(E, C): F \text{ can produce } (E, C)\} \tag{3.2}$$

$P_1(F)$ is a bounded and closed set and satisfies the following properties:

$P1^1$. Undesirable output is weak disposable, i.e., if $(E, C) \in P_1(F)$ and $0 \leq \theta \leq 1$, then $(\theta E, \theta C) \in P_1(F)$.

$P1^1$ states that proportional reduction of electricity generation (desirable output) and CO_2 emission (undesirable output) is feasible (the reduction of undesirable is costly).

$P2^1$. Outputs are null-joint, i.e., if $(E, C) \in P_1(F)$ and $C=0$, then $E=0$.

$P2^1$ states that CO_2 emissions in electricity generation from fossil-fuel combustions are inevitable. The only way to eliminate undesirable output is to end the production process.

$P3^1$. Desirable output is freely (strongly) disposable, i.e., $(E, C) \in P_1(F)$ and $E' \leq E$ imply $(E', C) \in P_1(F)$.

$P4^1$. Input is freely disposable, i.e., $(F, E, C) \in T_1$ and $F' \geq F$ imply $(F', E, C) \in T_1$.

The environmental production technology T_1 can be formulated with a nonparametric piecewise linear representation to employ efficiency measurement.

The environmental Data Envelopment Analysis (DEA) Technology under constant returns to scale (CRS) is represented by

$$T_1 = \{(F, E, C): \sum_{n=1}^{N} z_{1n} F_{1n} \leq F$$

$$\sum_{n=1}^{N} z_{1n} E_{1n} \geq E$$

$$\sum_{n=1}^{N} z_{1n} C_{1n} = C$$

$$z_{1n} \geq 0 \text{ , n=1,2,…,N}\} \tag{3.4}$$

N represents number of countries without CHP plants in selected years. Therefore, F_{1n} is fossil fuel input, E_{1n} electricity output and C_{1n} is CO_2 emission vectors of country n.

z_{1n} is intensity variable, which will be used to construct the best practice frontier.

In the CRS case, the sum of intensity variables is unrestricted. Imposing additional axioms on returns to scale implies less restrictive constraints for the intensity weights, which leads to the expansion of the estimated production possibility set (Kuosmanen et al. 2009).

It can be shown that disposability and null-jointness assumptions are satisfied with equation (3.4). The inequality constraints for input and desirable output allow a feasible vertical extension, implying the strong disposability. The equality constraint indicate that an increase in undesirable output decreases the vector of desirable outputs (weak disposability) (Sueyoshi and Goto 2012). The proofs can be found in Zhou et al. (2012).

3.3.2. Environmental Production Technology with CHP Plants

The production technology for the countries with CHP plants can be characterized as

$$T_2 = \{(F, E, H, C): F \text{ can produce } (E, H, C)\} \quad (3.3)$$

The environmental production technology implies that above properties (P1, P2, P3, P4) still holds.

P1^2. Undesirable output is weak disposable, i.e., if $(E, H, C) \in P_1(F)$ and $0 \leq \theta \leq 1$, then $(\theta E, \theta H, \theta C) \in P_1(F)$.

P2^2. Outputs are null-joint, i.e., if $(E, H, C) \in P_1(F)$ and C=0, then E=H=0.

P3^2. Desirable outputs are freely (strongly) disposable, i.e., $(E, H, C) \in P_1(F)$ and $H' \leq H$ imply $(E, H', C) \in P_1(F)$.

P4^2. Input is freely disposable, i.e., $(F, E, C) \in T_1$ and $F' \geq F$ imply $(F', E, C) \in T_2$.

Say that, there are M countries with CHP plants in selected years. Therefore, F_{2m} is fossil fuel input, E_{1m} electricity output and C_{1m} is CO_2 emission vectors.

$T_2 = \{(F, E, H, C): \sum_{m=1}^{M} z_{2m} F_{2m} \leq F$

$$\sum_{m=1}^{M} z_{2m} E_{2m} \geq E$$

$$\sum_{m=1}^{M} z_{2m} H_{2m} \geq H$$

$$\sum_{m=1}^{M} z_{2m} C_{2m} = C$$

$$z_{2m} \geq 0 \text{ , m=1,2,…,M}\} \tag{3.5}$$

z_{2m} is intensity variable, which will be used to construct the best practice frontier.

3.4. Non-radial Directional Distance Function

Efficiency is an important concept for production to indicate metrically input-output ratio. Distance functions are one way of measuring efficiency. Moreover, distance functions can be used to describe multi-input, multi-output technology. A directional distance function permits the simultaneous contraction of input/undesirable outputs and expansion of desirable outputs (Fare and Grosskopf, 2004). However, radial directional distance function which is characterized by Chambers et al. (1996, 1998) tries to look for the extension of desirable outputs and reduction of undesirable outputs and inputs at the same rate. However, this same rate maybe inappropriate for each input-output bundle. In this study, in order to measure full eco-efficiency, non-radial directional distance functions are defined upon earlier works by Fukuyama et al. (2011), Barros et al. (2012) and Zhou et al. (2012). The advantage of non-radial directional distance function approach is adjusting inputs and outputs freely.

3.4.1. Non-radial Directional Distance Function for the countries without CHP Plants

Denote the directional distance function as

$\vec{D}_1$ (F, E, C; g_1) = sup {w_1^T : ((F, E, C) + g_1 . diag(β_1)) ∈ T_1 }

$g_1 = (g_{1F}, g_{1E}, g_{1C})$ is directional vector (direction of change)

$w_1 = (w_{1F}, w_{1E}, w_{1C})^T$ represents normalized weight vector . The numbers of inputs and outputs of model characterizes the weight vector.

$\beta_1 = (\beta_{1F}, \beta_{1E}, \beta_{1C}) > 0$ is the vector of scaling factors

z_{1n} decision variable

The DEA type model formulation adopted from Fare and Grosskopf (2010) is as follows:

$\vec{D}_1$ (F, E, C; g_1) = max $w_{1F}\,\beta_{1F} + w_{1E}\,\beta_{1E} + w_{1C}\,\beta_{1C}$

$$\text{s.t.}\ \sum_{n=1}^{N} z_{1n} F_{1n} \leq F + \beta_{1F}\, g_{1F}\text{--}$$

$$\sum_{n=1}^{N} z_{1n} E_{1n} \geq E + \beta_{1E}\, g_{1E}$$

$$\sum_{n=1}^{N} z_{1n} C_{1n} = C + \beta_{1C}\, g_{1C}$$

$$z_{1n} \geq 0\ , n=1,2,\ldots,N, \quad \beta_{1F}, \beta_{1E}, \beta_{1C} \geq 0 \tag{3.6}$$

Likewise radial distance function, non-radial distance function also satisfies following basic properties:

(1) The translation property: $\vec{D}_1$ (F + α g_{1F}, E + α g_{1E}, C + α g_{1C} ; g_1) = $\vec{D}_1$ (F, E, C; g_1) −α , α ∈ $\mathcal{R}$.

(2) Homogeneous of degree -1: $\vec{D}_1$ (F, E, C; αg_1) = α^{-1} $\vec{D}_1$ (F, E, C; g_1), α > 0.

(3) Homogeneous of degree +1 : $\vec{D}_1$ (αF, αE, αC; g_1) = α $\vec{D}_1$ (F, E, C; g_1), α > 0 (as the technology exhibits constant returns to scale).

3.4.2. Non-radial Directional Distance Function for the countries with CHP Plants

We can also define non-radial directional function regarding $T_{2:}$

$\vec{D}_2$ (F, E, H, C; g_2) = sup {w_2^T : ((F, E, H, C) + g_2. diag(β_2)) ∈ T_2 }

G_2 = ($g_{2F,}$ g_{2E}, $g_{2H,}$ g_{1C}) is directional vector.

W_2 = (w_{2F}, w_{2E}, w_{2H} w_{2C})^T represents normalized weight vector.

$\beta_{2=}$ (β_{2F}, β_{2E}, $\beta_{2H,}$ β_{2C})>0 is the vector of scaling factors.

$\vec{D}_2$ (F, E, H, C; g_2) can be modeled by solving following model:

$\vec{D}_2$ (F, E, H, C; g_2) = max w_{2F} β_{2F} + w_{2E} β_{2E} + w_{2H} β_{2H} + w_{1C} β_{1C}

$$\text{s.t. } \sum_{m=1}^{M} z_{2m} F_{2m} \le F + \beta_{2F}\, g_{2F}$$

$$\sum_{m=1}^{M} z_{2m} E_{2m} \ge E + \beta_{2E}\, g_{2E}$$

$$\sum_{m=1}^{M} z_{2m} H_{2m} \ge H + \beta_{2E}\, g_{2E}$$

$$\sum_{m=1}^{M} z_{2m} C_{2m} = C + \beta_{2C}\, g_{2C}$$

$$z_{2n} \geq 0 \text{ , n=1,2,...,N,} \quad \beta_{2F}, \beta_{2E}, \beta_{2H}, \beta_{2C} \geq 0 \tag{3.7}$$

Similar to $\vec{D}_1$ (F, E, C; g_1), $\vec{D}_2$ (F, E, H, C; g_2) satisfies the basic properties of directional distance function mentioned above.

3.5. GAMS

The linear programming model of problem is solved in GAMS 23.5 (Generalized Algebraic Modeling System). This modeling system has own programming language syntax which allows to write mathematical optimization problem. Thus, the first step of solving an optimization problem under GAMS is the creation of an accurate GAMS model of a mathematical problem. GAMS modeling language has been used in variety of linear, non-linear, and mixed-integer programming models, general equilibrium models, and network models. GAMS is used for formulating, solving, and analyzing a small and simple optimization problem. These problems are related with policy or sector analysis.

The linear optimization programming in GAMS is efficient modeling system regarding below properties (Geletu, 2008):

- Providing a high-level language for the compact representation of large and complex models
- Allowing changes to be made in model speciation simply and safely
- Allowing unambiguous statements of algebraic relationships
- Permitting model descriptions that are independent of solution algorithms

Some of DEA studies in the literature have used GAMS. To illustrate, Olesen and Petersen (1996), Walden and Kirkley (2000). Olesen and Petersen (1996) have provided GAMS programming code for DEA. Walden and Kirkley (2000) have developed several GAMS programming for modelling production efficiency and fishing capacity in marine fisheries. Productivity Commission (1999) has used DEA for assessing the performance of Australian Railways.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

In this chapter, the results of DEA type model formulation and indexes of energy performance and CO_2 emission performance are presented. In this study, the non-radial directional distance function model is constructed and it is developed in GAMS program. The results are produced by using GAMS.

There are many studies on performance measurement models with undesirable outputs. Some studies give us radial-measure of efficiency, for instance model developed by Chambers et al. (1996, 1998). Some other studies give us non-radial efficiency measures, illustratively, Fukuyama and Weber (2009, 2010), Fare and Grosskopf (2010), Mahlberg and Sahoo (2011), Barros et al. (2012), and Zhou et al. (2012). Non-radial measure of efficiency is more effective as it gives more realistic result when there exist non-zero slacks. The directional distance function model used in this study is developed by Zhou at al. (2012) and it is very similar to the model described in Barros et al. (2012).

4.1. Results for Countries without CHP Plants

In order to model energy and ecological performance of countries without CHP plants, Model (3.6) is constructed. Model (3.6) examines the measurement of efficiency as a distance from the observed input-output vector of the evaluated decision making unit (DMU) to the efficient boundary of the benchmark technology in some pre-assigned direction $g_1 = (g_{1F}, g_{1E}, g_{1C})$. Thus, $\vec{D}_1$ (F, E, C; g_1) is non-radial measure of inefficiency. $\vec{D}_1$ (F, E, C; g_1) $=0$ indicates full efficiency in the g_1 direction and it means that evaluated DMU is located at the best practice frontier. $\vec{D}_1$ (F, E, C; g_1) >0 means that the evaluated DMU is inefficient. $g_1 = (g_{1F}, g_{1E}, g_{1C})$ indicates the direction of expansion or contraction. If the value of the directional vector is set equal to the observed values of the desirable and undesirable outputs (i.e. $g_{1E} =E$, $g_{1C} =C$), β_{1E} and β_{1C} indicates the proportionate expansion in desirable outputs and contraction in undesirable outputs. By specifying various directional vectors in the Model (3.6), energy and CO_2 emission performance can be modeled and measured.

4.1.1. Energy Performance Index (EPI) for the Countries without CHP Plants

In the Model (3.6), g_1 is set as (-F, E, 0) and thus there are two scaling factors; fossil fuel consumption and energy generation. The normalized weight vector could be (1/2, 1/2, 0) as it is relevant to the numbers of inputs and outputs that can be decreased (increased) for each observation (Färe and Grosskopf, 2010). Since there are two scaling factors, the model tries to contract fossil fuel consumption and expand electricity generation.

$$\text{The measurement of energy performance} = \frac{\text{actual energy efficiency}}{\text{potential energy efficiency}} \tag{4.1}$$

Energy efficiency means that the ratio of energy output to fossil fuel input. Potential energy efficiency indicates that the ratio of potential electricity output to fossil fuel input. When Model (3.6) is solved, the result of the model gives us potential fossil fuel input and potential electricity output (optimal values).

$$EPI_1 = \frac{E/F}{(E+\beta_{1E}^{*}E)/(F-\beta_{1F}^{*}F)} = \frac{1-\beta_{1F}^{*}}{1+\beta_{1E}^{*}} \tag{4.2}$$

β_{1E}^{*} and β_{1F}^{*} are the optimal solutions of the model with the (-F, E, 0) direction. When β_{1E}^{*} and β_{1F}^{*} equals to 0, then EPI_1 =1. This means that the country evaluated has the best energy performance in the regarding direction.

Appendix A presents the energy performance index (EPI) ranking of selected countries calculated for selected years. The latest year in the data set is 2011. Thus, for the year 2011, Haiti, Montenegro and Brazil have the highest EPI. However, Montenegro has no data for the other selected years, making it difficult to compare to other countries and observe its performance in other years. Thus, Montenegro can be omitted while comparing the countries in the sample. Haiti has very little electricity generation data comparing to other selected countries. To illustrate, Haiti's electricity generation from fuel combustions is 567 GWh while mean of non – CHP countries is 80030 GWh. Thus, Haiti also can be omitted from the sample. According to results, Brazil has the highest electricity generation per unit of fossil fuel consumption.

4.1.2. Carbon Performance Index (CPI) for the Countries without CHP Plants

In order to calculate the carbon efficiency or carbon performance index, g_1 is set as (0, E, -C), where two scaling factors are carbon emission and electricity generation. Thus, Model (3.6) seeks to reduce CO_2 emissions and expand electricity generation. The normalized weight vector could be (0, 1/2, 1/2). β_{1E}^* and β_{1C}^* are the optimal solutions of the model with the (0, E, -C) direction.

$$\text{carbon performance index (CPI)} = \frac{\text{potential carbon intensity}}{\text{actual carbon intensity}} \tag{4.3}$$

$$CPI_1 = \frac{(C-\beta_{1C}^* C) / (E+\beta_{1E}^* E)}{C/E} = \frac{1-\beta_{1C}^*}{1+\beta_{1E}^*} \tag{4.4}$$

Larger CPI_1 means that better CO_2 emission performance with the (0, E, -C) direction. Similar to $EPI_{1,}$ When β_{1C}^* and β_{1E}^* equal to 0, then CPI_1 =1. If CPI_1 is equal to unity, it means that regarding country has the best carbon emission performance in electricity production.

For the selected years and countries, CPI results are calculated. CPI results and ranking of the countries in each selected year are presented in Appendix B. According to 2011 year, Brazil, Brunei Darussalam and Haiti have the highest CPI score. The 2011 data also says that, Brazil has the best carbon emission and energy performance in electricity generation. GHG emissions of Brazil heavily come from agriculture, land use and forestry activities. Therefore, Brazil’s energy matrix is known as one of the cleanest in the world and CO_2 emissions from fuel combustion are small which is 1.3% of global CO_2 emissions (2011 CO_2 Emission Overview, IEA) whereas BRICS (Brazil, Russian Federation, India, China and South Africa) countries represented 39% of global CO_2 emissions from fuel combustion. However, Korea is one of the lowest CPI. Among selected countries, it is not surprising that Korea has the lowest CPI, as Korea is a major CO_2 emitter and among OECD countries, Korea has the highest CO_2 emissions growth rate since 1990 (BP, 2012). As Korea's fossil fuel power plants are dominated in electricity generation, one third of total CO_2 emissions are result of electricity generation (Park and Lim, 2009).

It is interesting that both highest and lowest indexes are belongs to member of G20 countries. G20 countries are the top 20 countries in the world according to their economic performance. Thus, it is interesting to investigate to how and to what extent the G20 countries' energy and environmental performances differ from one another. As these differences might point us to the differences in the paths chosen in energy efficiency and environmental performances of these countries which in turn helps us to provide information on their preferences over energy, environmental and ecological tradeoffs. Therefore, this study measures the G20 countries' energy and environmental performance indexes and map the differences across the countries in section 4.3.

4.1.3. Environmental Efficiency (Energy – Carbon Performance Index - ECPI) For the Countries without CHP Plants

To model energy and CO_2 emission performance at the same time, g_1 is set as (-F, E, -C). There are three scaling factors, so Model (3.6) seeks to reduce both CO_2

emission and fossil fuel consumption to expand electricity generation. Since there are three scaling factors, the normalized weight vector could be (1/3, 1/3, 1/3).

$$ECPI_1 = \frac{\frac{1}{2}\left((1-\beta^*_{1F}\ )+(1-\beta^*_{1C})\right)}{1+\beta^*_{1E}} = \frac{1-\frac{1}{2}(\beta^*_{1F}+\beta^*_{1C}\ )}{1+\beta^*_{1E}} \tag{4.5}$$

β^*_{1F} , β^*_{1E} and β^*_{1C} are the optimal solutions of the model with the (-F, E, -C) direction.

Larger $ECPI_1$ represents better mixed energy - CO_2 emission performance with the (-F, E, -C) direction since the numerator represents fossil fuel consumption and CO_2 emission reduction proportion while the denominator captures electricity generation expansion. Similar to other indexes, when β^*_{1F} , β^*_{1E} and β^*_{1C} equals to 0, then $ECPI_1$ =1. If $ECPI_1$ is equals to unity, it means that evaluated country has the best mixed energy - carbon emission performance in electricity production.

ECPI results are calculated for the selected years and countries. ECPI results and ranking of the countries in regarding year are presented in Appendix C. Haiti is excluded from data as explained in Section 4.1. According to the data in year 2011, Brazil, Mozambique, Cuba have the highest ECPI score (The scores are 1). According to data, Brazil has the best energy performance, carbon emission performance and energy - carbon performance, thus it might mean that these countries focusing on both energy and carbon performance while choosing their energy and environmental policy, as they leverage their electricity production with relatively less carbon intensive energy resources. Mozambique and Cuba are the best practice according to ECPI score whereas these countries are not best practice for other performance indices. This means that, when countries are aim to choose their direction towards sustainable energy production, they can choose reducing carbon emission and decreasing the use of fossil fuel inputs at the same time.

4.2. Results for the Countries with CHP Plants

Model (3.7) is developed to model energy and ecological performance of countries with CHP plants. The model tries to find the measurement of efficiency as a distance from the observed input-output vector of the evaluated decision making unit (DMU) to the efficient boundary of the benchmark technology in some pre-assigned direction $g_2 = (g_{2F}, g_{2E}, g_{2C}, g_{2H})$. Thus, $\vec{D}_2$ (F, E, C, H; g_2) is non-radial measure of inefficiency and $\vec{D}_2$ (F, E, C, H; g_2) $=0$ indicates full efficiency in the g_2 direction. This means that evaluated DMU is located at the best practice frontier. $\vec{D}_2$ (F, E, C, H; g_2) >0 means that evaluated DMU is inefficient. At the Model (3.7), $w_2 = (w_{2F}, w_{2E}, w_{2C}, w_{2H})^T$ represents the normalized weigh vector which is determined by the numbers of input and outputs. There is one more desirable output, so there should be one more weight for the output side. $\beta_2 = (\beta_{2F}, \beta_{2E}, \beta_{2C}, \beta_{2H})$ is the vector of the scaling factor with an additional scaling factor for the heat output.

By setting different directional vectors in the Model (3.7), energy and CO_2 emission performance scores can be calculated.

4.2.1. Energy Performance Index (EPI) for the Countries with CHP Plants

To calculate the energy performance or energy efficiency index, g_2 is set as (-F, E, 0, H) in the Model (3.7), then the model tires to reduce fossil fuel consumption and expand energy generation and heat output. There is no change in CO_2 emission. Thus, the normalized weight vector could be (1/2, 1/4, 1/4, 0) as there are two output and one input.

Similar to (4.1), EPI for the countries with CHP plants is defined below:

$$EPI_2 = \frac{1-\beta^*_{2F}}{1+ 1/2(\beta^*_{2E}+\beta^*_{2H})} \quad (4.6)$$

β^*_{2E}, β^*_{2H}, and β^*_{2F} are the optimal solutions of the model with the (-F, E, 0, H) direction. When β^*_{2E}, β^*_{2H}, and β^*_{2F} equal to 0, then EPI_2 =1. This means that the country evaluated has the best energy performance in the regarding direction.

Appendix D presents the energy performance index (EPI) ranking of CHP countries calculated for selected years. According to 2011 data; Denmark, Switzerland, Sweden, Ukraine and Macedonia have the highest EPI among CHP countries. Denmark is at the best practice frontier for almost all selected years (except 1993). It is not surprising that Denmark is one of the efficient countries, as the country has some of the most efficient coal-fired power plants in the world, including a new generation of pulverized coal supercritical plants that were introduced in the 1990s (IEA, 2007).

4.2.2. Carbon Performance Index (CPI) for the Countries with CHP Plants

As the aim is to measure the carbon efficiency index, g_2 is set as (0, E, -C, H) in the Model (3.7) which seeks to reduce CO_2 emissions while expands electricity generation and heat output. The normalized weight vector could be (0, 1/4, 1/2, 1/4). We can use Model (3.7) and above defined parameters to estimate the ratio of CO_2 emission reduction while electricity and heat outputs are increased and the fossil fuel consumption is steady. This ratio is defined as follows:

$$CPI_2 = \frac{1-\beta_{2C}^*}{1+\frac{1}{2}*(\beta_{2E}^* + \beta_{2H}^*)} \tag{4.7}$$

β_{2E}^*, β_{2H}^*, and β_{2C}^* are the optimal solutions of the model with the g_2 direction.

Appendix E shows the carbon performance index (CPI) ranking calculated for the selected years and the CHP countries in the data set. According to 2011 data, Denmark, Switzerland, Sweden, have the highest CPI among CHP countries. The results are similar to Section 4.2.1.

4.2.3. Environmental Efficiency (Energy - Carbon Performance Index - ECPI) for the Countries with CHP Plants

Energy – Carbon performance index or ecological efficiency index is measured by relying on the performance of the countries on both energy efficiency and efficiency in carbon emission reduction. The direction vector g_2 is set as (-F, E, -C, H) to model energy and CO_2 emission performance at the same time. Model (3.7) tries to reduce CO_2 emission and fossil fuel consumption to expand electricity generation and heat output. The normalized weight vector could be (1/3, 1/6, 1/3, 1/6).

$$ECPI_2 = \frac{1-\frac{1}{2}(\beta_{2F}^{*}+\beta_{2C}^{*})}{1+\frac{1}{2}(\beta_{2E}^{*}+\beta_{2H}^{*})} \tag{4.8}$$

Energy – carbon performance of electricity generation for the countries with CHP plants is defined in equation (4.6). β_{2F}^{*}, β_{2E}^{*}, β_{2C}^{*} and β_{2H}^{*} are the optimal solutions of the model with the (-F, E, -C, H) direction. We can use Model (3.7) and above defined parameters to estimate the ratio of reduction of CO_2 emission and fossil fuel consumption while electricity and heat outputs are increased.

ECPI results are calculated for the selected years and CHP countries. ECPI results and ranking of the countries in regarding year are presented in Appendix F. According to 2011 year data, Switzerland and Sweden have the highest ECPI score (The scores are 1). According to data, these two countries have the best carbon emission performance and energy performance for 2011 data. Thus, their energy - carbon performance is also at the best practice frontier.

4.3. Results for G20 Countries

G20 (The Group of Twenty) is an international forum for the governments and central bank governors from 20 major economies representing about two-thirds of the world's population, 85 percent of global gross domestic product and over 75 percent of global trade. There are no specific criteria for G20 membership. However, countries which have significance for the international financial system are included. Some aspects such as geographical balance and population representation have been effectual in determining G20 membership. There are 19 members of these forum; Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, South Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United States - along with the European Union (EU). The countries meet annually to discuss ways to strengthen the global economy, reform international financial institutions improve financial regulation and implement the key economic reforms that are needed in each member economy (http://g20.org.tr/about-g20/g20-members).

In this study, in order to evaluate G20 countries' energy and environmental performance, the new model which only includes G20 countries is developed and run. The new model develops the best practice frontier of G20 countries and measures their performances. Among G20 countries, there are both CHP and non-CHP countries, so heat output produced from CHP plants has to be converted to its electricity equivalent for analyzing efficiency scores. This could be done by converting useful heat to its electricity equivalent. Therefore, when CHP plants are included the electricity generation, conversion of useful heat to electricity equivalent is given by below equation (Ang et al. 2011):

$$Y = E + Hs \tag{4.9}$$

E is the electricity production from electricity plants and CHP plants, H is the useful heat output from CHP plants, and s is the conversion factor from heat to electricity. Previous studies show that s varies between 0.15 and 0.20 (Phylipsen et al. (1998) and IEA (2008)). In this study, it assumed to be 0.175 as in Ang et al. 2011. EP, CP and ECPI results are calculated for the selected years of G20 countries. Russian

Federation and Italy are excluded from our dataset as they have declared very little CO_2 emission data (e.g. Russia CO_2 emission data for 2011 is 7.4 ktoe, whereas the mean of G20 coutries is 470.6 ktoe). Thus, all indices for all years for these countries are 1 and these results are not reliable. G20 countries' input and outputs are presented in Table 2. According to Table 2, Brazil has reported the lowest CO_2 emission data in 2011 and CO_2 emission intensity which is given by the total CO_2 emissions from electricity production divided by the electricity produced is computed. Brazil has also lowest CO_2 emissions intensity and United Kingdom has lowest CO_2 emissions intensity among G20 countries with CHP plants. The performance results for these countries are also parallel to these emission intensity calculations.

Table 2 G20 Countries' Input and Outputs

Countries	Electricity output (GWh)	Heat output (GWh)	CO2 (Mt)	F (ktoe)
Brazil	52270	0	19,67	10974
United Kingdom	260103	15877	149,93	50106
Japan	808436	4107	510,48	156404
Korea	356866	49068	241,16	79610
China	3854151	871339	3560,36	918912
South Africa	243609	0	225,69	58155
Mexico	238784	0	133,14	46515
Turkey	171169	14041	104,63	34455
Germany	362103	105593	253,87	79862
United States	2960191	129485	2051,94	634289
Argentina	88807	0	50,55	19191
Canada	145006	6121	101,7	32781
Australia	227052	0	201,47	56350
Indonesia	160395	0	137,62	40483
France	47504	35985	28,72	13241
India	835711	0	900,63	241401
Saudi Arabia	250077	0	188,66	68598

Results for 2011 year data are presented in Table 3. According to 2011 year data, Brazil and United Kingdom have the highest performance scores for three indexes (The scores are 1). As it is presented in section 4.1.2, agriculture, land use and forestry activities are responsible from Brazil's GHG emissions rather than the energy sector. Moreover, World Bank's Partnership for Market Readiness, provides funding and technical assistance to developing countries for capacity building toward the development and piloting of market-based instruments for GHG reduction. The developing countries which have implemented these instruments are Brazil, Chile, China, Columbia, Costa Rica, India, Indonesia, Mexico, Morocco, Peru, South Africa, Thailand, Turkey, Ukraine and Vietnam (2011 CO_2 Emission Overview, IEA). China is also one of these countries which has the best performance score according to EPI for 2011 year data. The main reason for this result might be China's policy strategy. Chinese government has been trying to control its energy consumption and GHG emissions especially CO_2 emissions after increasing concern on climate change. To illustrate, in China's Eleventh Five – Year Plan, presents the target of decreasing energy use per unit GDP by 20% with 2005 (Wang et al., 2013).

According to Table 3, United Kingdom has the best performance score for three indices. United Kingdom government's approach about climate change is cutting GHG emissions by at least 34% by 2020 and 80% by 2050 below the 1990 levels. The fourth Carbon Budget was set in law in June 2011, committing reductions of 50% from 1990 (Energy Policies of IEA Countries, 2012). According to Table 3, Japan has the best performance for EPI scores. As a member of Kyoto Annex-II countries, Japan has offered not only 25% reduction target but also more aid to help developing countries in dealing with the global warming and climate change (Sueyoshi, and Goto, 2012).

Table 3 G20 Countries' Performance Indices in 2011

G20 Countries	EPI	CPI	ECPI
Brazil	1	1	1
United Kingdom	1	1	1
Japan	1	0.86	0.93
Korea	1	0.57	0.77
China	1	0.43	0.67
South Africa	1	0.40	0.65
Mexico	0.98	0.95	0.98
Turkey	0.97	0.82	0.91
Germany	0.92	0.57	0.79
United States	0.91	0.55	0.77
Argentina	0.88	0.66	0.82
Canada	0.86	0.54	0.74
Australia	0.86	0.42	0.64
Indonesia	0.8	0.44	0.64
France	0.79	0.7	0.78
India	0.78	0.35	0.54
Saudi Arabia	0.7	0.49	0.64

According to index results, some countries have high EPI scores while some countries have high CPI scores. Figure 6 shows that CPI and EPI scores positioned as "x" and "y" axes, respectively. This representation enables the reader to visually compare the countries more easily with respect to their relative performance on energy and carbon efficiencies. The crossing lines represents median of G20 countries. The median of CPI indices is 0.57 and the median of EPI indices is 0.92. This means that G20 countries mainly focus on improving their energy performance rather than carbon performance. As shown in Figure 6, Canada, Germany, United States and Australia are located around the median lines.

G20 countries are tracked in years according to their efficiency index, Appendix 7 shows countries' path in years. According to Appendix G, Brazil and United Kingdom have the best performance scores for the most recent years.

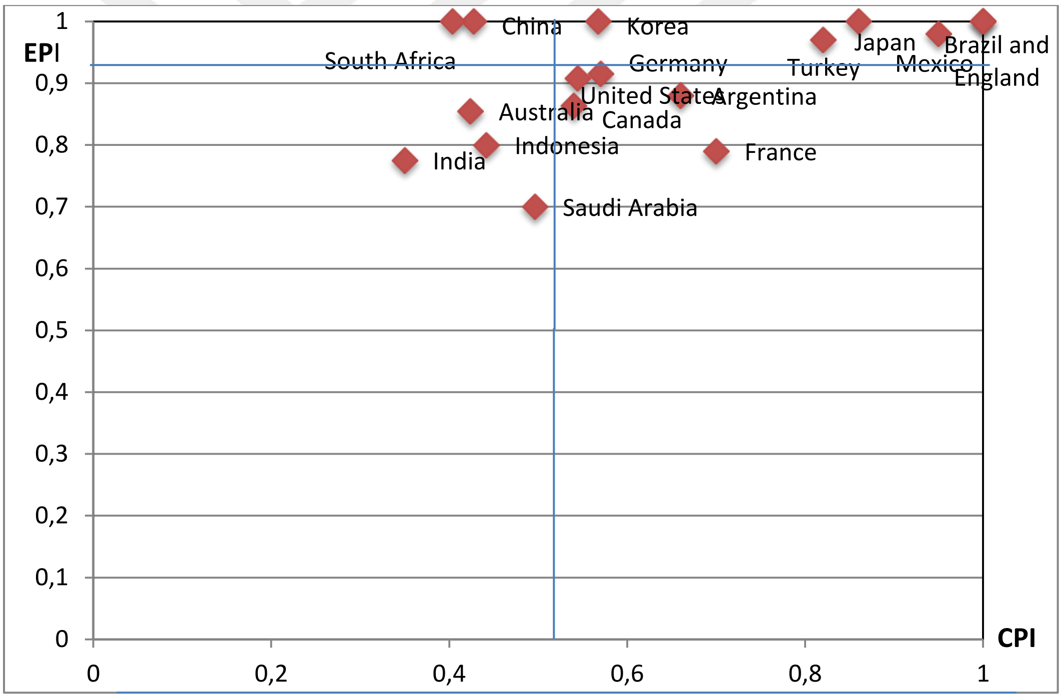

Figure 6 CPI vs. EPI for G20 Countries (2011 data)

It is interesting that Brazil has the highest CPI while this country is known as destroying Amazon forests. However, in this study, only CO_2 emissions because of electricity generation are considered while measuring environmental performance as this study captures energy and environmental performance of countries because of electricity generation from fuel combustions. Environmental performance is not only related with CO_2 emissions, there are also many polluting factors and pollution because of other industries. This study and used dataset is not aligning with measuring all environmental factors. When all environmental factors are available, Brazil's polluting effect on Amazon forests can be presented using the same methods.

4.4. Turkey's Energy and Ecological Performance

Turkey has been tracking of its GHG emissions since 2006 as a member of UNFCCC and Kyoto Protocol (Ari and Koksal, 2011). Turkey declined to make any commitment to reduce GHG emissions because of historically low GHG emissions. Nonetheless Turkey plans to limit future GHG emissions that will not compromise its sustainable development. Turkey also projects that GHG emissions will be 21% lower by 2030 (Turkey's Sixth National Communication under UNFCCC). The Country's GDP has increased 139% while GHG emissions have increased 47.7% between 2000 and 2013. GHG emission per person is 3.96 tone of CO_2 emission equivalent in 1990 and 6.04 tone of CO_2 emission equivalent in 2013. However, this value is lower than the mean of OECD countries which is 12.47 tone of CO_2 emission equivalent per person in 2012, while it is higher than its CO_2 emission equivalent per person in 2012, i.e. 4.88 tone (Turkey's Sixth National Communication under UNFCCC). According to the national GHG emissions inventory of Turkey, GHG emissions have increased by 95%, CO_2 emissions increased by 210% and CO_2 emissions from electricity generation have increased by 234% between 1990 and 2008 (UNFCCC, 2010). Thus, given its economic and environmental goals, it is important to investigate Turkey's energy and environmental performances in electricity generation.

Turkey is a member of UNFCCC Annex-I countries which are responsible to lead the mitigation of GHG emissions responsibilities such as providing financial resources and technology transfer to developing countries called Annex-II countries (UNFCCC, 1992). Thus, in this study, in order to evaluate Turkey's energy and environmental performance, the new model which only includes UNFCCC Annex-I countries is developed and run. UNFCCC Annex-I countries are Belarus, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Liechtenstein, Lithuanian, Monaca, Poland, Romania, Russian Federation, Slovak Republic, Slovenia, Turkey, and Ukraine. However, in the model, Liechtenstein and Monaca are excluded as they are not included IEA dataset. In addition, Latvia, Lithuanian and Poland have not been included as they have not recorded CO_2 emissions data in regarding years. Russian Federation has been dropped from the sample and in the model as Russia's data does not seem to be reliable as it is explained in section 4.3. Remaining countries in the model are Economies in Transition (EITs) which are those countries in Annex-I that are undergoing the process of transition to a market economy.

Among these countries, there are both CHP and non-CHP countries, so heat output produced from CHP plants has been converted to its electricity equivalent for analyzing efficiency scores. The conversion method has been detailed in section 4.3.

EP, CP and ECPI results are calculated for the selected countries in selected years. Results for 2011 year are presented in Table 4. According to the results for 2011, Belarus and Slovak Republic have the highest performance scores for three indexes (The scores are 1). Policies in Belarus are expected to result in a 24-30% decrease from 1990 levels while the country has guaranteed to reduce its emissions by 8% relative to 1990 levels by 2020 (The 2015 Global Climate Legislation Study). Slovak Republic has significant electricity production from natural gas. As the overall efficiency of fossil fuel-fired electricity production is strongly influenced by the mix of fuels used, countries with a large share of natural gas generally have much higher average efficiencies than countries that mainly rely on coal and oil. Thus, higher efficiency score for Slovak Republic is owed to large share of the natural gas in electricity production in the country.

Table 4 Turkey and EITs Countries' Performance Indexes for 2011 Data

Annex 1 Countries	**EPI**	**CPI**	**ECPI**
Belarus	1	1	1
Slovak Republic	1	1	1
Ukraine	1	0.18	0.59
Estonia	1	0.04	0.34
Hungary	0.87	0.11	0.53
Turkey	0.83	0.06	0.43
Croatia	0.83	0.12	0.52
Bulgaria	0.78	0.05	0.38
Romania	0.73	0.09	0.44
Czech Republic	0.68	0.07	0.41
Slovenia	0.34	0.64	0.55

According to index results, some countries have high EPI scores while some countries have high CPI scores. Figure 7 shows that CPI and EPI scores positioned as "x" and "y" axes, respectively. The crossing lines represents median of these indices for these countries. The median of CPI indices is 0.11 and the median of EPI indices is 0.83. As shown in Figure 7, Hungary, Turkey and Croatia are located around the median lines.

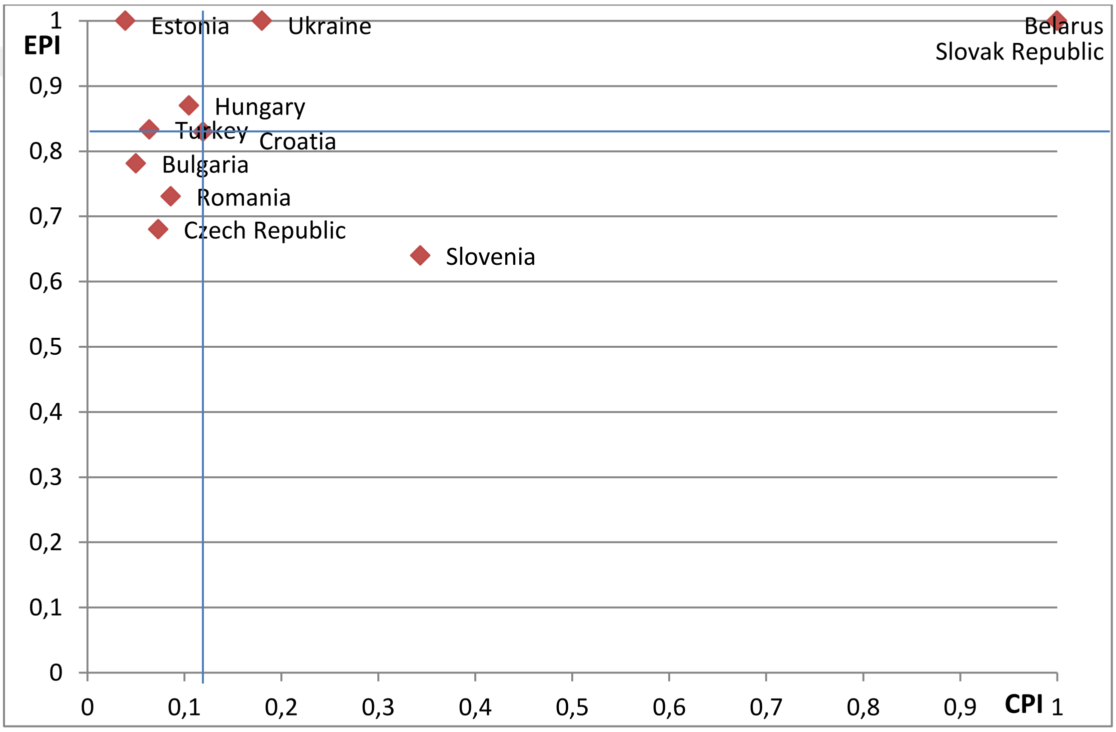

Figure 7 CP vs. EPI for Turkey and EITs Countries (2011 data)

These countries are tracked in years according to their efficiency index, Figure 8 shows Turkey's performance path in years. According to Figure 8, generally Turkey has decreasing CPI path, while EPI and ECPI are increasing. This means that, Turkey has increasing energy performance while the carbon performance is decreasing relatively. However, both performance indices are around median lines. From 1990 to 2009, there was an increase by 110.65% in greenhouse gas emissions from the energy sector in Turkey. Figure 8 shows that CO_2 emission performance among UNFCC countries has also been decreasing between these years due to economic development and population growth trend in Turkey.

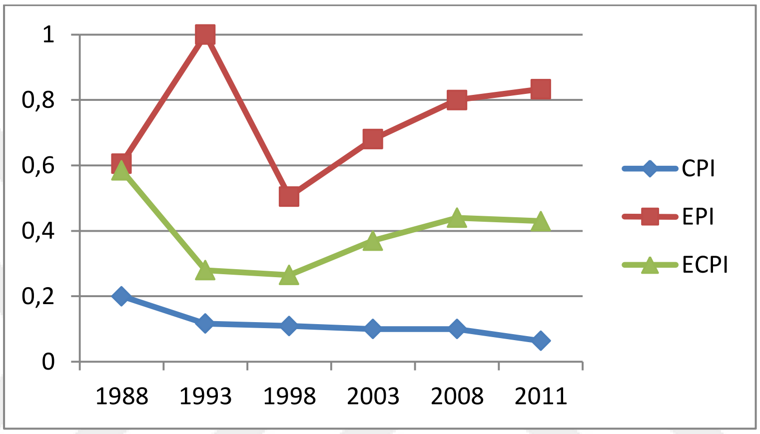

Figure 8 Turkey's Performance Path among UNFCCC Annex-I Countries

Appendix H shows countries' path in years. According to Appendix H, Belarus has the best efficiency scores for all indices and for all selected years. However, Slovak Republic has increased their scores in years and reached 1 for the most recent years. In addition, Ukraine's EPI scores is 1 for all selected years and it means that this country is trying to fix its energy performance (the best practice 1) and decreasing its carbon performance.

CHAPTER FIVE

CONCLUSION

One of the biggest challenges for humans is global warming and the only way to prevent global warming is to reduce GHG emissions. Efficient use of natural resources helps to reduce GHG emissions, specifically CO_2 emissions that are supplied by humans through use of fossil fuels in energy production. However, the efficient use of natural resources has not been fully captured by traditional efficiency measures in the literature. Recently, DEA and directional distance function approaches are provided by researchers for constructing energy efficiency measures and developing energy and environmental performance indices of various types of decision making units. Because of growing electricity demand and demand for fossil fuels, these methods are applied to measure performances of decision making units in electricity generation and CO_2 emission. Efficiency and performance analysis in electricity generation and CO_2 emission reduction will help efforts to tackle global warming.

In this study, non-radial directional distance function is used and three performance indices are created to measure energy and CO_2 emission performance of three different groups of countries in electricity generation. Firstly, for each group, the environmental production technology is defined and constructed. First group is constructed by categorizing the countries with respect their use of CHP technology, i.e. countries with CHP plants and without CHP plants. Second group is G20 countries which are 20 major economies of the world. The other group is UNFCCC Annex-1 countries which have responsibilities similar to Turkey in terms of GHG emissions. Since the method used in the study presents relative performance of a country in reference to the best practice frontier constructed for the group, this three-types of grouping allows comparison of energy and CO_2 emission performance of countries in a more consistent and plausible way. The environmental production technology in this study is constructed within joint production framework of desirable and undesirable outputs. This framework specifies electricity generation, in the form of desirable output, and CO_2 emission, in the form of undesirable output, and thus allows analyzing both energy and environmental performance of countries separately as well as interactively when it is referred as energy-carbon performance or environmental performance. The other desirable output for countries with CHP plants is heat energy. For the first set of analysis consist of two groups of countries: CHP and non-CHP countries. Since in these groups, each country has the same electricity production technology as the others, the heat energy produced from CHP plants does not need to be converted to its electricity equivalent. For the other two sets of analysis, the groups consist of countries with electricity output as well as countries with different electricity production technology. Therefore, for the countries with CHP technology, the heat output has to be converted to its electricity equivalent and useful heat and electricity generation summed to one output, as useful energy.

Environmental production technology is represented by DEA models. DEA facilitates a non-parametric piece-wise frontier over the existing data by using linear programming to evaluate the relative efficiency of countries among the same group. The relative efficiency is determined by maximal contraction or expansion of inputs or outputs. Distance functions are used to measure efficiency in terms of simultaneous contraction of input/undesirable outputs and expansion of desirable outputs. In this study, non-radial distance function approach is used for calculating inefficiency scores and this approach allows for the adjustments of inputs and outputs non-proportionally.

The DEA type directional distance function model is applied to evaluate electricity generation and CO_2 emission performance of 72 non-CHP countries and 40 CHP countries over 5 years period from 1988 to 2011. Three performance indices named energy performance index, carbon performance index and energy-carbon index (alternatively called ecological performance index in the literature) are calculated for countries to measure environmental performance.

Among countries without CHP plants (mainly 72 countries), Brazil has the highest EPI for the latest years. Energy performance index is electricity generation per unit of fossil fuel consumption. Since Brazil has low share of fossil fuel consumption in electricity generation, the highest EPI is expected from Brazil among non-CHP countries. Carbon performance indices are also calculated in this study. Brazil has the highest performance score among non-CHP countries not surprisingly as this country's energy matrix is known as one of the cleanest in the world.

Among the CHP countries (mainly 40 countries), Denmark, Switzerland, Sweden, Ukraine, Macedonia appear in the best practice frontier for the latest year EPI performance. Denmark, Switzerland, Sweden also have the highest CPI. These countries have success fully expanded the use of CHP and over the past two decades, the countries' GHG emissions have been declined in parallel to growth of CHP technology (IEA 2008, Combined Heat and Power Report).

CHP technology provides lower-carbon, more efficient, lower-cost and reliable energy future. This technology investment's payback period is lower than six years and project lifetime is around 25 years. Therefore, this technology investment is reimbursable and countries should adopt this technology. The studies and reports about CHP show that CHP can reduce CO_2 emissions from new generation in 2030 by more than 10%. Therefore, CHP can make a meaningful contribution about emission stabilization to avoid major climate disruption. CHP technology can also reduce need for transmission and distribution network investments by 7% of total projected power sector investment over the period 2005-2030. Moreover, CHP technology can reduce the delivered costs of electricity to end consumers. Therefore, CHP technology offers an important opportunity to tackle global warming. However, reduction potential based on CHP technology depends on different national circumstances and opportunities such as renewable energy sources, nuclear energy technology, clean fossil fuel mixture with carbon dioxide capture and storage (IEA 2008, Combined Heat and Power Report). Therefore, it is seen that energy and environmental performance are affected by not only technology used, they are also affected by countries energy sources and fossil fuel mixture used while generating electricity.

The CHP and non-CHP countries' result for the year 2005 is consistent with the result obtained from Zhou et al. (2012) as the methodology used is the same. Different than Zhou et al. (2012), this study runs analysis for different time periods to allow for cross country comparison in selected time periods as well as comparisons of individual performance of countries across different time periods. It is important to study relative efficiency changes over time as there is continuously changing demand and supply conditions in energy sectors. This study has investigated 6 different years from 1988 to 2011 consistent with Kyoto Protocol's time frame and to understand how countries evolve in regard to energy and environmental performance.

Among the G20 countries, Brazil and United Kingdom appear in the best practice frontier. This result is explained by these countries' proactive climate policy approach. The United Kingdom Policy Framework is set out United Kingdom Energy Efficiency Action Plan Update published in 2011. This framework includes action in the industrial sector including the Climate Change Agreements with the energy intensive sectors of Energy Efficiency Scheme and fiscal incentives. Brazil imposed global carbon budget constraints in planning processes such as National Energy Plan and the Ten-Year Energy Expansion Plan (G20 Clean Energy, And Energy Efficiency Deployment and Policy Progress, 2011). Establishing regulations according to countries' path from 1988 to 2011 is important for establishing Kyoto targets. According to these paths, Brazil and United Kingdom are the most successful countries among G20 countries' relative performance.

G20 leaders stressed that their major objective is to strengthen the global economy and lay the foundation for strong, sustainable and balanced growth in June 2010 G20 Communiqué. Then, November 2010 Seoul G20 Communiqué committed to support country-led green growth policies. Thus, countries agreed to take steps to develop clean energy technologies and policies and the countries' practices in these policies should be shared among others (G20 Clean Energy, And Energy Efficiency Deployment and Policy Progress, 2011).

In this study, Turkey's energy and environmental performance have been evaluated among G20 countries and UNFCCC Annex-I countries. Energy performance of Turkey is around median lines among both G20 countries and UNFCCC Annex-I countries. However, Turkey's carbon performance is higher than median in the group of G20 while Turkey is located at the median line for the carbon performance among UNFCCC Annex-I countries.

When we consider Turkey's path among UNFCCC Annex-I countries, the path is parallel to climate change and sustainably policies steps. Figure 4 shows Turkey's path among UNFCCC Annex-I countries. The first step for Turkey's climate change and sustainability policies is Turkey's Sixth Five Year Development Plan (1990-1994). Figure 9 shows that Turkey's performance indices are increasing after this step (year 1994).

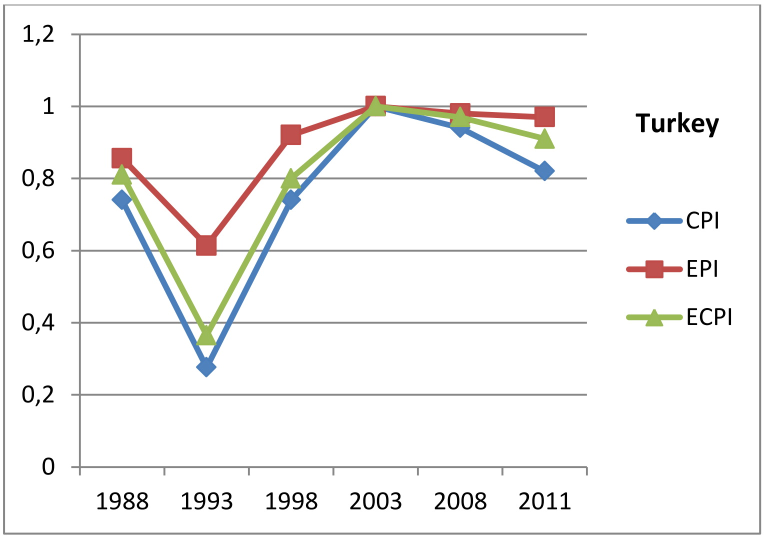

Figure 9 Turkey's Performance Path among G20 Countries

It should be pointed out that this study demonstrates energy, environmental and ecological performance changes over time. However, further research may present using time series data observed over a longer time horizon. In addition, the future research might include incorporation of time dependent nature of dynamic efficiency and performances of these dimensions. Moreover, the empirical study can also be applied to plant level data for balancing society's desire for environmental protection with the economic burden on industry. This study captures only energy related input and output with country-level data, the non-radial directional distance function can also be applied in cases, when non-energy data is available. In addition, this study incorporates CO_2 emissions in the form of undesirable output into the empirical analysis. In this regard, future research should demonstrate wider range of pollutants, such as SO_2 (sulfur dioxide), CH_4 (methane), N_2O (nitrous oxide), NO_X (nitrogen oxides) to better asses the energy and emission performance of electricity generation if all emission data needed are available.

This study provides important clues for energy and environmental efficiency for various groups of countries and compares their respective performances with respect to each other and over time. Modeling only energy inputs are adequate to assess environmental performance when there is pollution as an undesirable output. The production technology specified in some earlier studies on examining the performance of electricity generation at the plant level may include non-energy inputs such as capital stock, labor, and generation capacity. However, including these inputs require gathering large amount of data from different sources which does not align with the data sets used in the study. Incorporation of other non-energy inputs in the production process could be done in a future study.

Due to the fact that the breakdown of fossil fuel data is not matching the breakdown of CO2 data, it was not possible to calculate energy and carbon efficiency of electricity generation for electricity facilities which run by different fossil fuel inputs. In addition, if there is sufficiently recorded data on renewable resources for almost all countries for longer periods of time, an interesting future study would be to incorporate the energy generation activities of countries from renewable resources into the model to have more complete understanding of environmental performance.

BIBLIOGRAPHY

B.W. Ang, P. Zhou, L.P._Tay, 2011. "Potential for reducing global carbon emissions from electricity production—A benchmarking analysis." Energy Policy 39 (5): 2482-2489.

Ball, E., Fare, F., Grosskopf, S., Nehring, R.F., 2001. "Productivity of the US agricultural sector: the case of undesirable outputs." In: Hulten, Ch., Dean, E.R., Harper, M.J.(Eds.), New Developments in Productivity Measurement. NBER, The University of Chicago Press, Chicago.

Banker RD, Charnes A, Cooper WW., 1984. "Some models for estimating technical and scale inefficiencies in Data Envelopment Analysis." Management Science 30:1078–92.

Barros C.P. , Peypoch N., 2008. "Technical efficiency of thermoelectric power plants." Energy Economics 30 (2008): 3118-3127.

Barros et al. (2012). "The technical efficiency of the Japanese banks: Non-radial directional performance measurement with undesirable output." Omega 40 (1): 1–8.

Barros, C.P., Managi, S., Matousek, R., 2012. "The technical efficiency of the Japanese banks: non-radial directional performance measurement with undesirable outputs." Omega 40: 1–8.

Bevilacqua, M., Braglia, M., 2002. "Environmental efficiency analysis for ENI oil refineries. J. Clean. Prod." 2002: 85–92.

Bilen, K., Ozyurt, O., Bakırcı, K., Karslı, S., Erdogan, S., Yılmaz, M., Comaklı, O., 2008. "Energy production, consumption, and environmental pollution for sustainable development: a case study in Turkey." Renewable and Sustainable Energy Reviews 12 (6): 1529–1561.

Boyd, G.A., Pang, J.X., 2000. "Estimating the linkage between energy efficiency and productivity." Energy Policy 28: 289–296.

BP, 2012. Statistical Review of World Energy. Available at: /http://www.bp.com/ statistical reviews (accessed 10.04.2016).

Chambers RG, Chung Y, Fare R., 1996. "Benefit and distance functions." Journal of Economics Theory 70:407–419.

Chambers, R.G., Chung, Y., Fare, R., 1998. "Profit, directional distance functions and Nerlovian efficiency. Journal of Optimization Theory and Applications 98: 351–364.

Chang, T.P., Hu, J.L., 2010. "Total-factor energy productivity growth, technical progress, and efficiency change: an empirical study of China." Appl. Energy 87: 3262–3270.

Charnes A, Cooper WW, Rhodes E., 1978. "Measuring the efficiency of decision making units." European Journal of Operational Research 2:429–44.

Choi, Y., Zhang, N., Zhou, P., 2012. "Efficiency and abatement costs of energy-related CO2 emissions in China: a slacks-based efficiency measure." Appl. Energy 98: 198–208.

Chung, Y., Fare, R., Grosskopf, S., 1997. "Productivity and undesirable outputs:a directional distance function approach." Journal of Environmental Management 51: 229–240.

Coelli, T.J., D.S.P. Rao, C.J. O'Donnell, and G.E. Battese. 2005. "An Introduction to Efficiency and Productivity Analysis (Second Edition)." New York: Springer Science+Business Media, Inc.

Cooper, W.W., Huang, Z., Li, S., Lelas, V., Sullivan, D.W., 1996. "Survey of mathematical programming models in air pollution management." Eur. J. Oper. Res. 96: 1–35.

Cooper, W.W., Seiford, L.M., Tone, T., 2006. "Introduction to Data Envelopment Analysis and Its Uses: With DEA-Solver Software and References." Springer, New York.

Cooper, W.W., Tone, K., 1997. "Measures of inefficiency in data envelopment analysis and stochastic frontier estimation." European Journal of Operational Research 99: 72-88.

Energy Policies of IEA Countries, 2012. http://www.iea.org/publications/countryreviews/ (accessed 10.05.2016).

Fare R, Grosskopf S, Lovell CAK, and Pasurka C., 1989. "Multilateral Productivity Comparisons When Some Outputs Are Undesirable: A Nonparametric Approach." The Review of Economics and Statistics 71 (1): 90-98.

Fare R, Grosskopf S, Lovell CAK., 1985. "The Measurement of efficiency of production." Boston: Kluwer-Nijhoff.

Fare R, Lovell CAK., 1978. "Measuring the technical efficiency of production." Journal of Economic Theory 19:150–162.

Fare R, Grosskopf S, Pasurka C., 2007. "Polution abatement activities and traditional productivity." Ecological Economics 62 (13): 3-4, Amsterdam,Elsevier

Fare, R., Grosskopf, S., 2010. “Directional distance functions and slacks-based measures of efficiency.” European Journal of Operational Research 200: 320–322.

Fare, R., Grosskopf, S., Hernandez-Sancho, F., 2004. “Environmental performance: An index number approach.” Resource and Energy Economics 26: 343–352.

Fare, R., Grosskopf, S., Tyteca, D., 1996. “An activity analysis model of the environmental performance of firms – application to fossil-fuel-fired electric utilities.” Ecological Economics 18: 161–175.

Farrell MJ., 1957. “The measurement of productive efficiency.” Journal of the Royal Statistical Society A120:253–61.

Forsund, F.R., Sarafoglou, N., 2002. “On the origins of data envelopment analysis.” Journal of Productivity Analysis 17: 23–40.

Forsund, F.R., Sarafoglou, N., 2005. “The tale of two research communities: The diffusion of research on productive efficiency.” International Journal of Production Economics 98: 17–40.

Fukuyama, H., Weber, W.L., 2009. “A directional slacks-based measure of technical efficiency.” Socio-Economic Planning Sciences 43: 274–287.

Fukuyama, H., Weber, W.L., 2010. “A slacks-based inefficiency measure for a two stage system with bad outputs.” Omega 38: 239–410.

Fukuyama, H., Yoshida, Y., Managi, S., 2011. “Modal choice between air and rail: a social efficiency benchmarking analysis that considers CO2 emissions.” Environmental Economics and Policy Studies 13: 89–102.

Geletu (2008), “GAMS - Modeling and Solving Optimization Problems.” Institute of Mathematics Department of Operations Research & Stochastic Ilmenau University of Technology.

Gregan Tendai, Johnson Martin, 1999. “Impacts of Competition Enhancing Air Services Agreements: A Network Modeling Approach.” Productivity Commission.

Hu, J.L., Kao, C.H., 2007. “Efficient energy-saving targets for APEC economies.” Energy Policy 35: 373-382.

Hu, J.L., Wang, S.C., 2006. “Total-factor energy efficiency of regions in China.” Energy Policy 34: 3206–3217.

Huang, J.P., Poh, K.L., Ang, B.W., 1995. “Decision analysis in energy and environmental modeling.” Energy 20: 843-855.

IEA (2007), Fossil Fuel-Fired Power Generation. Case Studies of Recently Constructed Coal- and Gas-fired Power Plants, IEA/OECD, Paris. http://www.iea.org/w/bookshop/add.aspx?id=313https://en.wikipedia.org/wiki/G-20_major_economies (accessed 15.04.2016).

IEA (International Energy Agency), 2011. "G20 Clean Energy, And Energy Efficiency Deployment and Policy Progress" https://www.iea.org/publications/freepublications/publication/g20-clean-energy-and-energy-efficiency-deployment-and-policy-progress.html (accessed 27.04.2016).

IEA (International Energy Agency), 2013. "CO_2 Emissions Overview."

IEA 2008, Combined Heat and Power Report. https://www.iea.org/publications/freepublications/publication/chp_report.pdf (accessed 30.05.2016).

IEA, 2008. Energy Efficiency Indicators for Public Electricity Production from Fossil Fuels. International Energy Agency, OECD, Paris.

Jūratė J., Maria, C. D., 2012. "Efficiency, productivity and environmental policy: A case study of power generation in the EU." Energy Economics 34 (5): 1557–1568.

Koopmans, T.C., 1951. "Analysis of production as an efficient combination of activities." In: Koopmans, T.C. (Ed.), Activity Analysis of Production and Allocation. John Wiley, New York.

Korhonen, P.J., Luptacik, M., 2004. Eco-efficiency analysis of power plants: an extension of data envelopment analysis. Eur. J. Oper. Res. 2004: 437–446.

Kousmanen, T., 2005. "Weak disposability in nonparametric production analysis with undesirable outputs." Am. J. Agric. Econ. 87: 1077–1082.

Kumar, S., 2006. "Environmentally sensitive productivity growth: a global analysis using Malmquist–Luenberger index." Ecol. Econ. 56: 280–293.

Kuosmanen, T., Kuosmanen, N., 2009. "How not measure sustainable value (and how one might)." Ecological Economics 69, 235–243.

Liu LC, Wang JN, Wu G, Wei YM., 2010. "China's regional carbon emissions change over 1997–2007." Int J Energy Environ 1(1): 161–176.

Luenberger DG., 1992. "Benefit functions and duality." Journal of Mathematical Economics 21: 461–481.

Luenberger DG., 1995. "Microeconomic theory." New York: McGraw Hill.

Mahlberg, B., Sahoo, B.K., 2011. “Radial and non-radial decompositions of Luenberger productivity indicator with an illustrative application.” International Journal of Production Economics 131: 721–726.

Michael E. Porter and Claas van der Linde, 1995. “Toward a New Conception of the Environment-Competitiveness Relationship.” Journal of Economic Perspectives 9 (1995): 97-118.

Michael E. Porter and Claas van der Linde, 1995. “Toward a New Conception of the Environment-Competitiveness Relationship.” Journal of Economic Perspectives 9 (4): 97-118.

Mukherjee, K., 2010. “Measuring energy efficiency in the context of an emergingeconomy: the case of indian manufacturing.” European Journal of Operational Research 20: 933–941.

OECD, Organization for Economic Co-operation and Development, 1998. Ecoefficiency, OECD, Paris.

Olesen OB and NC Petersen (1996). “A Presentation of Gams for DEA.” Computer and Operations Research 23(4): 323-339.

Ozbugday, F.C., Erbas, B.C., 2015. “How effective are energy efficiency and renewable energy in curbing CO_2 emissions in the long run? A heterogeneous panel data analysis.” Energy 82 (2015): 734-745.

Palmer, K.W., Oates, W.E., Portney, P.R., 1995. “Tightening environmental standards the benefit–cost or the no-cost paradigm.” J. Econ. Perspect. 9: 119–132.

Park, H., Lim, J., 2009. “Valuation of marginal CO_2 abatement options for electric power plants in Korea.” Energy Policy 37: 1834–1841.

Pastor JT, Ruiz JL, Sirvent I., 1999. “An enhanced Russell graph efficiency measure.” European Journal of Operational Research 115: 596–607.

Pastor JT, Ruiz JL, Sirvent I., 1999. “An enhanced Russell graph efficiency measure. European Journal of Operational Research 115:596–607.

Pasurka Jr., C.A., 2006. “Decomposing electric power plant emissions within a joint production framework.” Energy Economics. 28: 26–43.

Phylipsen, G.J.M., Blok, K.,Worell,E.,1998. “Benchmarking the energy efficiency of the Dutch energy–intensive industry. A Preliminary Assessment of the Effect on Energy Consumption and CO2 Emissions.” Energy Policy 30 (8): 663–679.

Ramanathan, R., 2000. “A holistic approach to compare energy efficiencies of different transport modes.” Energy Policy 28, 743–747.

Ramanathan, R., 2003. “An Introduction to Data Envelopment Analysis: A Tool for Performance Measurement.” Sage Publications, New Delhi.

Ramanathan, R., 2005. An analysis of energy consumption and carbon dioxide emissions in countries of the Middle East and North Africa. Energy 30, 2831–2842.

Seiford, L.M., Thrall, R.M., 1990. “Recent developments in DEA: The mathematical programming approach to frontier analysis.” Journal of Econometrics 46: 7–38.

Seiford, L.M., Zhu, J., 2002. “Modeling undesirable factors in efficiency evaluation.” European Journal of Operational Research 142: 16–20.

Shephard, R.W., 1970. “Theory of Cost and Production Functions.” Princeton University Press, Princeton.

Sozen, A., Alp, I., Ozdemir, A., 2010. “Assessment of operational and environmental performance of the thermal power plants in Turkey by using data envelopment analysis.” Energy Policy 38(10): 6194–6203.

Stewart, T.J., 1996. “Relationships between data envelopment analysis and multicriteria decision analysis.” Journal of the Operational Research Society 47: 654–665.

The 2015 Global Climate Legislation Study. http://www.lse.ac.uk/GranthamInstitute/publication/2015-global-climate-legislation-study/ (accessed 26.05.2016).

Tone, K., 1999. “A slacks-based measure of efficiency in data envelopment analysis.” European Journal of Operational Research 130 (2001): 498-509.

Torgersen, A.M., Forsund, F.R., Kittelsen, S.A.C., 1996. “Slack-adjusted efficiency measures and ranking of efficiency units.” Journal of Productivity Analysis 7: 379-398.

Toshiyuki Sueyoshi and Mika Goto, 2011. “DEA approach for unified efficiency measurement: Assessment of Japanese fossil fuel power generation.” Energy Economics 33(2): 292–303.

Toshiyuki Sueyoshi and Mika Goto, 2012.” Weak and strong disposability vs. natural and managerial disposability in DEA environmental assessment: Comparison between Japanese electric power industry and manufacturing industries.” Energy Economics 34 (2012): 686–699.

Triantis, K., Otis, P., 2004. “Dominance-based measurement of productive and environmental performance for manufacturing.” Eur. J. Oper. Res. 154: 447–464.

Tyteca, D., 1996. “On the measurement of the environmental performance of firms – a literature review and a productive efficiency perspective.” Journal of Environmental Management 46: 281–308.

Tyteca, D., 1997. “Linear programming models for the measurement of environmental performance of firms – concepts and empirical results.” Journal of Productivity Analysis 8: 183–197.

UNFCCC (United Nations Framework Convention on Climate Change), 1992. https://unfccc.int/resource/docs/convkp/conveng.pdf (accessed 20.04.2016).

UNFCCC (United Nations Framework Convention on Climate Change), 2010. http://unfccc.int/meetings/cancun_nov_2010/meeting/6266.php (accessed 16.05.2016).

Von Neumann, J., 1945. “A model of general economic equilibrium.” The Review of Economic Studies 13: 1–9.

Walden, John B., Kirkley, James E., 2000. “Measuring Technical Efficiency and Capacity in Fisheries by Data Envelopment Analysis Using the General Algebraic Modeling System (GAMS): A Workbook.” NOAA Technical Memorandum NMFS-NE-160.

WBCSD (World Business Council for Sustainable Development), 2000. Measuring Ecoefficiency. A Guide to Reporting Company Performance. WBCSD, Geneva.

WEO (World Energy Outlook), 2013. “New Policies Scenario”

Yang, H., Pollitt, M., 2009. “Incorporating both undesirable and uncontrollable variables into DEA: the performance of Chinese coal-fired power plants.”European Journal of Operational Research 197: 1095–1105.

Yang, H., Pollitt, M., 2010. “The necessity of distinguishing weak and strong disposability among undesirable outputs in DEA: environmental performance of Chinese coalfired power plants.” Energy Policy 38: 4440–4444.

Zaim, O., 2004. “Measuring environmental performance of state manufacturing through changes in pollution intensities: a DEA framework.” Ecol. Econ. 48: 37–47.

Zaim, O., Taskin, F., 2000a. “Environmental efficiency in carbon dioxide emissions in the OECD: A non-parametric approach.” Journal of Environmental Management 58: 95–107.

Zaim, O., Taskin, F., 2000b. “A Kuznets curve in environmental efficiency: An application on OECD countries.” Environmental and Resource Economics 17: 21–36.

Zhou, P., Ang, B.W., 2008. “Linear programming models for measuring economy-wide energy efficiency performance.” Energy Policy 36: 2911–2916.

Zhou, P., Ang, B.W., Han, J.Y., 2010. “Total factor carbon emission performance: a Malmquist index analysis.” Energy Economics 32: 194–201.

Zhou, P., Ang, B.W., Poh, K.L., 2006a. “Decision analysis in energy and environmental modeling: An update.” Energy 31: 2604–2622.

Zhou, P., Ang, B.W., Poh, K.L., 2006b. “Slacks-based efficiency measures for modeling environmental performance.” Ecological Economics 60: 111–118.

Zhou, P., Ang, B.W., Poh, K.L., 2008. “A survey of data envelopment analysis in energy and environmental studies.” Eur. J. Oper. Res. 189: 1–18.

Zhou, P., Ang, B.W., Wang H., 2012. “Energy and CO_2 emission performance in electricity generation: A non-radial directional distance function approach.” European Journal of Operational Research 221(2012): 625-635.

Zofio, J.L., Prieto, A.M., 2001. “Environmental efficiency and regulatory standards: The case of CO2 emissions from OECD industries.” Resource and Energy Economics 23: 63–83.

APPENDICES

Appendix A EPI Ranking of non-CHP Countries

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	EPI	Ranking	EPI	Ranking	EPI	Ranking	EPI	Ranking	EPI	Ranking	EPI	Ranking
Haiti	1	1	1	1	0.91	7	0.06	16	0.44	41	0.24	61
Brazil	1	2	1	2	0.83	16	0.05	42	0.5	21	0.42	35
Montenegro	1	3	0.13	72								
South Africa	0.99	4	0.28	69	1	3	0.05	31	0.52	16	0.53	13
Philippines	0.87	5	0.63	30	0.93	6	0.06	12	0.59	5	0.55	7
Honduras	0.86	6	0.76	12	1	1	1	2	0.18	69	0.53	12
Hong Kong	0.86	7	0.61	33	0.93	5	0.07	3	0.56	10	0.57	6
Tunisia	0.84	8	0.96	5	0.89	8	0.05	28	0.51	19	0.45	27
Morocco	0.81	9	0.49	52	0.87	12	0.05	26	0.45	36	0.45	26
Australia	0.8	10	0.37	64	0.88	11	0.05	24	0.52	15	0.5	19
Thailand	0.79	11	0.89	7	0.86	14	0.06	11	0.57	8	0.57	4
Singapore	0.79	12	0.97	4	0.84	15	0.05	23	0.37	60	0.53	10
Guatemala	0.78	13	0.44	57	0.77	30	0.04	56	1	2	0.41	40
Jamaica	0.77	14	0.76	13	0.69	43	0.05	43	0.41	54	0.43	33
Vietnam	0.77	15	0.78	11	0.78	25	0.04	49	0.43	47	0.29	58
Egypt	0.76	16	0.93	6	1	2	0.06	7	0.54	12	0.5	18
Netherlands Antilles	0.76	17	0.67	22	0.83	17	0.06	13	0.56	9	0.54	9
Panama	0.76	18	0.63	31	0.79	22	0.04	47	0.46	30	0.34	55
India	0.75	19	0.13	71	0.76	31	0.04	52	0.42	52	0.41	39
El Salvador	0.75	20	0.63	32	0.75	35	0.05	27	0.44	45	0.41	42
Nicaragua	0.75	21	0.58	39	0.79	23	0.05	41	0.45	39	1	1
Chinese Taipei	0.74	22	0.72	18	0.81	19	0.06	9	1	1	0.52	16
Yemen	0.74	23	0.81	10	0.65	51	0.04	54	0.51	18	0.44	30
Trinidad and Tobago	0.73	24	0.48	54	0.6	62	0.04	53	0.39	57	0.39	46
Gibraltar	0.72	25	0.54	42	0.78	26	0.06	20	0.53	13	0.52	14
Korea	0.72	26	0.51	47	0.69	42	1	1	0.38	58	1	3
Indonesia	0.72	27	0.43	58	0.78	24	0.05	21	0.47	27	0.46	25
Argentina	0.72	28	0.86	9	0.89	9	0.05	30	0.47	28	0.39	44
Jordan	0.72	29	0.72	17	0.82	18	0.05	35	0.45	37	0.44	29
Sri Lanka	0.71	30	0.54	43	0.68	48	0.06	5	0.34	64	0.42	36
Colombia	0.71	31	0.71	20	0.77	29	0.06	18	0.46	33	0.44	31
Nigeria	0.71	32	0.88	8	0.86	13	0.06	8	0.53	14	1	2
Uruguay	0.71	33	0.5	51	0.41	71	0.05	37	0.45	40	0.54	8
Costa Rica	0.71	34	0.35	67	0.61	60	0.05	38	0.46	31	0.41	43
Cyprus	0.69	35	0.56	41	0.7	41	0.05	36	0.48	23	0.47	23

Appendix A (Continued)

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	EPI	Ranking	EPI	Ranking	EPI	Ranking	EPI	Ranking	EPI	Ranking	EPI	Ranking
Pakistan	0.69	36	0.65	26	0.81	20	0.06	10	0.58	6	0.42	38
Iran	0.68	37	0.74	15	0.81	21	0.06	19	0.5	22	0.48	20
Lebanon	0.67	38	0.59	37	0.75	36	0.05	39	0.48	25	0.48	21
Libya	0.67	39	0.6	35	1	4	0.04	66	0.54	11	0.37	50
Malaysia	0.67	40	0.6	36	0.88	10	0.06	6	0.51	17	0.52	17
Benin	0.66	41	0.65	28	0.74	39	0.06	14	0.45	38	0.35	53
Senegal	0.66	42	0.65	29	0.68	46	0.05	45	0.41	53	0.39	48
Algeria	0.66	43	0.67	23	0.71	40	0.05	40	0.58	7	0.39	47
Zimbabwe	0.66	44	1	3	0.69	44	0.04	60	0.42	51	0.42	37
Tanzania	0.66	45	0.75	14	0.55	65	0.04	67	0.37	61	0.22	62
Bangladesh	0.65	46	0.69	21	0.78	27	0.05	33	0.48	26	0.18	66
Syrian Arab Republic	0.65	47	0.66	24	0.75	34	0.06	17	0.51	20	0.52	15
Sudan	0.63	48	0.45	56	0.62	57	0.04	55	0.37	63	0.35	51
Cambodia	0.62	49	0.41	61	0.68	45	0.05	32				
Togo	0.61	50	0.56	40	0.76	32	0.04	64	0.47	29	0.34	56
Malta	0.61	51	0.42	59	0.61	59	0.05	46	0.4	56	0.29	59
Gabon	0.6	52	0.59	38	0.63	55	0.04	62	0.44	43	0.35	52
Ghana	0.6	53	0.41	63								
CotedIvoire	0.59	54	0.51	48	0.75	37	0.04	59	0.83	4		
Eritrea	0.58	55	0.47	55	0.6	63	0.03	69	0.26	67		
Dominican Republic	0.58	56	0.32	68	0.61	61	0.04	48	0.42	50	0.21	63
Cameroon	0.58	57	0.65	27	0.78	28	0.04	50	0.45	34	0.43	32
Peru	0.57	58	0.74	16	0.67	49	0.05	34	0.43	49	0.42	34
Ecuador	0.57	59	0.51	49	0.29	72	0.06	15	0.44	44	0.45	28
Venezuela	0.57	60	0.5	50	0.66	50	0.04	51	0.41	55	0.37	49
Kenya	0.56	61	0.35	66	0.64	54	0.04	63	0.29	66	0.2	64
Zambia	0.56	62	0	73	0.65	52	0.04	65	0.37	62	0.27	60
Bolivia	0.54	63	0.61	34	0.75	33	0.04	61	0.43	48	0.47	22
Brunei Darussalam	0.51	64	0.54	44	0.55	67	0.06	4	0.46	32	0.41	41
Botswana	0.51	65	0.35	65	0.44	68	0.04	58	0.38	59	0.33	57
Myanmar	0.5	66	0.41	62	0.63	56	0.04	57	0.48	24	0.34	54
Cuba	0.48	67	0.52	46	0.65	53	0.05	29	0.44	42	0.46	24
Mozambique	0.48	68	0.66	25	0.61	58	0.05	25	0.44	46	0.16	67
Namibia	0.48	69	0.48	53	0.56	64	0.03	71	0.45	35		
Iraq	0.46	70	0.53	45	0.55	66	0.04	68	0.31	65	0.53	11

Appendix A (Continued)

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**
Ethiopia	0.45	71	0.27	70	0.74	38	0.05	44	1	3	0.39	45
Angola	0.37	72	0.42	60	0.42	69	0.03	72	0.25	68	0.19	65

Appendix B CPI Ranking of non–CHP Countries

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**
Brazil	1	1	1	1	0.96	4	0.07	11	0.83	4	0.54	15
Brunei Darussalam	1	2	0.63	32	0.65	28	0.09	3	0.54	43	0.41	44
Haiti	1	3	1	2	0.77	15	0.06	21	0.56	32	0.24	59
Tunisia	0.87	4	0.95	5	0.93	5	0.07	8	0.73	13	0.55	12
Singapore	0.77	5	0.96	4	0.76	16	0.06	26	0.51	48	0.58	9
Egypt	0.76	6	0.91	6	1	1	0.07	6	0.78	8	0.34	52
Trinidad and Tobago	0.75	7	0.63	33	0.61	34	0.06	24	0.65	20	0.52	18
Thailand	0.7	8	0.86	7	0.8	10	0.06	13	0.75	11	0.46	38
Nigeria	0.69	9	0.84	8	0.88	7	0.08	4	0.79	6	1	1
Algeria	0.67	10	0.74	15	0.72	19	0.06	12	0.83	5	0.51	22
Tanzania	0.66	11	0.78	10	0.39	67	0.03	67	0.37	61	0.22	60
Argentina	0.66	12	0.83	9	0.89	6	0.06	16	0.71	16	0.47	34
Bangladesh	0.65	13	0.74	16	0.78	12	0.07	9	0.77	9	0.11	65
Chinese Taipei	0.65	14	0.7	21	0.74	17	0.06	18	1	1	0.55	13
Vietnam	0.63	15	0.74	13	0.65	24	0.04	54	0.49	50	0.29	57
Iran	0.62	16	0.74	12	0.81	8	0.07	7	0.75	10	0.58	10
Colombia	0.62	17	0.66	26	0.65	26	0.06	19	0.59	28	0.5	26
CotedIvoire	0.61	18	0.65	29	0.77	14	0.05	34	0.86	3	0	67
Senegal	0.6	19	0.63	34	0.55	48	0.05	48	0.53	45	0.43	41
Sri Lanka	0.6	20	0.58	46	0.54	51	0.06	17	0.34	64	0.48	32
Cameroon	0.6	21	0.66	27	0.66	23	0.04	53	0.5	49	0.52	19
Yemen	0.59	22	0.78	11	0.52	53	0.04	55	0.65	22	0.49	28
Pakistan	0.59	23	0.67	24	0.81	9	0.07	10	0.79	7	0.53	16
Honduras	0.59	24	0.72	18	1	2	1	1	0.18	69	0.59	8
Libya	0.59	25	0.64	31	1	3	0.04	60	0.69	19	0.41	47
Morocco	0.59	26	0.53	55	0.49	59	0.05	47	0.54	44	0.49	30
Jordan	0.59	27	0.74	14	0.68	21	0.05	37	0.58	31	0.5	27
Syrian Arab Republic	0.58	28	0.66	25	0.68	22	0.06	20	0.71	17	0.6	4
Ecuador	0.58	29	0.58	47	0.65	25	0.06	23	0.56	33	0.5	24
Sudan	0.57	30	0.54	54	0.5	58	0.04	56	0.37	63	0.39	48
Eritrea	0.57	31	0.55	53	0.49	60	0.03	66	0.26	67	0	68
Ghana	0.57	32	0.52	56	0.57	43	0.04	59	0.55	39	0	69
Dominican Republic	0.57	33	0.48	65	0.46	63	0.04	52	0.53	46	0.21	61
Cambodia	0.56	34	0.52	59	0.55	49	0.05	39	0	71	0	70
Philippines	0.56	35	0.61	40	0.69	20	0.05	29	0.72	15	0.6	5

Appendix B (Continued)

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	CPI	Ranking	CPI	Ranking	CPI	Ranking	CPI	Ranking	CPI	Ranking	CPI	Ranking
Indonesia	0.56	36	0.51	60	0.56	45	0.05	28	0.58	30	0.49	29
Bolivia	0.55	37	0.7	22	0.77	13	0.05	31	0.73	12	0.31	55
Jamaica	0.55	38	0.71	20	0.55	47	0.05	45	0.41	58	0.47	35
Malta	0.55	39	0.52	58	0.49	61	0.04	50	0.4	59	0.29	56
Guatemala	0.55	40	0.52	57	0.55	50	0.04	58	0.02	70	0.47	36
Peru	0.55	41	0.73	17	0.56	44	0.05	32	0.55	38	0.49	31
Togo	0.54	42	0.67	23	0.6	35	0.04	62	0.47	52	0.43	42
Uruguay	0.54	43	0.57	50	0.51	56	0.05	41	0.59	27	0.61	3
Gabon	0.54	44	0.65	30	0.58	40	0.05	46	0.47	51	0.35	50
Australia	0.53	45	0.48	64	0.5	57	0.04	51	0.55	40	0.5	25
Netherlands Antilles	0.53	46	0.63	35	0.65	27	0.06	22	0.7	18	0.6	6
Myanmar	0.53	47	0.56	52	0.59	39	0.05	33	0.55	41	0.34	51
El Salvador	0.53	48	0.62	38	0.6	37	0.05	36	0.55	37	0.45	39
Nicaragua	0.53	49	0.59	44	0.62	31	0.05	44	0.55	36	0.08	66
Kenya	0.53	50	0.49	62	0.52	54	0.04	61	0.29	66	0.2	62
Benin	0.52	51	0.63	36	0.6	36	0.06	15	0.45	55	0.41	45
Costa Rica	0.52	52	0.5	61	0.48	62	0.05	38	0.59	26	0.48	33
South Africa	0.52	53	0.44	69	0.51	55	0.04	57	0.54	42	0.52	21
Lebanon	0.51	54	0.61	41	0.61	33	0.05	42	0.73	14	0.6	7
Malaysia	0.51	55	0.63	37	0.8	11	0.07	5	0.6	25	0.53	17
Venezuela	0.5	56	0.6	42	0.59	38	0.06	27	0.65	21	0.47	37
Zambia	0.5	57	0.44	68	0.39	66	0.04	63	0.37	62	0.27	58
Cyprus	0.5	58	0.58	45	0.55	46	0.05	43	0.6	24	0.52	20
Panama	0.5	59	0.61	39	0.63	29	0.04	49	0.46	54	0.34	53
Gibraltar	0.49	60	0.57	51	0.62	32	0.05	30	0.64	23	0.55	14
Cuba	0.48	61	0.58	49	0.54	52	0.05	35	0.56	34	0.51	23
Mozambique	0.48	62	0.65	28	0.57	42	0.06	25	0.44	56	0.16	64
Iraq	0.48	63	0.6	43	0.46	64	0.04	65	0.31	65	0.37	49
India	0.44	64	0.39	72	0.44	65	0.04	64	0.52	47	0.41	43
Namibia	0.41	65	0.43	70	0.32	71	0.02	71	0.56	35	0	71
Montenegro	0.4	66	0.48	63	0	73	0	0	0	72	0	72
Ethiopia	0.39	67	0.46	66	0.74	18	0.05	40	1	2	0.44	40
Korea	0.39	68	0.46	67	0.38	68	1	2	0.46	53	1	2
Angola	0.36	69	0.42	71	0.34	70	0.03	70	0.25	68	0.19	63
Zimbabwe	0.34	70	1	3	0.35	69	0.03	69	0.42	57	0.41	46

Appendix B (Continued)

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**
Botswana	0.27	71	0.35	73	0.23	72	0.03	68	0.38	60	0.33	54
Hong Kong	0.06	72	0.58	48	0.58	41	0.06	14	0.58	29	0.56	11

Appendix C ECPI Ranking of non–CHP Countries

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	ECPI	Ranking	ECPI	Ranking	ECPI	Ranking	ECPI	Ranking	ECPI	Ranking	ECPI	Ranking
Brazil	1	1	1	1	0.9	12	0.99	69	0.73	36	0.53	58
Haiti	1	2	1	2	0.87	16	1	30	0.6	55	1	1
Mozambique	1	3	0.82	23	0.6	63	1	37	1	1	1	2
Cuba	1	4	0.72	49	0.61	59	1	1	0.6	56	0.5	65
Angola	1	5	1	3	0.95	5	1	20	1	2	1	3
Hong Kong	1	6	0.79	33	0.72	36	1	42	0.67	43	0.56	54
Ethiopia	0.99	7	0.58	69	0.74	30	1	38	1	3	0.96	27
Iraq	0.99	8	0.72	46	0.52	71	1	32	1	4	0.6	43
Namibia	0.99	9	0.95	9	0.91	9	1	49	0.55	66	0	67
Botswana	0.96	10	1	4	0.93	6	1	54	1	5	1	4
Zimbabwe	0.95	11	1	5	0.89	14	1	53	1	6	1	19
India	0.95	12	0.54	70	0.56	69	1	51	0.51	68	1	5
Korea	0.95	13	0.52	71	0.89	13	1	2	0.93	22	1	6
Montenegro	0.93	14	0	72	0	72	0	72	0	70	0	68
Tunisia	0.92	15	0.98	7	0.92	8	0.99	65	0.74	32	0.54	57
Singapore	0.86	16	0.98	6	0.83	20	1	29	0.51	69	0.58	51
Egypt	0.85	17	0.96	8	1	1	0.99	57	0.76	29	0.59	47
Trinidad and Tobago	0.83	18	0.68	58	0.61	60	0.99	67	0.61	53	0.51	62
Thailand	0.82	19	0.93	10	0.85	18	1	43	0.78	25	0.66	42
Nigeria	0.8	20	0.92	11	0.89	15	0.99	70	0.75	30	1	7
Argentina	0.78	21	0.92	12	0.9	11	0.99	59	0.7	40	0.93	38
Chinese Taipei	0.78	22	0.83	20	0.8	24	1	39	1	7	0.55	55
Vietnam	0.78	23	0.87	14	0.74	31	1	36	0.55	65	1	18
Algeria	0.76	24	0.8	28	0.72	37	0.99	68	0.77	27	0.5	66
Tanzania	0.75	25	0.85	17	0.92	7	1	41	1	8	1	8
Honduras	0.75	26	0.86	15	1	2	1	3	1	9	0.58	52
Colombia	0.75	27	0.83	21	0.73	34	1	48	0.62	51	0.95	34
Bangladesh	0.75	28	0.81	24	0.78	25	0.99	66	0.72	38	0.95	33
Yemen	0.74	29	0.89	13	0.61	61	1	17	0.69	41	0.96	28
Iran	0.73	30	0.84	18	0.83	19	0.99	63	0.73	34	0.57	53
Jordan	0.73	31	0.82	22	0.78	26	1	28	0.61	54	0.96	29
Philippines	0.73	32	0.79	30	0.82	22	1	46	0.77	28	0.59	46
Pakistan	0.72	33	0.79	34	0.83	21	1	47	0.78	26	0.52	61
Jamaica	0.72	34	0.86	16	0.64	49	1	26	1	10	0.96	26
Libya	0.71	35	0.76	38	1	3	1	34	0.73	35	0.97	23

Appendix C (Continued)

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**
Netherlands Antilles	0.69	36	0.81	25	0.75	29	1	21	0.75	31	0.59	48
Syrian Arab Republic	0.69	37	0.8	29	0.73	35	1	44	0.73	37	0.59	49
El Salvador	0.69	38	0.79	31	0.7	42	1	19	0.59	59	0.96	24
Nicaragua	0.69	39	0.76	39	0.72	38	1	18	0.59	57	0.82	41
Uruguay	0.69	40	0.71	50	0.95	4	1	4	0.62	52	0.6	44
CotedIvoire	0.68	41	0.69	53	0.76	27	0.99	61	0.92	23	0	69
Costa Rica	0.67	42	0.63	65	0.56	67	1	33	0.63	48	0.94	37
Benin	0.66	43	0.8	26	0.69	43	1	45	1	11	0.94	36
Ghana	0.66	44	0.66	62	0.64	50	1	31	0	71	0	70
Panama	0.66	45	0.78	36	0.74	32	1	5	1	12	1	9
Gibraltar	0.65	46	0.74	44	0.72	39	1	35	0.7	39	0.55	56
Malaysia	0.65	47	0.77	37	0.87	17	0.99	60	0.74	33	0.58	50
Lebanon	0.65	48	0.76	40	0.7	40	1	6	0.64	45	0.52	59
Cyprus	0.65	49	0.75	42	0.65	47	1	27	0.65	44	0.51	63
Gabon	0.64	50	0.75	43	0.62	57	1	50	0.99	20	1	10
Peru	0.63	51	0.84	19	0.63	53	1	40	0.58	61	0.95	35
Morocco	0.63	52	0.72	47	0.63	55	1	52	0.58	60	0.97	20
Brunei Darussalam	0.63	53	0.64	63	0.6	62	0.99	71	0.96	21	1	11
Sri Lanka	0.63	54	0.74	45	0.63	56	1	22	1	13	0.95	32
Senegal	0.62	55	0.8	27	0.64	51	1	7	0.57	63	0.96	25
Bolivia	0.62	56	0.76	41	0.76	28	0.99	64	0.68	42	0.6	45
Venezuela	0.61	57	0.69	54	0.63	54	0.99	58	0.62	50	0.91	40
Cameroon	0.6	58	0.79	32	0.73	33	1	23	0.56	64	0.51	64
Zambia	0.6	59	0.78	35	0.9	10	1	14	1	14	1	12
Guatemala	0.59	60	0.69	55	0.66	46	1	15	0.79	24	0.95	31
Sudan	0.59	61	0.69	56	0.58	65	1	16	1	15	0.97	22
Indonesia	0.59	62	0.69	57	0.67	44	1	8	0.63	49	0.97	21
Australia	0.59	63	0.66	61	0.65	48	1	56	0.64	46	1	13
Cambodia	0.58	64	0.67	59	0.64	52	1	9	0	72	0	71
South Africa	0.58	65	0.63	66	0.67	45	1	55	0.63	47	0.52	60
Ecuador	0.58	66	0.71	51	0.81	23	1	10	0.59	58	0.96	30
Eritrea	0.58	67	0.7	52	0.56	68	1	11	1	16	0	72
Dominican Republic	0.57	68	0.61	68	0.54	70	1	24	0.57	62	1	14
Malta	0.56	69	0.67	60	0.57	66	1	25	1	17	1	15
Togo	0.56	70	0.72	48	0.7	41	1	12	1	18	0.92	39

Appendix C (Continued)

Year	2011		2008		2003		1998		1993		1988	
non-CHP Countries	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**
Kenya	0.54	71	0.62	67	0.6	64	1	13	1	19	1	16
Myanmar	0.53	72	0.64	64	0.62	58	0.99	62	0.52	67	1	17

Appendix D EPI Ranking of CHP Countries

Year	2011		2008		2003		1998		1993		1988	
CHP Countries	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**
Denmark	1	1	1	1	1	1	1	1	0.82	12	1	1
Switzerland	1	2	1	2	1	2	0.69	7	1	3	0	0
Sweden	1	3	1	3	0.95	7	1	5	1	1	1	2
Ukraine	1	4	1	4	0.55	10	1	6	1	2	0	0
Macedonia	1	5	1	5	0.18	25	0.28	22	1	6	0	0
Russia	0.87	6	1	6	1	3	0	0	1	9	0	0
Belarus	0.78	7	0.67	13	1	6	1	4	0.95	11	0	0
Finland	0.77	8	0.65	14	0.47	11	0.61	8	1	4	1	3
Slovak Republic	0.68	9	0.7	11	0.68	8	0.44	11	0.47	20	0.08	13
Austria	0.68	10	0.51	15	0.33	17	0.36	15	0.49	19	0.41	8
Mongolia	0.64	11	0.69	12	0.67	9	0.56	10	0.44	21	1	5
Hungary	0.63	12	0.43	20	0.34	16	0.39	13	0.58	17	0.67	6
France	0.56	13	0.43	19	0.38	12	0	0	0	0	0	0
Croatia	0.55	14	0.35	23	0.28	22	0.33	17	0	0	0	0
Romania	0.53	15	0.36	22	0.38	13	0.61	9	0.7	14	0	0
Belgium	0.52	16	0.3	27	0.14	27	0.12	25	0.26	26	0.17	12
Bulgaria	0.52	17	0.43	18	0.28	23	0.33	18	0.76	13	0.36	9
Netherlands	0.51	18	0.34	24	0.37	14	0.35	16	1	5	0	0
Moldova	0.5	19	0.05	38	0.18	26	0.3	20	0.32	23	0	0
Estonia	0.48	20	1	7	0.29	21	0.42	12	0	0	0	0
Czech Republic	0.48	21	0.38	21	0.32	18	0.39	14	0.56	18	1	4
Germany	0.45	22	0.44	17	0.24	24	0.22	23	0.6	15	0.31	10
Uzbekistan	0.41	23	0.34	25	0.31	20	0.33	19	0.29	24	0	0
China	0.39	24	0.72	10	1	5	1	3	0.6	16	0.51	7
Serbia	0.38	25	0.24	29	0.11	29	0.13	24	1	7	0	0
Norway	0.37	26	1	8	1	4	1	2	0.95	10	0.27	11
Slovenia	0.34	27	0.31	26	0.31	19	0.3	21	0.29	25	0	0
Portugal	0.34	28	0.18	31	0.07	30	0.04	29	0.1	29	0.08	14
Italy	0.32	29	0.19	30	0	0	0	0	0	0	0	0
Korea	0.23	30	0.28	28	0.14	28	0.07	26	0	0	0	0
Bosnia and Herzegovina	0.2	31	0.44	16	0.03	35	0.06	27	0	0	0	0
Luxembourg	0.2	32	0.13	33	0.07	31	0	0	0	0	0	0
Turkey	0.17	33	0.14	32	0.04	34	0	0	0	0	0	0
United Kingdom	0.13	34	0.11	35	0.06	32	0	0	0	0	0	0
Azerbaijan	0.09	35	0.08	37	0.37	15	0	0	0.35	22	0	0

Appendix D (Continued)

Year	2011		2008		2003		1998		1993		1988	
CHP Countries	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**	**EPI**	**Ranking**
United States	0.09	36	0.1	36	0.01	37	0.03	30	0.13	28	0	0
Canada	0.08	37	0.12	34	0.05	33	0.05	28	0.18	27	0.03	15
Greece	0.02	38	0.01	40	0.01	38	0.01	31	0	0	0	0
Kosovo	0.02	39	1	9	0.01	36	0	0	0	0	0	0
Japan	0.01	40	0.02	39	0	39	0.01	32	1	8	0.01	16

Appendix E CPI Ranking of CHP Countries

Year	2011		2008		2003		1998		1993		1988	
CHP Countries	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**
Sweden	1	2	1	2	0.88	8	1	5	1	1	1	1
Denmark	1	1	1	1	1	1	1	1	0.12	8	1	4
Switzerland	1	3	1	3	1	2	0.45	6	0.06	11	0	0
Russia	0.59	4	1	4	1	3	0	0	1	5	0	0
Ukraine	0.14	5	0.32	6	0.27	13	0.36	7	0.03	14	0	0
Mongolia	0.13	6	0.19	16	0.1	28	0.17	15	0.17	7	1	3
Netherlands	0.11	7	0.26	11	0.17	17	0.22	11	1	3	0	0
Finland	0.11	8	0.3	8	0.3	10	0.3	8	1	2	1	2
Slovak Republic	0.07	9	0.06	30	0.05	33	0.01	26	0.01	27	0.08	8
Slovenia	0.07	10	0.19	17	0.17	18	0.01	24	0.06	10	0	0
Belgium	0.06	11	0.14	20	0.14	22	0.04	20	0.07	9	0.02	13
Austria	0.06	12	0.26	10	0.17	19	0.09	17	0.05	13	0.36	6
Norway	0.06	13	0.33	5	1	5	1	2	0.03	16	0.07	10
Croatia	0.05	14	0.24	13	0.16	20	0.24	10	0	0	0	0
Hungary	0.05	15	0.3	7	0.2	14	0.21	12	0.01	21	0.07	9
Italy	0.04	16	0.16	19	0	0	0	0	0	0	0	0
Luxembourg	0.03	17	0.1	24	0.07	31	0	0	0	0	0	0
Portugal	0.03	18	0.07	29	0.07	30	0.01	27	0.01	22	0.01	14
Belarus	0.03	19	0.1	23	1	6	1	3	0.06	12	0	0
Moldova	0.03	20	0.05	31	0.13	25	0.26	9	0.01	24	0	0
Germany	0.02	21	0.12	22	0.09	29	0.07	19	0.03	15	0.05	11
Serbia	0.02	22	0.24	14	0.11	26	0.04	21	0	29	0	0
France	0.02	23	0.25	12	0.19	15	0	0	0	0	0	0
Macedonia	0.01	24	0.07	28	0.16	21	0.08	18	0.01	25	0	0
Azerbaijan	0.01	25	0.08	26	0.37	9	0	0	0.29	6	0	0
Korea	0.01	26	0.08	25	0.14	23	0.02	23	0	0	0	0
Romania	0.01	27	0.29	9	0.28	12	0.02	22	0.02	17	0	0
Turkey	0.01	28	0.04	32	0.04	35	0	0	0	0	0	0
China	0.01	29	0.07	27	1	7	1	4	0.01	28	0.03	12
United Kingdom	0.01	30	0.03	35	0.06	32	0	0	0	0	0	0
Czech Republic	0.01	31	0.22	15	0.17	16	0.21	13	0.01	20	0.12	7
Uzbekistan	0.01	32	0.04	33	0.29	11	0.01	29	0.01	23	0	0
Bulgaria	0.01	33	0.18	18	0.13	24	0.17	14	0.02	18	0.36	5
United States	0	34	0.02	37	0.01	37	0.01	30	0.02	19	0	0
Canada	0	35	0.02	36	0.05	34	0.01	25	0.01	26	0	15

Appendix E (Continued)

Year	2011		2008		2003		1998		1993		1988	
CHP Countries	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**	**CPI**	**Ranking**
Estonia	0	36	0.13	21	0.11	27	0.16	16	0	0	0	0
Bosnia and Herzegovina	0	37	0.03	34	0.03	36	0.01	28	0	0	0	0
Greece	0	38	0	38	0.01	38	0	32	0	0	0	0
Japan	0	39	0	39	0	39	0	31	1	4	0	16

Appendix F ECPI Ranking of CHP Countries

Year	2011		2008		2003		1998		1993		1988	
CHP Countries	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**
Sweden	1	2	0.61	3	0.02	4	0.65	6	1	1	1	1
Switzerland	1	1	1	1	0.03	3	0.68	5	0.91	5	0	0
Finland	0.71	3	0.6	4	0.01	5	0.55	7	1	2	1	2
Belarus	0.7	4	0.56	5	0.01	11	1	3	0.9	6	0	0
Russia	0.67	5	0.55	6	0.01	13	0	0	1	4	0	0
Denmark	0.63	6	0.46	9	0.01	8	0.42	9	0.68	11	0.52	3
Ukraine	0.61	7	0.54	7	0.01	6	0.7	4	0.85	7	0	0
Slovak Republic	0.59	8	0.51	8	0.01	12	0.41	10	0.44	16	0.08	13
Hungary	0.53	9	0.38	12	0.01	14	0.37	11	0.49	14	0.5	4
Austria	0.52	10	0.39	11	0.01	10	0.36	13	0.46	15	0.4	7
Mongolia	0.48	11	0.42	10	0.01	25	0.36	15	0.42	17	0.49	5
Croatia	0.48	12	0.31	18	0.01	17	0.32	17	0	0	0	0
France	0.46	13	0.36	13	0.01	9	0	0	0	0	0	0
Netherlands	0.45	14	0.32	15	0.01	7	0.34	16	0.84	8	0	0
Romania	0.44	15	0.34	14	0.01	19	0.48	8	0.68	12	0	0
Moldova	0.43	16	0.03	37	0.01	27	0.3	20	0.28	22	0	0
Czech Republic	0.39	17	0.31	16	0.01	16	0.36	14	0.49	13	0.44	6
Uzbekistan	0.38	18	0.31	17	0.01	21	0.31	18	0.28	21	0	0
Belgium	0.38	19	0.22	24	0.01	26	0.1	25	0.14	25	0.09	12
Bulgaria	0.36	20	0.3	20	0.01	22	0.31	19	0.69	10	0.21	8
Slovenia	0.33	21	0.25	21	0.01	20	0.25	21	0.28	20	0	0
Serbia	0.32	22	0.24	22	0.01	29	0.11	24	0.14	26	0	0
Germany	0.31	23	0.23	23	0.01	18	0.2	23	0.26	23	0.2	9
Estonia	0.27	24	0.3	19	0.01	15	0.37	12	0	0	0	0
Italy	0.27	25	0.18	25	0	0	0	0	0	0	0	0
Norway	0.26	26	0.64	2	0.03	2	1	2	0.74	9	0.18	10
Portugal	0.25	27	0.12	29	0	30	0.03	29	0.03	28	0.04	14
China	0.24	28	0.17	27	1	1	1	1	0.25	24	0.18	11
Macedonia	0.2	29	0.18	26	0.01	23	0.22	22	0.34	19	0	0
Luxembourg	0.16	30	0.11	30	0	31	0	0	0	0	0	0
Korea	0.15	31	0.15	28	0.01	28	0.06	26	0	0	0	0
Bosnia and Herzegovina	0.11	32	0.08	31	0	35	0.05	27	0	0	0	0
Turkey	0.1	33	0.07	32	0	34	0	0	0	0	0	0
United Kingdom	0.08	34	0.06	34	0	32	0	0	0	0	0	0
Azerbaijan	0.08	35	0.07	33	0.01	24	0	0	0.35	18	0	0

Appendix F (Continued)

Year	2011		2008		2003		1998		1993		1988	
CHP Countries	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**	**ECPI**	**Ranking**
United States	0.05	36	0.04	36	0	36	0.03	30	0.05	27	0	0
Canada	0.05	37	0.05	35	0	33	0.04	28	0.03	29	0.01	15
Greece	0.01	38	0.01	38	0	37	0.01	31	0	0	0	0
Japan	0.01	39	0.01	39	0	38	0.01	32	1	3	0	16

Appendix G EPI, CPI and ECPI Scores for G20 Countries in Years

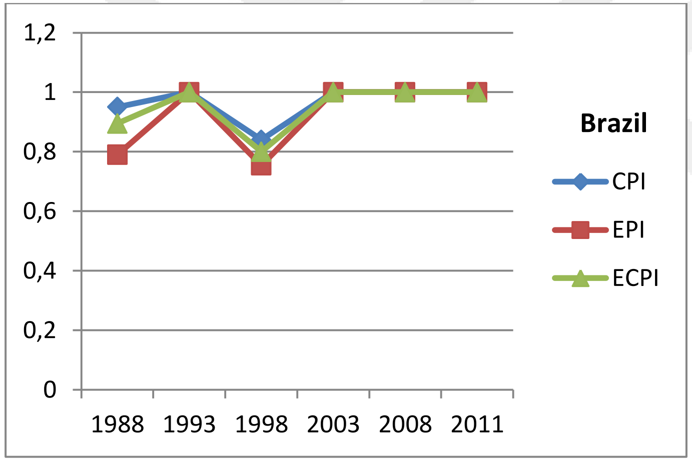

Figure G.1 Brazil

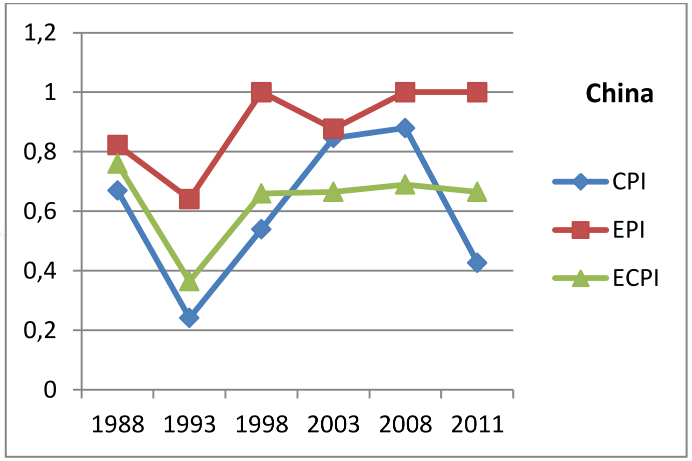

Figure G.2 China

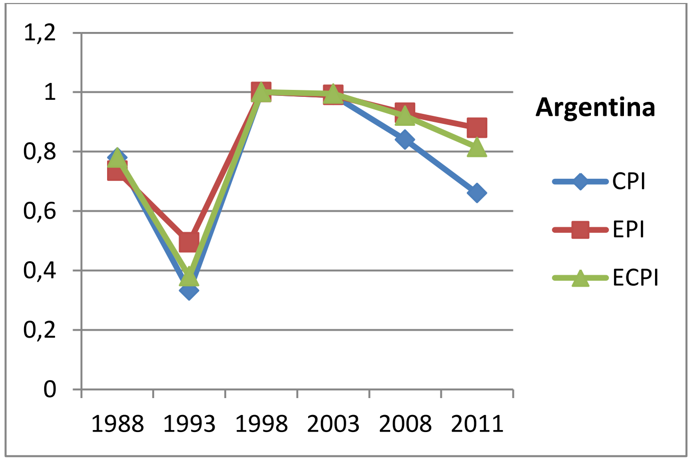

Figure G.3 Argentina

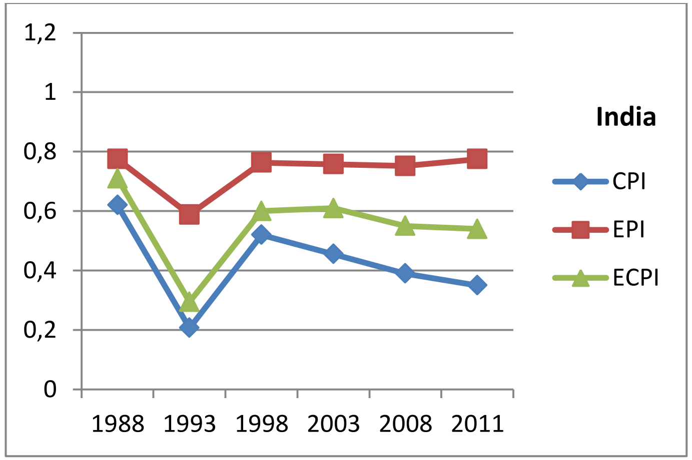

Figure G.4 India

Appendix G (Continued)

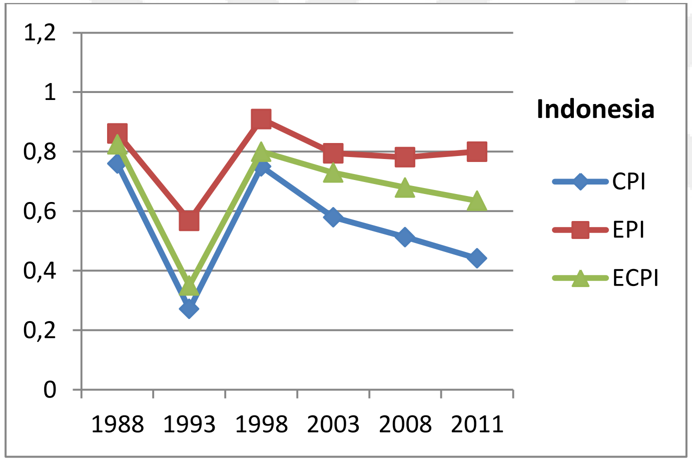

Figure G.5 Indonesia

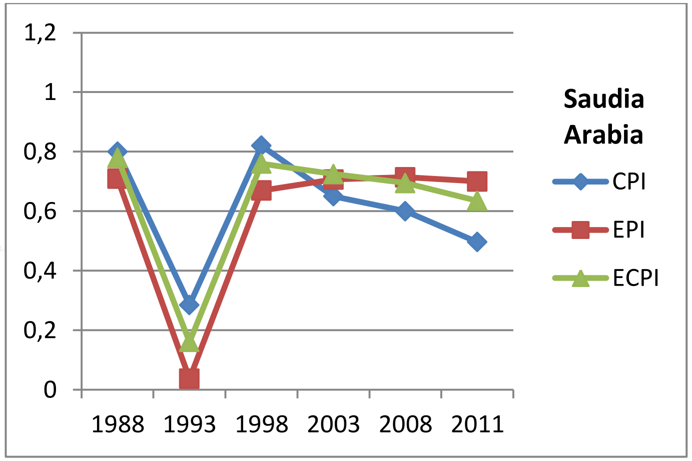

Figure G.6 Saudia Arabia

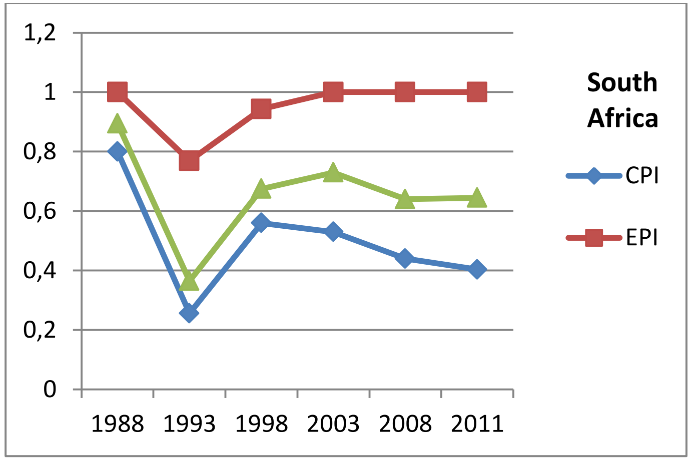

Figure G.7 South Africa

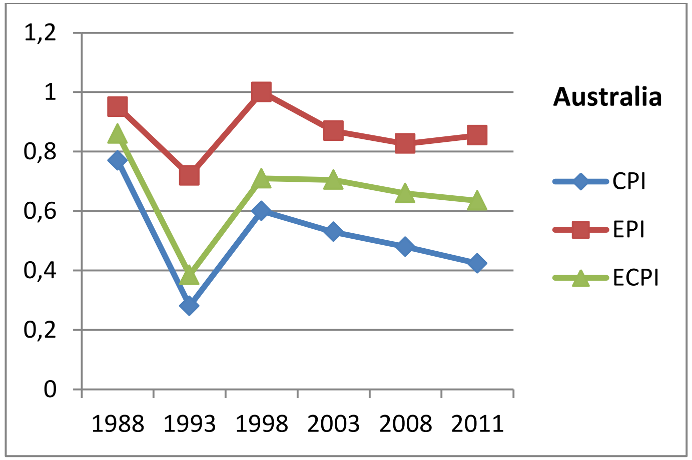

Figure G.8 Australia

Appendix G (Continued)

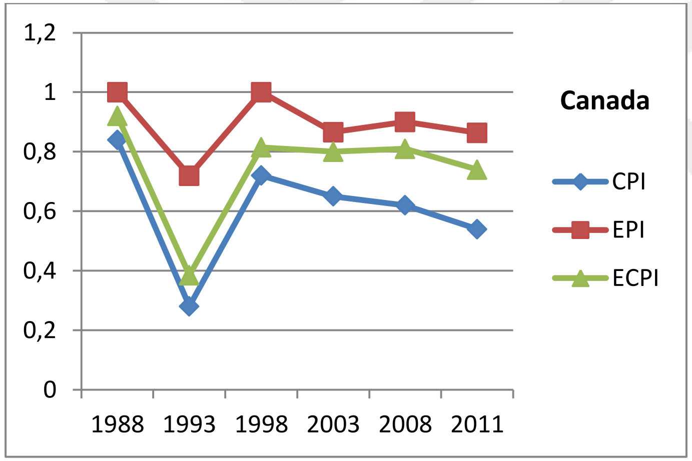

Figure G.9 Canada

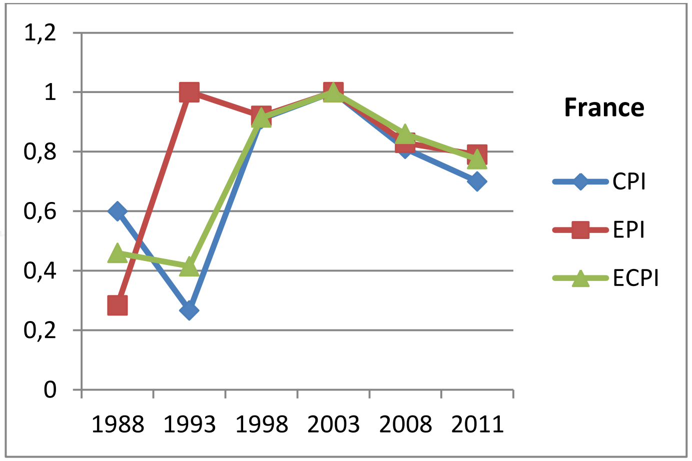

Figure G.10 France

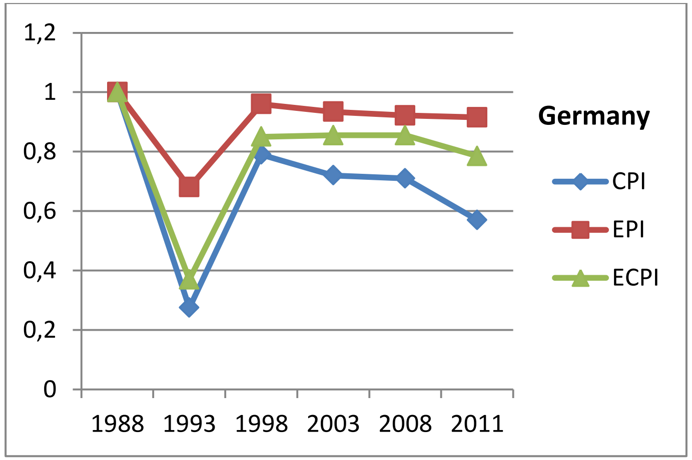

Figure G.11 Germany

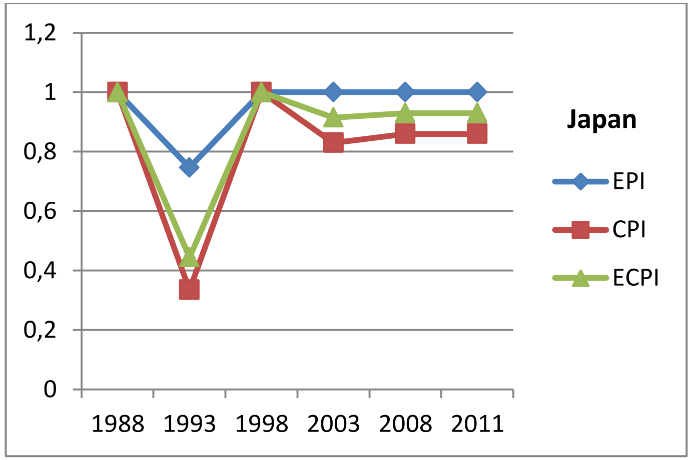

Figure G.12 Japan

Appendix G (Continued)

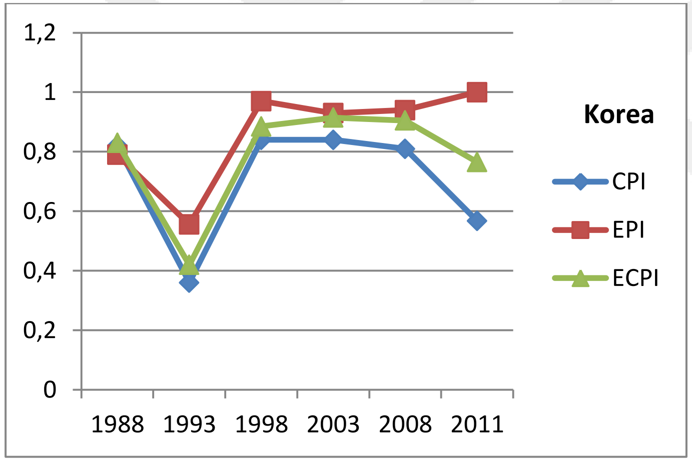

Figure G.13 Korea

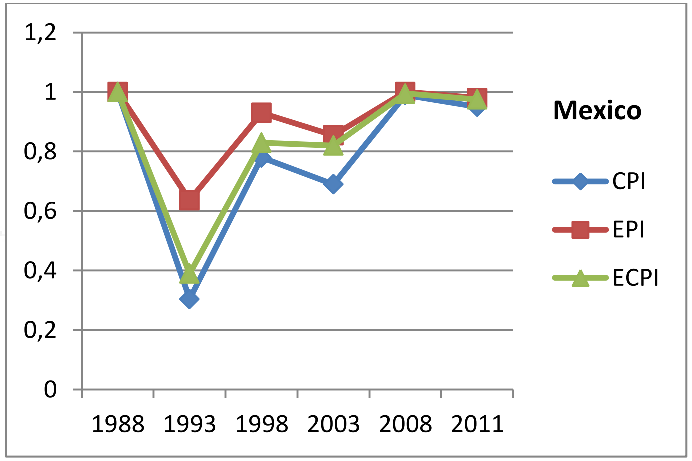

Figure G.14 Mexico

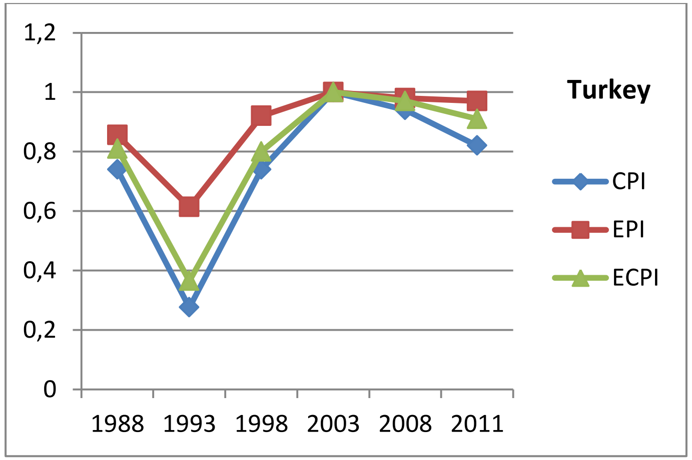

Figure G.15 Turkey

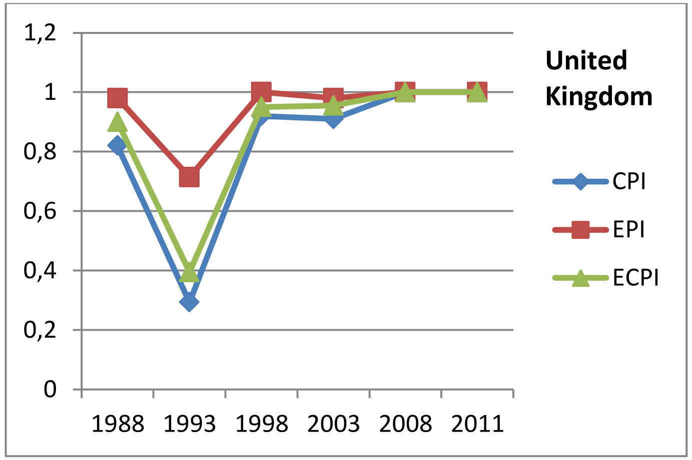

Figure G.16 United Kingdom

Appendix G (Continued)

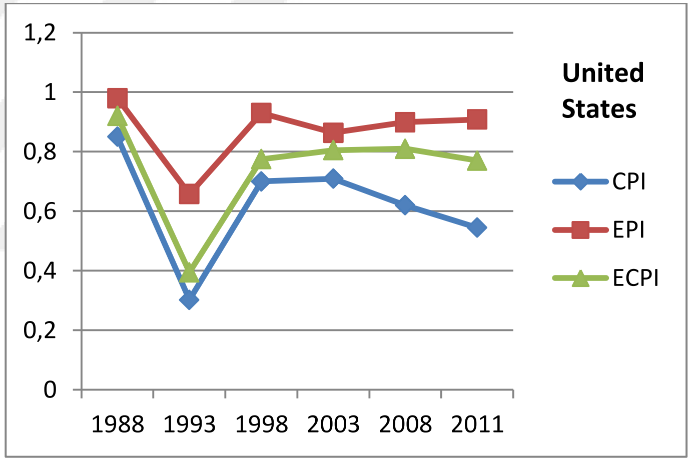

Figure G.17 United States

Appendix H CPI, EPI and ECPI Scores for EITs Countries in Years

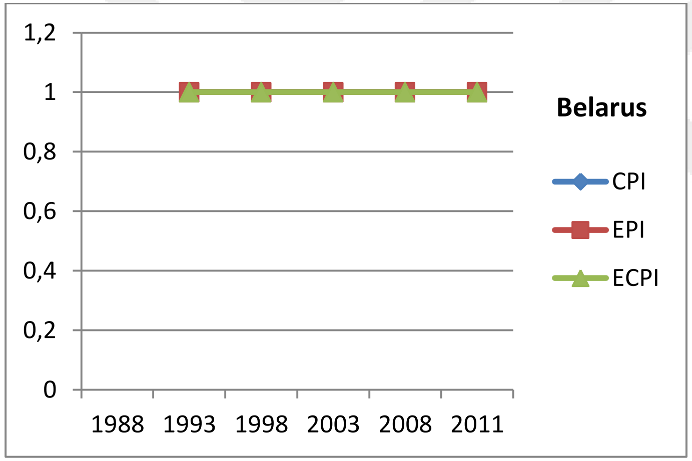

Figure H.1 Belarus

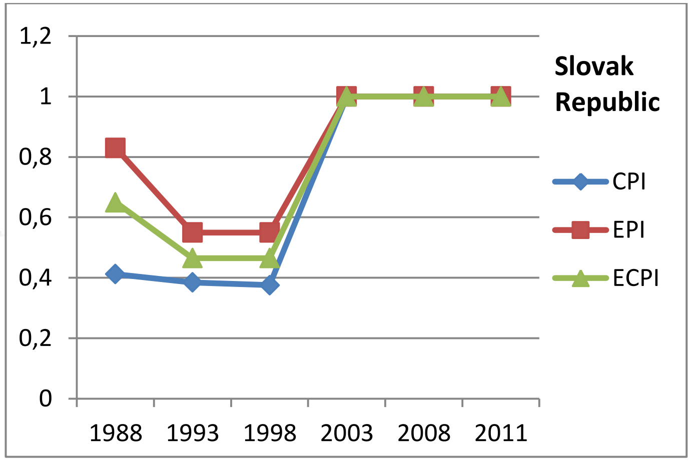

Figure H.2 Slovak Republic

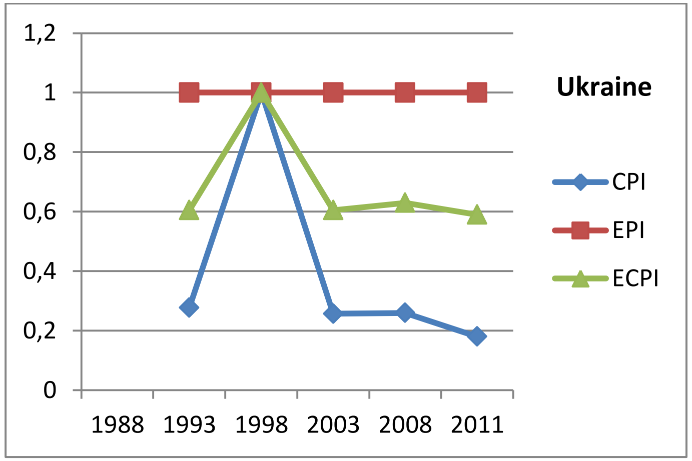

Figure H.3 Ukraine

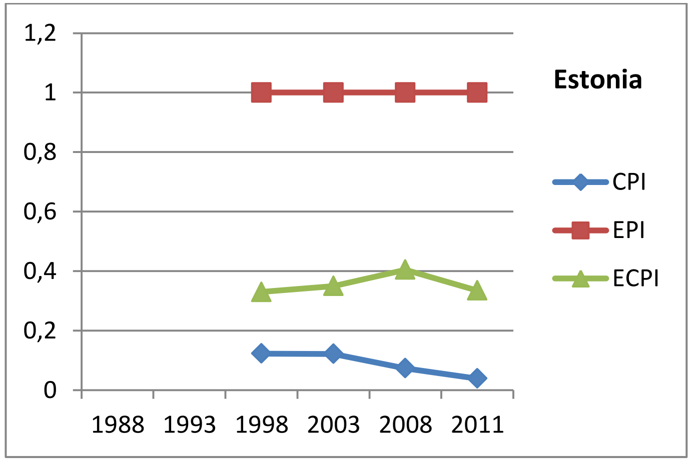

Figure H.4 Estonia

Appendix H (Continued)

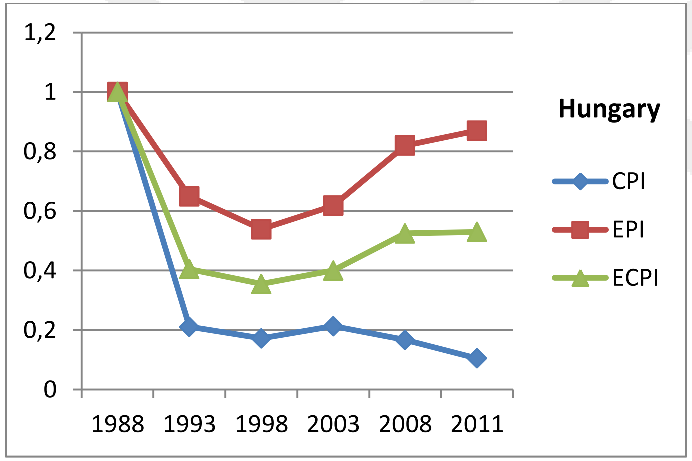

Figure H.5 Hungary

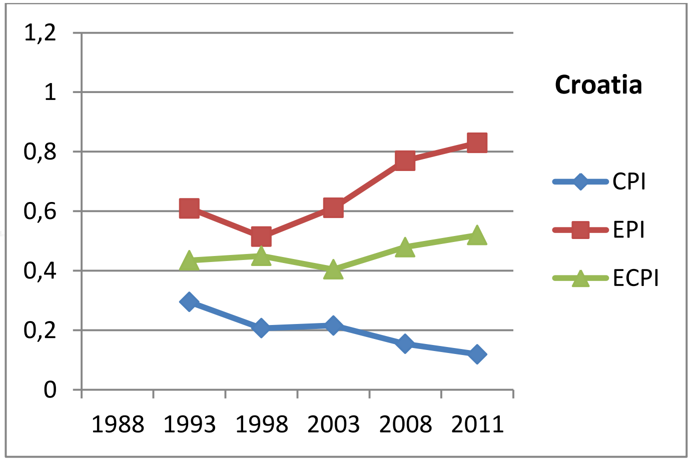

Figure H.6 Croatia

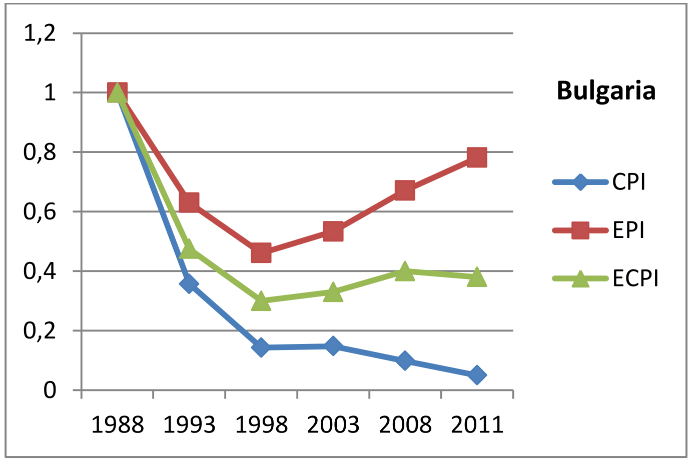

Figure H.7 Bulgaria

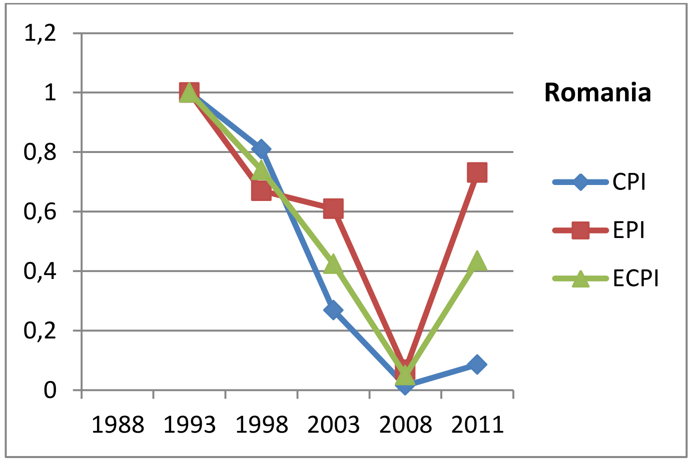

Figure H.8 Romania

Appendix H (Continued)

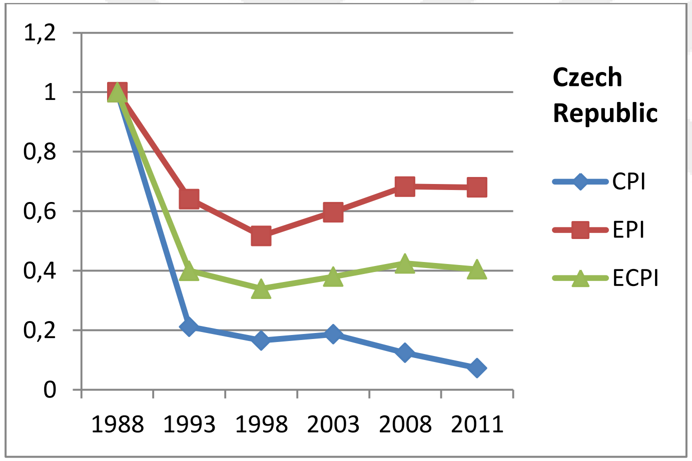

Figure H.9 Czech Republic

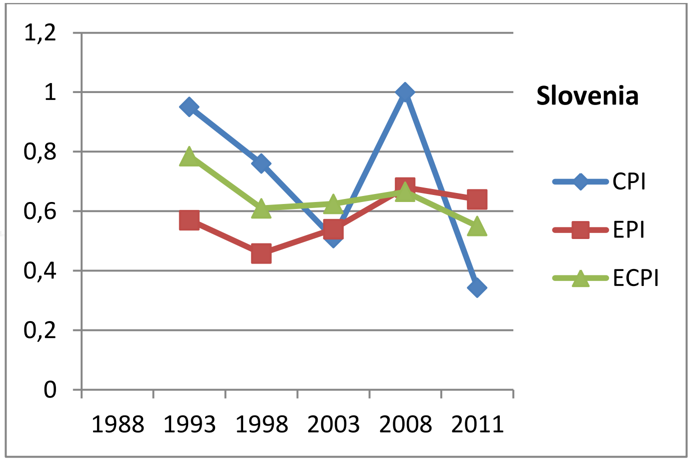

Figure H.10 Slovenia