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A Framework for the Efficiency Evaluation of Ireland's Electricity Power System using Data Envelopment Analysis (DEA)

By

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Thesis submitted for the degree of
PHILOSOPHIAE DOCTOR
from the
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March 2013

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"The fact is, there are only two qualities in the world:
efficiency, and inefficiency and only two sorts of people:
the efficient and the inefficient."

George Bernard Shaw, *John Bull's Other Island*, 1907.

Declaration

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Shane Mullarkey
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Summary

The complex modern Electricity Power System (EPS) is the most significant pervasive infrastructure underpinning the social, technological, and economic development of modern economies. The context in which modern EPSs operate is consistently evolving. EPSs face dynamic challenges in the form of market liberalisation, increased competition and interconnection, sustainability, mitigating CO_2 emissions, fuel price volatility, issues of security of supply, the introduction of new and varying sources and most importantly improving energy efficiency. The European Union (EU) has set a number of 2020 energy efficiency targets which include i) 20% reduction in Greenhouse Gas (GHG) emissions ii) increasing the share of renewable energy in final energy consumption to 20%, and iii) reducing total consumption relative to projections by 20%. These challenges will require a shift from the present centralised, base loaded, fossil fuel paradigm towards a dispersed, multi generation technological, renewables supported energy efficient EPSs of significantly greater complexity.

This research thesis has two main objectives. The first is to construct a comprehensive methodological framework for evaluating technical efficiency performance of EPSs and the second objective is to apply this framework to the all island Single Electricity Market (SEM). The SEM system commenced operation in November 2007 when the Republic of Ireland (ROI) and Northern Ireland (NI) established a single wholesale electricity market. These two objectives are achieved by applying Data Envelopment Analysis (DEA). DEA is a non-parametric linear programming technique, employed in technical efficiency performance measurement and benchmarking, to determine the relative efficiencies of a set of homogeneous (comparable) Decision Making Unit (DMU)s. Empirical DEA applications to EPSs research have seen extensive growth due to i) its minimal underlying assumptions, ii) facilitation of multiple input and output contexts and iii) its versatility in establishing technical efficiency performance.

The thesis incorporates a three tier technical efficiency framework application to the electricity generation and distribution functions of the all island SEM. Comprehensive DEA models are constructed at National, County and Individual levels to reflect the underlying operational characteristics of electricity generation (Thermal, Wind and Hydro) and distribution functions of the Irish EPS. The research study examines the technical, policy and market challenges associated with increasing energy efficiency in these two functions with emphasis on wind power. At the national level, average Total Technical Efficiency (TTE) and Pure Technical Efficiency (PTE) across all three forms of electricity generation was 51% and 78% respectively, whilst at the county level, average TTE and PTE of electricity distribution was 83% and 91% respectively. This thesis offers new insights into the technical efficiency measurement performance of EPSs. The findings presented in this thesis indicate considerable scope for technical efficiency improvement and corrective policy procedures to improve the generation and distribution functions of the all island Irish SEM.

Acknowledgements

Upon submission of this thesis I have had the opportunity to reflect. The completion of this research thesis represents a significant milestone in my life. It is clearly evident that successful academic research is attained through positive relationships, teamwork, support and a research fostering environment. As such, I would like to thank everyone who helped and contributed to the completion of this thesis, in particular, special thanks to the following people:

Firstly, I wish to express my deepest gratitude to my supervisor Dr. Brian Caulfield for his invaluable contributions, endless guidance, support, constructive criticism, proof reading, encouragement and effective insight throughout my PhD time. I would also like to acknowledge with much appreciation my co-supervisors Prof. Biswajit Basu, Dr. Sarah McCormack and Dr. Aoife Foley for their guidance and advice which were instrumental in completing this thesis. It is important to express due recognition and thanks for the financial support and opportunity to conduct research provided by the Department of Civil, Structural and Environmental Engineering, Trinity College Dublin.

Secondly, sincere thanks to my parents, David and Teresa for their continuous unconditional love, inspiration, encouragement and financial support not just for these past three years but for my entire schooling, college and academic life. They have consistently put my education first and foremost and for this I am blessed and eternally grateful. Also particular thanks to my father David for proof reading my thesis, it can't have been easy!!! To my brothers, my closest friends, Conor, Donal and Cian, thanks for your understanding, enduring patience and unquestionable support. In particular, Conor for his many kind timely financial investments and to finally answer the two questions that have preoccupied your mind "Yes I am finished that Ph.D thing and yes hopefully now I will get a real Job ".

To the members club of 17 Bath street, past and present thank you for your friendship, dinner clubs, chats, pots of tea, rivalry, jiben, cheeseballing and endless nights out socialising giving me lighter moments of joy! - Kev, Findins, K-balls, Tony-T, Mac-Attack, Quinnskeens, Mick, Gracianne, Andrea. Thank you for everything.

To the inhabitants of Pearse street room 192, it has been a long arduous journey but thanks to Mairead, Ciaran, Seanie, Aidan and Tara for all the moral support, laughs, tea breaks, sighs of frustration, help, camaraderie, stories, debates and hours of endless discussion I have enjoyed over the last few years, but mostly thanks for facilitating my various oddities which have no doubt tested your tolerance levels on numerous occasions. Special thanks to Aidan and Tara in whom I have gained lifelong friendships. Thanks to all of you for creating a friendly, enjoyable research environment and wholeheartedly welcoming an economist into the world of engineering!

Thanks to all my home and college friends for putting up with me and supporting my social life for the past three years. We've shared some great moments over the past few years, here's to many more in the future where I will put my hand in my pocket!!

List of Publications

Journal Papers:

1. Bailey, D., Caulfield, B., Mullarkey, S. 2012 "Using Data Envelopment Analysis (DEA) as a Public Transport Project Appraisal Tool Transport Policy", *Transport Policy*, Accepted.

2. Mullarkey, S., Caulfield, B., Foley, A., McCormack, S. and Basu, B. 2012 " Efficiency Assessment of Ireland's Electricity Power Generation using Data Envelopment Analysis (DEA) ", *Journal of Energy Engineering*, American Society of Civil Engineering (ASCE), (Under Review).

3. Mullarkey, S., Caulfield, B., McCormack, S. and Basu, B. 2012 "A Framework for Establishing the Technical Efficiency of Electricity Distribution Counties (EDC) based on Data Envelopment Analysis ", *Journal of Cleaner Production*, (Under Review).

Conference Papers:

1. Mullarkey, S., Caulfield, B., McCormack, S. and Basu, B. " Efficiency Assessment of Thermal Power Generation in Ireland using Data Envelopment Analysis ", 9th International Conference on Data Envelopment Analysis (DEA2011), Thessaloniki, Greece, August, 2011.

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List of Acronyms

AIG	All Island Grid
AIGES	All Island Generation Efficiency Study
BCC	Banker Charnes Cooper
CBA	Cost Benefit Analysis
CCGT	Combined Cycle Gas Turbines
CCR	Charnes Cooper Rhodes
CER	Commission for Energy Regulation
CRS	Constant Returns to Scale
CSO	Central Statistics Office
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
DRS	Decreasing Returns to Scale
EDC	Electricity Distribution Counties
EDZ	Electricity Distribution Zones
EPS	Electricity Power System
EU	European Union
ESB	Electricity Supply Board
FUI	France United Kingdom Ireland
GB	Great Britain
GHG	Greenhouse Gas
GW	Gigawatt
GWh	Gigawatt-hour
IRS	Increasing Returns to Scale
km	Kilometre
kV	Kilovoltage
MCA	Multi Criteria Analysis
MPSS	Most Productive Scale Size

MW	Megawatt
MWh	Megawatt-hour
NDSC	Non-Discretionary
NGUK	National Grid United Kingdom
NI	Northern Ireland
NIAUR	Northern Ireland Authority for Utility Regulation
NIE	Northern Ireland Electricity
NiRO	Northern Ireland Renewables Obligation
NIRS	Non Increasing Returns to Scale
PK	Pareto-Koopmans
PPS	Production Possibility Set
PSO	Public Service Obligation
PTE	Pure Technical Efficiency
UDC	Urban Distribution Counties
UK	United Kingdom
UKNG	United Kingdom National Grid
USA	United States of America
RDC	Rural Distribution Counties
REFIT	Renewable Energy Feed in Tariff
RES	Renewable Energy Sources
RESE	Renewable Energy Sources from Electricity
ROI	Republic of Ireland
ROIDES	Republic of Ireland Distribution Efficiency Study
ROIWES	Republic of Ireland Wind Efficiency Study
RTS	Returns to Scale
SE	Scale Efficiency
SFA	Stochastic Frontier Analysis
SEM	Single Electricity Market
SEMC	Single Electricity Market Committee
SEMO	Single Electricity Market Operator
SONI	Systems Operator Northern Ireland
TE	Technical Efficiency

TJ	TeraJoules
TTE	Total Technical Efficiency
TWh	Terawatt-hour
VRS	Variable Returns to Scale

Glossary

BCC Model: DEA model allowing for variable returns to scale (VRS) characteristics when estimating the pure technical efficiency (PTE) of DMUs.

CCR Model: DEA model allowing for constant returns to scale (CRS) characteristics when estimating the total technical efficiency (TTE) and scale efficiency (SE) of DMUs.

CRS: Constant Returns to Scale. A proportionate increase in inputs results in the same proportionate increase in outputs.

DEA: Data Envelopment Analysis is a non-parametric technique based on linear programming for the estimation of production frontiers to establish the relative efficiency of a group of similar units entitled "Decision Making Units DMUs".

DMU: Decision Making Unit. A DMU is an entity responsible for converting inputs into outputs and whose performances are to be evaluated in the DEA analysis.

DRS: Decreasing Returns to Scale. A proportionate increase in inputs results in a less than proportionate increase in outputs.

Efficiency: The ability to attain the outputs with a minimum level of resources.

Efficiency Frontier: The frontier of best possible production.

Envelopment Frontier: A frontier or surface determined from the best observed or best practice units.

Input Oriented Model: DEA model where the objective is to minimize inputs while producing at least the given output level.

IRS: Increasing Returns to Scale. A proportionate increase in inputs results in a higher proportionate increase in outputs.

Isoquant: The isoquant represents the boundary such that the observed production of Y cannot be achieved with any equiproportional reduction in all inputs. The definition of the isoquant for the input set provides the theoretical basis for input-oriented models of technical efficiency. Alternatively, production can be represented by an output set.

LP: Model Linear Programming model. A mathematical programming model in which the objective function and all the constraint are linear.

Output Oriented Model: DEA model where the objective is to maximise outputs while not exceeding the observed input levels.

Glossary

Parameter: Any inputs or outputs employed in DEA Model.

Pareto-Koopmans: A DMU is fully efficient if and only if it is not possible to improve any input or output without worsening some other input or output.

Peer Group: A set of efficient DMUs to which the inefficient DMU is compared.

PPS: Production Possibility Set is defined as the set of feasible activities. DEA models implicitly use PPS to evaluate relative the efficiency of DMUs.

Production Function: Function in which outputs are defined as functions of inputs.

Productivity: Ratio of outputs to inputs.

PTE: The efficiency of converting inputs to outputs.

SE: Investigates if a DMU is operating in its optimal size. It is a function of TTE divided by PTE.

Sensitivity Analysis: Examines the sensitivity of DEA results to perturbation in the data.

Slack Variable: A standard Linear Programming (LP) terminology for additional variables added to the model in order to convert inequality constraints to equality constraints. In DEA refers to addition improvements which is possible in specific inputs or outputs.

Translation Invariance: Property of a DEA model in which translating the original inputs or outputs has no effect on the efficiency score obtained.

TTE: Composed of pure technical efficiency PTE and scale efficiency SE.

Units Invariance: Property of a DEA model in which the efficiency scores are independent of the units in which inputs and outputs are measured.

Variable: Any inputs or outputs employed in DEA Model.

VRS: Variable Returns to Scale. A proportionate increase in inputs results in a non-proportionate increase in outputs.

Weights: The relative importance of the inputs and outputs in the DEA model.

CHAPTER 1

Introduction

1.1 Introduction

The worlds energy system is at a defining juncture. Current global trends in energy supply and consumption are patently unsustainable environmentally, economically and socially (IEA, 2008). The current global energy challenge is the greatest threat to humanity in the 21st century. Acknowledging the current global energy mix, the magnitude of the challenge is apparent: conventional energy sources are unsustainable. Sanyal (2012) states that coal accelerated the industrial revolution, oil accelerated the transport boom of the 20th century and now gas is expected to be the significant contributor to energy growth up to 2030. Oil's share of global energy demand has declined in the past few decades whilst gas has risen significantly and coal has fluctuated. The fossil fuel sources of oil, gas and coal are expected to each have a market share of 27% of total energy consumption by 2030. Non-fossil fuels nuclear, hydro and non-hydro renewable forms of energy are expected to each have a share of 6% of total consumption by 2030, fossil fuels are expected to have an 80% share of consumption in 2030. Non-fossil fuels will contribute significantly to energy growth over the next twenty years but fossil fuels are still expected to account for as much as 80% of energy consumption (Sanyal, 2012).

The Electricity Power System (EPS) is arguably one of the most critically important, technologically sophisticated and economically valuable infrastructural investments in the history of human civilisation (Burke, 2010). Electricity infrastructure is an indispensable vertebra in the backbone of developed and developing countries. The ability to generate and transmit electrical power through a nation's transmission and distribution system, in an efficient manner is paramount to sustained development and growth in today's technology reliant society. The contribution of a cost effective, reliable and secure electricity supply network is crucial to a well functioning, productive modern economic society (Burke, 2010). The worlds electricity gen-

eration sector is dominated by fossil fuel sources and consequently is a significant contributor to anthropogenic climate change through Greenhouse Gas (GHG) and other emissions. Both the Republic of Ireland (ROI) and Northern Ireland (NI) are extremely fossil fuel dependent as imports account for a significant portion of primary energy consumed (SEI, 2009; DETI, 2008). This reliance on fossil fuel weakens economic competitiveness, exposes EPSs to fuel price fluctuations and issues of supply. This problem is not confined to Ireland, but is a global issue.

The European Union (EU) has outlined numerous policy objectives to achieve a sustainable energy future through systematic measures i) to tackle climate change, ii) to ensure energy security and iii) to enhance energy competitiveness (EC, 2008*a*, 2009). The European energy efficiency 2020 targets include i) 20% reduction in GHG emissions ii) increasing the share of renewable energy in final energy consumption to 20%, and iii) reducing total consumption relative to projections by 20%. The attainment of these targets will be achieved by tackling the issue of i) climate change by mitigating CO_2 emissions, ii) energy security by increasing the share of Renewable Energy Sources from Electricity (RESE), and iii) enhancing energy competitiveness through electricity market reform and interconnection. The implications for EPSs within Europe are extensive as Keane (2007) states dwindling fossil fuel resources, volatile fuel price markets and electricity market reform through unbundling and liberalisation are significantly altering the context and environment in which EPSs are operated and regulated. The benefits of electricity market reform include i) improved sector efficiency, ii) fostering of competitive environment, iii) driving low carbon investment, and iv) adding to energy security.

Under EU and National governmental persuasion EPSs are shifting towards a "low carbon society" due to considerable concerns over the sustainability of the world's electricity supply resulting in added Renewable Energy Sources (RES)s, in particular wind power. As Europe strives towards a single electricity market by 2014, the Irish Government and the NI Executive are implementing strategies to increase the share of RESE. Both the ROI and NI have a target of 40% share of RESE by 2020 (DCENR, 2009; DETI, 2009). Due to its zero CO_2 emissions, environmentally friendly and cost predictive characteristics, wind power is acknowledged as a viable alternative electricity power generation source in the face of depleting fossil fuel reserves and unknown anthropogenic climate change consequences (EWEA, 2008). Numerous governments and countries are considering and adopting ambitious future wind energy penetration scenarios (USDE, 2008). Installed wind energy capacity has seen extensive growth in recent years with this trend expected to continue. In 1990, installed wind energy capacity was 0.4 GW, 2011 103.3 GW and is expected to rise to 249 GW by 2020 and 400 GW by 2030 (EWEA, 2011). In the Irish context, currently the installed capacity of wind power is approximately 1600 MW which is expect to rise to 5000 MW by 2020 (IWEA, 2010). Productivity assessment and particularly efficiency measurement of the energy and power sector is intricately linked to a nations economic development and growth. The improvement in efficiency of the generating and distribution functions of EPSs is playing an ever-increasing critical role in the

energy strategies of many government nations (Ang, 2006; Zhou and Ang, 2008). The Irish electricity market entitled the All Island Single Electricity Market (SEM) consists of two interconnecting systems, the ROI in the south and NI in the north. It has been fully operational since 2008, prior to the adoption of the SEM, electricity market reform and liberalisation failed in both electricity markets. Having regard to the EUs energy efficiency objectives and the national RESE in the ROI and NI, this research thesis concentrates on establishing the technical efficiency on the newly adopted SEM and improving the efficiency of the Irish EPS as a solution to achieving 2020 energy efficiency targets. Subsequently, the efficiency of the RES wind power is investigated, thus refining the objectives of the research. This is conducted by the application of Data Envelopment Analysis (DEA) to the generation and distribution functions of the Irish EPS.

DEA is a non-parametric multi input-output linear programming technique employed to calculate an efficiency frontier and measure the relative efficiency of a set of comparable Decision Making Unit (DMU)s[1]. DEA is a relative technical efficiency measurement tool employing operations research techniques to automatically calculate the weights assigned to the inputs and outputs of the DMUs being assessed. The actual input-output data values are then multiplied with the calculated weights to determine the efficiency scores obtained (Kabnurkar, 2001). The key contribution of DEA to efficiency analysis, and empirical production analysis in general, is the possibility to approximate unobservable production technologies from empirical input-output data of DMUs without imposing overly restrictive parameter assumptions (Kuosmanen, 2001). This DEA technique has been applied for measuring the relative efficiency of DMUs in various sectors such as hospitals, financial institutions and transport but most importantly has been extensively applied to EPS worldwide.

1.2 Aims and Objectives of the Research

In summation, gaps in the current international EPSs literature exist relating to i) the efficiency of the sector as a whole, ii) a proven economic analysis tool to evaluate complex EPS markets, iii) corrective measures and policies to improve EPS efficiency, and iv) the application of DEA to the Irish EPS. This research thesis attempts to address the lack of understanding in these areas. To address these research gaps the thesis entails the application of DEA to the generation and distribution functions of the Irish EPS. The aim of the research thesis and associated DEA model development is to explore how the Irish 2020 energy efficiency objectives can be attained and in particular the pivotal role the Irish EPS can contribute through improved operational efficiency. The primary objectives of the research are the following:

1. To conduct a comprehensive literature review in the following areas;

    i Global energy challenge, climate change, EU 2020 objectives - policy implications

[1]In the literature on productivity and efficiency analysis the term "Decision Making Unit" (DMU) is used to describe a productive entity in instances when the term "firm" may not be entirely appropriate. Examples of DMUs include power plants, electricity distribution zones, schools, hospitals, universities and police forces.

for Ireland.

ii Irish electricity generation renewable energy policy obligations through added installed wind power.

iii Operational characteristics of the All Island SEM system - ROI and NI.

iv Economic efficiency and frontier estimation techniques in particular DEA.

The thesis presents a three tier efficiency evaluation framework for the Irish EPS sector.

2. To estimate the technical efficiency of thermal, wind and hydro power generation on the All Island Grid (AIG) system by implementing an All Island Generation Efficiency Study (AIGES).

3. To establish the technical efficiency associated with the distribution of electricity by developing a Republic of Ireland Distribution Efficiency Study (ROIDES).

4. With regards Ireland's 2020 wind energy commitments for electricity generation, evaluate the technical efficiency of existing wind farms by conducting a Republic of Ireland Wind Efficiency Study (ROIWES). The focus is on onshore wind power.

5. Investigate the potential framework, strategies and directions for the efficiency improvement in the generation and distribution functions of the Irish EPS.

6. To show and verify the adopted DEA methodology can be employed to attain the research aims and objectives.

1.3 Structure and Layout of the Thesis

This research thesis incorporates seven chapters and three appendices related to the application of DEA to the Irish EPS. The structure of this thesis is as follows:

Chapter 1 introduces the subject area and background, academic rationale underpinning the research, sets out the primary aims and objectives and describes the structure and layout of the thesis.

Chapter 2 presents the conceptual framework to the research by setting the scene with regards to the present global energy challenge, EU energy efficiency objectives and electricity market reform. The all island SEM test system attributes and underlying structural characteristics are described in detail and the Irish potential from RESs from a policy and market perspective are discussed.

Chapter 3 defines the theory and concept of economic efficiency and the techniques employed in efficiency and productivity measurement by focusing on the contrasting parametric

and non-parametric frontier estimation techniques. Particular emphasis is extended to the widely acknowledged DEA technique, and its alternative Stochastic Frontier Analysis (SFA). The chapter incorporates a systematic review of the pertinent empirical literature on the applications of DEA to EPSs research.

Chapter 4 presents the theoretical and methodological mathematical notation underpinning the DEA models employed in the efficiency evaluation of the Irish EPS. The chapter develops the fundamental Charnes Cooper Rhodes (CCR) and Banker Charnes Cooper (BCC) DEA models and their extensions.

Chapter 5 details the conceptual DEA three tier efficiency analysis framework applied to the Irish EPS, with particular emphasis on the generation and distribution functions of the EPS. The incorporation and application of data parameters, sources and models constructed is discussed, defended and justified for each tier level. A sensitivity analysis procedure is outlined.

Chapter 6 applies the fundamental DEA models developed in Chapter 4 and the conceptual three tier efficiency framework presented in Chapter 5 to the test system - the all island SEM. The chapter presents the key findings of the research undertaken by providing insight, interpretation and discussion of the results obtained. The results of the sensitivity analysis and model validation are presented.

Chapter 7 concludes with a synopsis of the key findings, contributions and discussion of the salient issues established in the thesis and policy implications. Also possible directions for further research are acknowledging and presented.

Appendix A provides an extensive and detailed literature review of DEA applications to EPSs. Appendix B specifies the underlying transmission and distribution characteristics of the Irish EPS. Also included is wind rose data from 2000-2010 and the correct procedural steps for the application of DEA. Finally, Appendix C contains information pertaining to sensitivity analysis and model validation.

CHAPTER 2

Contextual Framework

2.1 Introduction

This Chapter forms the conceptual background to the research study undertaken by outlining its context relative to the present global energy challenge, EU energy efficiency objective, implications of electricity market reform, liberalisation and the adoption of RESs in the form of wind power and linking these themes with the chosen test system, the all-island SEM. The unique characteristics of the underlying test system the all-island SEM are discussed in relation to its structure, electricity demand, interconnection, regulation along with current and future generation portfolios.

2.2 Energy Challenge

Over the past two centuries, human activity primarily fossil fuel combustion has increased the concentration of GHG (carbon dioxide CO_2 is the most important anthropogenic GHG) in the Earth's atmosphere resulting in a rise in the Global Mean Surface Temperature (GMST). The "natural" greenhouse effect makes most of the life present on Earth possible, as it effectively keeps the surface 34^0C warmer than it would otherwise be -19^0C (Vorgelegt, 2004). There is a significant body of literature on the science of climate and consequences of climate change. The periodically compiled seminal reports provided by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 1990, 1995, 2001, 2007)[1] are the most comprehensive. The following paragraphs discuss the salient effects and issues related to climate change. The purpose of this Chapter is to put the current research thesis into context and distill the objectives. Increased energy consumption since the industrial revolution is the primary factor that has led to the accelerated accumulation of GHGs. Other factors include land use changes, agricultural production

[1]The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) is currently being researched and will be finalised in 2014.

and industrial activities (IPCC, 2001). The last 100 years has show an increase in Global Mean Surface Temperature (GMST) of 0.75^0C with the rate of global warming over the last 25 years accelerating at over 0.18^0C per decade (WHO, 2010). The temperature increases are greater at higher northern latitudes with average Arctic temperatures increasing at almost twice the global average rate in the past 100 years (IPCC, 2007).

Compared to a pre-industrial levels of about 280 parts per million (ppm) by volume, the concentration of CO_2 had increased to about 390 parts per million (ppm) in 2011 (NOAA, 2012). These levels of concentration have never been experienced in 20 million years. Caused by thermal expansion and melting land ice, the global average sea level has risen at an average rate of 1.8 millimetre (mm) per year over 1961 to 2003 and at an average rate of about 3.1 millimetre (mm) per year from 1993 to 2003 (IPCC, 2007). There has been decreases in snow and ice extent since 1978 shown by annual average Arctic sea ice extent shrinking by 2.7% per decade. Mountain glaciers and snow cover on average have declined in both hemispheres. In the second half of the 20th century, average northern hemisphere temperatures were highest in the last 1300 years. Since 1970 there is evidence indicating increased intense tropical cyclone activity in the north Atlantic (IPCC, 2007).

Saidur et al. (2010) stipulate climate change and increased GHG emissions impose large scale and global environmental hazards to human health in the form of stratospheric ozone depletion, loss of biodiversity, changes in hydrological systems and the supplies of freshwater, land degradation, air pollution and stresses on food systems. The global warming occurrence since the 1970s was causing over 140,000 excess deaths annually by the year 2004. The contributing factors include diarrhoeal diseases, malnutrition, malaria and dengue which are highly climate sensitive and are expected to worsen (WHO, 2010). IPCC (2007) state the implications of climate change are so profound and devastating in that *"unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt"*. Stern (2006) states ignoring climate change will result in significant disruption to economic and social activity later this century, on a similar scale experienced with the great wars and the economic depression of the first half of the 20th century, and it will be difficult if not impossible to reverse these effects.

The world's energy supply is dominated by fossil fuels, Figure 2.1 illustrates that in 2009 81% of the world energy was produced from fossil fuels, composed of coal 27%, oil 33% and gas 21%. The remaining sources were nuclear 6% and other 13% (IEA, 2011). Current policy scenarios[2] expect world energy demand to increase from 12,150 million tonnes of oil equivalent (mtoe) in 2009 to 18,300 million tonnes of oil equivalent (mtoe) in 2035, 51% higher than 2009 representing an average growth of 1.6% per year. The fossil fuel sources (oil, coal and natural gas) remain the dominant sources of energy in 2035 accounting for 79% of supply (IEA, 2011).

[2]The International Energy Agency (IEA) predicts future energy demand by employing current policies scenarios which incorporate government policies and measures enacted or adopted by mid-2011 remaining unchanged.

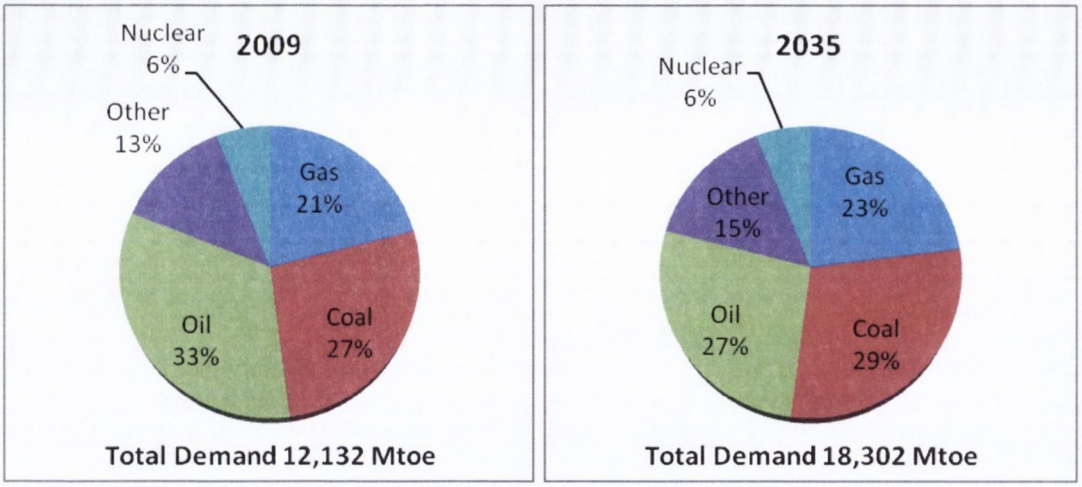


Fig. 2.1: World's Energy Supply by Fuel Source 2009-2035

The modelled energy scenario for 2035 reflects high fossil fuel intensity, resulting in GHG emissions increasing inexorably and the issue of security of supply will become significant. BP (2012) state based on 2009 consumption levels, estimated fossil fuel reserve depletion times for gas, coal and oil, are 63, 112, and 54 years respectively. Global warming and the associate implications in the world climate patterns have been acknowledged as the gravest threat to humanity in the 21st century. Consequently, to avoid the devastating and detrimental effects of high fossil fuel energy intensity, the EU has enacted a number of policy objectives to achieve a sustainable energy future incorporating three pillars - i) to tackle climate change, ii) to ensure security of supply for the future and iii) to enhance competitiveness EC (2008*a*, 2009). The EU has committed to limiting global mean warming to less than 2 degrees C (above pre-industrial levels) by stabilising GHG concentrations in the atmosphere this century (EC, 2008*b*). The European energy efficiency 2020[3] targets include i) 20% reduction in GHG emissions ii) increasing the share of renewable energy in final energy consumption to 20%, and iii) reducing total consumption relative to projections by 20%. These energy efficiency targets are also referred to as "20-20-20" targets (EC, 2008*b*). The EU issued a mandatory targets to each member state in order to achieve the mentioned energy efficiency objectives for Europe.

These energy efficiency objectives are clearly reflected in the energy policy strategies of the ROI and NI to be implemented by 2020 (DCMNR, 2007; DETI, 2004). The ROIs obligation under EU initiatives is that 16% of its total primary energy consumption is to come from RES by 2020. This target will consist of contributions of 40% renewable energy in electricity (RES-E), 10% renewable energy in transport (RES-T) and 12% renewable energy for heat and cooling (RES-H) by 2020 (DCENR, 2009). NI has a renewable target of 40% renewable energy in electricity (RES-E) and 10% renewable energy for heat and cooling (RES-H) by 2020 (DETI,

[3]The EU has offered to increase its emissions reductions in 2020 to 30% and also advocated for a 50% global emissions (80% reduction by developed countries) by 2050 Eskeland et al. (2012)

2009). Under Kyoto[4] guidelines Ireland's share of EU GHG emissions must not exceed 1990 levels by 13% by 2012 (DEHLG, 2000). However in 2006, Ireland was 26.7% above 1990 levels SEI (2009) and recently Environmental Protection Agency (EPA) studies have shown levels to be above Kyoto targets in 2010 (EPA, 2010). The stated renewable energy electricity targets for both the ROI and NI will be predominately met with added onshore and offshore installed wind power capacity. There has been an extensive shift towards the promotion of clean renewable technologies for electricity generation. Over the next decade, on the island of Ireland public policy both domestic and European, provides the context within which there will be i) added pressure to improve electricity market efficiency in terms of generation and distribution, ii) a reduction in emissions through improved efficiency, and iii) a significant expansion in the employment of RES in the form of wind power.

2.3 Electricity Market Reform

The structural adjustment of EPS over the last 20 years worldwide has seen a significant shift in focus to liberalisation and regulated environment to enhance technical efficiency, financial viability and guard against the threat of dwindling fossil fuel resources and increasing fuel prices. The underlying rationale behind these reforms is to foster a shift from an inefficient monopolised vertically integrated industry to an competitive efficient electricity market environment (Trevino, 2008)[5]. Electricity market liberalisation entails one or a combination of the following inter-related steps: sector restructuring, introduction of competition in wholesale generation and retail supply, incentive regulation of transmission and distribution networks, establishing an independent regulator, and privatisation (Jamasb and Pollitt, 2005; Joskow, 1998).

The transmission and distribution networks of a country's electricity system are natural monopolies, and as such are less affected by the recent EPS liberalisation and unbundling. However, as electricity policy thinking has altered with private sector participants in the generation and retail sectors, regulatory reform and incentive regulation of electricity transmission and distribution networks have become more common (Farsi et al., 2007). Jamasb and Pollitt (2003) state the recent regulatory reforms have tended to move away from the traditional rate-of-return regulation towards incentive-based regulation models in the form of price or revenue cap regulation based on the RPI-X formula, which fosters cost savings and lower prices for the end-users. The RPI-X formula is discussed in detail in Section 2.4.5. Numerous countries are employing incentive regulation to promote efficiency improvement in electricity transmission and distribution systems. Incentive regulation incorporates a form of benchmarking or comparison of actual versus reference performance (Jamasb and Pollitt, 2001). Effective regulation in terms of

[4]The Kyoto Protocol is an agreement made under the United Nations Framework Convention on Climate Change (UNFCC) UNFCCC (1992) and countries that ratify this protocol commit to reducing their emissions of carbon dioxide CO_2

[5]The UK was the exemplar of electricity market reform, with the liberalisation process initialised in 1983 and restructuring impacts on the industry by 1989, demonstrating the importance of ownership unbundling and competition in generation and supply.

electricity transmission and distribution, network access, network interconnection and delivery prices, network investment and network service quality are paramount components of successful EPS liberalisation programs worldwide (Joskow, 2008). The energy market liberalisation process evident in Europe represents the world's most extensive cross-jurisdictional reform by integrating distinct national electricity markets (Jamasb and Pollitt, 2005). Certain individual EU countries have made significant progress towards electricity market liberalisation and integration, however the EUs goal of a single European electricity market remains an ongoing process and a target yet to be achieved.

2.4 Island of Ireland: The Test System

The island of Ireland is 84,421 km^2 located in the North West periphery of Europe. The island itself is dichomised politically into two jurisdictions ROI in the south and NI in the north. In 2011, the combined island population was approximately 6.4 million, 4.6 million in the ROI and 1.8 million in NI (CSO, 2011*a*; NISRA, 2011). Export led economic growth in the ROI during the 1990s resulted in a rise in Irish income per capita from two thirds of the EU average in the 1980s to above average levels but since 2000 the economy lost competitiveness and the rate of export growth slowed.

Gross Domestic Product (GDP) growth averaged 6% between 1995-2007, but economic activity has dropped sharply since the onset of the global financial crisis (CIA, 2012). Resulting consequences include the emergence of net outward migration and an unemployment rate of 14.4% by 2011 (ESRI, 2012). The export sector, dominated by foreign multinationals, has become a key component of Ireland's slow economic recovery (BOIERU, 2012). Between 1997 and 2007, the extent of economic growth in NI was less pronounced than in the ROI with the average rate of growth was 5.5% and the impact of the global recession less severe (NIE, 2012). Economic growth is the most significant factor in determining electricity demand and as such the ROI and NI encountered consistent growth in electricity demand over the last two decades until the onset of the global financial crisis stunted demand.

2.4.1 Liberalisation of Irish Electricity Markets

The primary objective of electricity market liberalisation is to establish a reliable electricity system at least cost to consumers by advocating competition in the generation and supply of electricity which fosters improved efficiency levels and innovation. Prior to the liberalisation of the Irish electricity markets, Electricity Supply Board (ESB)[6] and Northern Ireland Electricity (NIE)[7] were the dominant incumbent electricity entities responsible for the generation,

[6]The ESB was founded in 1927 with the establishment of a hydro power station at Ardnacrusha. ESB is a state owned 95% electricity company with the remaining shares held with employees operating in a liberalised and competitive market.

[7]NIE was founded in 1991, owns and operates the transmission and distribution infrastructure in NI and is a subsidiary of ESB Group.

transmission, distribution and supply of electric power in their respective ROI and NI electricity markets. Liberalisation of the Irish electricity market is contained in the Electricity Regulation Act, 1999, which implements the EU Directive 96/92/EC concerning common rules for the internal market in electricity (Electricity Act, 1999). This allowed new independent entrants into the electricity generation and supply market in the ROI. The liberalisation process occurred in phases with sections of the market being progressively opened for competition, with the market entirely open since 2005. In NI, the electricity market was privatised in 1992 and restructured when the generation capacity was sold to three companies[8] (NIAO, 1994). Post-privatisation the transmission, distribution and retails sections of the market remained under NIE control (Diffney et al., 2009).

Effective market liberalisation in both jurisdictions was hindered significantly by the relative small nature of the systems and the dominant positions of ESB and NIE, so an integrated electricity market regime for the island was proposed. The long term benefits to consumers would allow for a lower level of installed capacity for a given level of supply Fitzgerald (2004) whilst also facilitating more efficient dispatch and increased electricity generation competition in the two jurisdictions (Diffney et al., 2009). Consequently, in August 2004, the Commission for Energy Regulation (CER) and the Northern Ireland Authority for Utility Regulation (NIAUR) (the regulators) signed a Memorandum of Understanding (MOU) stipulating both parties agreed principles pertaining to the development of a single wholesale electricity market on the island of Ireland (NIAER and CER, 2004; AIP, 2004).

2.4.2 SEM Market Structure and Electricity Demand

The present Irish EPS encompasses two separate jurisdictions sharing a synchronous power system, the ROI in the south and NI in the north of the island. This relatively newly formed system entitled the AIG or the SEM has been operational since the 1st November 2007 and is governed by the Single Electricity Market Committee (SEMC) consisting of the CER in Ireland, the NIAUR and an independent member. The SEM initiative established a wholesale pool electricity market for the island, which subsequently formed the All-Island Market for Electricity (AIME). The SEM is operated and administered by the Single Electricity Market Operator (SEMO), which is a contractual joint venture between Eirgrid and the Systems Operator Northern Ireland (SONI), the Transmission System Operator (TSO) in the ROI and NI respectively (Both are Independent System Operator (ISO)). The Distribution System Operator (DSO)s in the ROI and NI are ESB Networks and NIE respectively. The SEM as all-island small isolated electricity market encompasses approximately 2.5 million electricity customers, 1.8 million in the ROI and 0.7 million in NI (Nepal and Jamasb, 2012). Table 2.1 illustrates the main electricity market operators in the ROI and NI. The SEM consists of a centralised gross mandatory pool market for any generator with an export capacity of more than 10MW, with 48 trading periods per day commencing with the first period at 06.00. Through the pool

[8]These companies were Premier Power, AES and Electricity Supply Board (ESB).

under a market clearing mechanism, all electricity generated on or imported onto the all-island system must be sold, and from which all wholesale electricity consumption on or export from the all-island system must be purchased (SEMO, 2010).

Table. 2.1: Electricity Sector Market Operators in the ROI and NI

	Republic of Ireland			**Northern Ireland**		
Market Segment	**Owner**	**Operator**	**Regulator**	**Owner**	**Operator**	**Regulator**
Generation	ESB and Others	ESB and Others	CER	ESB and Others	ESB and Others	NIAUR
Transmission System	ESB	Eirgrid	CER	NIE	SONI	NIAUR
Distribution System	ESB Networks	ESB Networks Ltd	CER	NIE	NIE	NIAUR
Suppliers	N/A	Various	CER	N/A	Various	NIAUR

The structure of the all-island gross pool market is displayed in Figure 2.2. In the all-island system conventional electricity generators receive three payments i) capacity payments relating to power plant's availability to provide electricity based on maintenance schedules and maximum output. These payments occur monthly and encourage continued future investment in generation, ii) the uplift price component pertains to payments through which generating units can recover their production costs such as start-up and maintenance costs, iii) shadow price refers to the marginal cost of producing electricity for a given period reflecting the cost of supplying an infinitesimal change in demand (O'Mahony and Denny, 2011; CSO, 2011*b*).

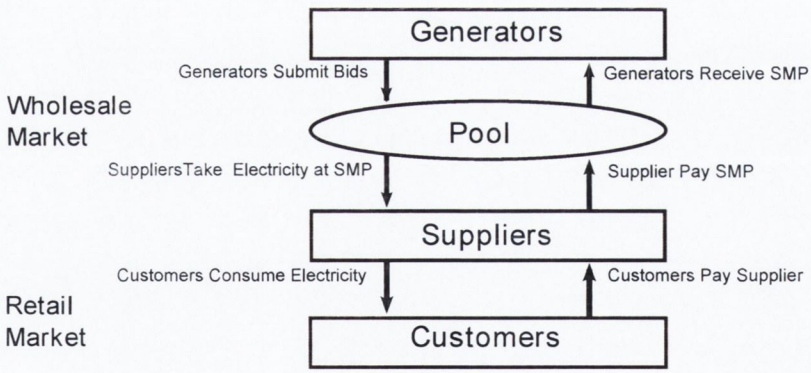


Fig. 2.2: Gross Pool Market Structure

In order to sell electricity into the SEM generators must submit day ahead cost bids in the form of Short Run Marginal Cost (SRMC) reflecting the full opportunity cost of the electricity produced which is the economic activity the generator forgoes to produce electricity and the uplift element (Conlon, 2010). Based on these generator costs and electricity customer demand the System Marginal Price (SMP) is formulated by the Market Operator (MO) SEMO reflecting the

SRMC of the marginal generating unit, a single price for each half hour of electricity. Generators receive the SMP for their scheduled dispatch quantities, capacity payments for their actual availability, and constraint payments for changes in the market schedule due to system constraints. Suppliers purchasing energy from the pool will pay the SMP for each trading period, capacity costs, and system support charges. The SMP is composed of the uplift and shadow price elements and is paid daily to generators.

The SEM is designed around a single unconstrained marginal pricing structure, i.e. the price determined will ignore transmission and reserve constraints but respect generator physical abilities. The SEM market design has features reminiscent of markets in other jurisdictions (most notably Nordpool, the Eastern Australian market and the former British pool) but is a unique dual currency (£GBP and €) inter-jurisdictional market, the first of its kind in the world (Conlon, 2010). Since its inception, the SEM structure has enhanced competition, added transparency, enabled greater choice for customers on the island of Ireland whilst also fostering the use of renewable, sustainable or alternative energy sources, exerting downward pressure on customer prices, providing security of supply and environmental benefits. Peat and renewables are supported separately through a Public Service Obligation (PSO) levy implying they have a regulatory mandatory purchase agreement which stipulates all electricity generated by these units must be consumed regardless of their marginal costs (O'Mahony and Denny, 2011). Peat and renewable energy electricity is supplied via the pool. The PSO levy is discussed further in Section 2.4.7.

All-island peak electricity demand in 2011 was 6,504MW dichotomized into 4,736MW for the ROI and 1,805MW in NI. Electricity consumption for the EU 15 countries is represented in Figure 2.3, clearly evident is the diminutive status of Ireland's and Luxembourg's electricity demand relative to the other countries (IEA, 2012). Ireland experienced economic growth rates during the 1990s which were unprecedented, either historically or in other European countries (Kelly and Everett, 2004). This coincided with continuous accelerated electricity demand growth for the same period. Electricity consumption rose by over 5% per cent a year between 1990 and 2007 (Diffney et al., 2009). Research into the electricity economic growth nexus has seen extensive focus in recent years (Adom, 2011; Altinay and Karagol, 2005). Irish electricity consumption has seen a 408% increase since 1973, an annual positive percentage change of 3.9%, considerably higher than the Organisation for Economic Co-Operation and Development (OECD)[9] European average of 2.3% per annum (IEA, 2012).

[9]Organisation for Economic Co-Operation and Development (OECD)- Europe comprises of all European Union Member countries, i.e. countries in EU15 plus the Czech Republic, Hungary, Iceland, Norway, Poland, Slovak Republic, Switzerland, Turkey.

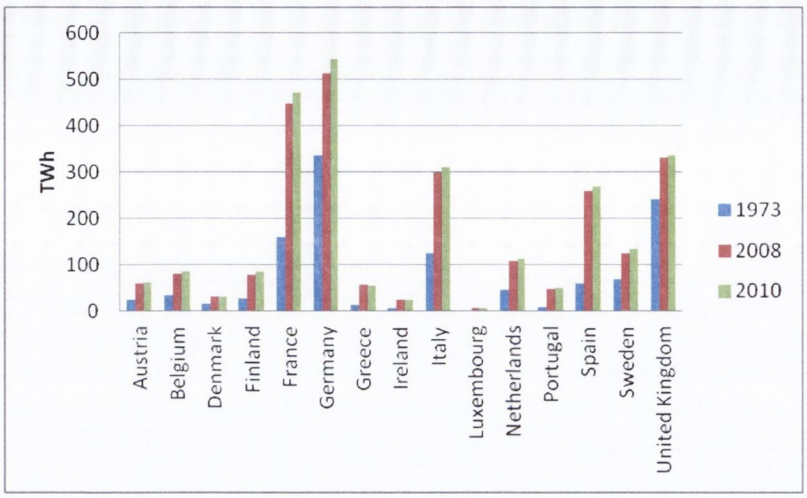


Fig. 2.3: Comparison of Electricity Consumption in the EU 15

Demand forecasts are initially compiled separately for the ROI and NI, and subsequently amalgamated to form all-island energy and peak demand forecasts. In the Republic, forecasts of electricity demand are appraised by the System Operator Eirgrid and divulged (Eirgrid, 2008). Annual electricity demand forecasts are based on the future growth predictions in the economic parameters of Gross Domestic Product (GDP) and Personal Consumption of Goods and Services Index (PCGS) (SONI, 2012). Acknowledging the impact of the global economic crisis in curtailing electricity demand since 2008 and the continued high degree of economic uncertainty into the future, it is anticipated that demand levels in 2012 will only rise moderately before electricity demand resumes its upward trend in 2014. Three differing growth scenarios exhibiting low (pessimistic), medium (realistic) and high (optimistic) future electricity demand are proposed accounting for current economic outlook predictions. Figure 2.4 illustrates the combined all-island Total Energy Requirement forecasts for the two jurisdictions.

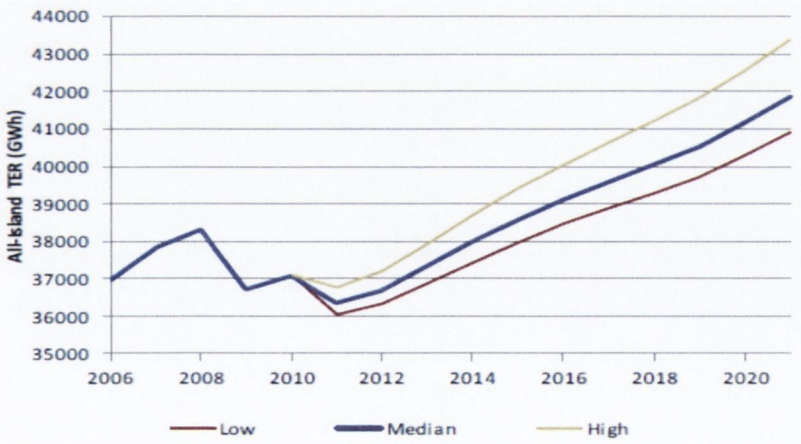


Fig. 2.4: All-Island Total Energy Requirement Forecast SONI (2012)

The weekly peak demand for the past three years is presented in Figure 2.5. Observing the graph it alludes to a greater magnitude of demand in the early weeks of the year, followed by low demand in the summer months with higher demand returning as winter sets in. The trend is similar for each year, however growth in peak demand, year on year, can be seen quite clearly. Electricity demand fluctuates by second, minute, hour, week, month and season over every year into the future planning horizon and is induced by economic conditions, weather conditions and consumer usage patterns (Foley, 2010). (Denny, 2007; Eirgrid, 2008) illustrate for the ROI, peak demand occurs during winter weekday evenings and minimum demand occurs during summer weekend night-time hours. NIs electricity demand follows a similar pattern to the ROI (SONI, 2012).

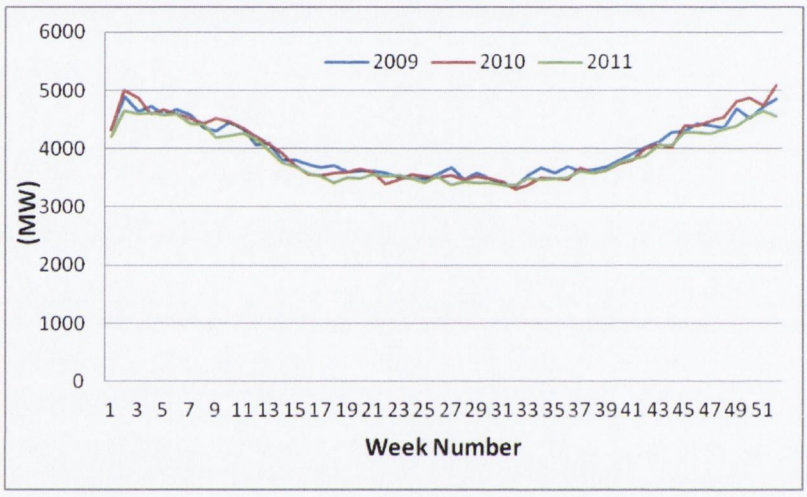


Fig. 2.5: Weekly Peak Demand for 2009, 2010, 2011

2.4.3 Current and Future Generation Portfolios Within the SEM

As of August 2012, the registered capacity of the all island SEM was 10,293MW with thermal plants contributing 8,698MW (79%), wind 1,698MW (16%), pumped storage 292MW (2.8%), hydro 222MW (2.1%), biomass 13MW (0.1%) with 103 registered participating generation units (SEMO, 2012). Placing the SEM size into context, Great Britain (GB)s power system National Grid United Kingdom (NGUK) is nine times larger than the all island SEM and the Nordel power system in Scandinavia is 30% larger than NGUK (Foley, 2010). The SEMs annual electricity generation peaked in 2008 at 38GWh and forecasts for 2012 estimate the requirement will be 27,500GWh in the ROI and between 9,000 and 10,000GWh in NI. The AIG system has an existing installed dispatchable capacity of 9,356MW, of which 6,585MW is located in the ROI and 2,771MW in NI (SONI, 2011). This indicates supply is significantly exceeding demand. The all-time system peak demand for the ROI was 5,090MW, recorded on December 21st 2010 (Davy, 2012). Malaguzzi Valeri and Tol (2006) state Ireland's generation plant portfolio is older than average, which leads to one of the lowest average availability rates in Europe. However,

Smith (2010) state improved performance of the electricity sector in recent years is due to a number of factors i) the introduction of highly efficient Combined Cycle Gas Turbines (CCGT) generating plants, ii) the phasing out of older, oil and peat-burning generation plant, and iii) increased penetration of natural gas in the generation fuel mix. The SEM is powered using a combination of fossil fuels (coal, oil, peat and natural gas) and renewable sources (hydro, wind, biomass). Figure 2.6 illustrates the current installed generating mix on the island of Ireland. The generation characteristics of the SEM is composed of a lack of domestic energy resources and a high dependency on imported energy resources which peaked at 80% in 2008 (Smith, 2010). All coal and oil is imported and the SEM is entirely dependent on the UK for gas imports (Limited, 2010).

The significant dependency on imports for electricity generation and the SEMs lack of interconnectivity with other electricity markets, leaves the all island SEM exposed to supply disruptions and potential price increases in the current economic climate. In recent years, EirGrid and SONI have conducted pioneering research to simulate the dynamic behaviour of the SEM power system and examine the technical challenges with significant volumes of wind power integration. Figure 2.7 depicts the expected all island SEM generation portfolio for 2020 compared with 2010. The underlying characteristics of the all-island generation portfolio for 2020 incorporate significant reductions in thermal fuel sources such as peat, coal and oil, significant increases in CCGTs, along with high levels of wind penetration of the transmission and distribution systems, added interconnection with electricity markets within the France United Kingdom Ireland (FUI) region.

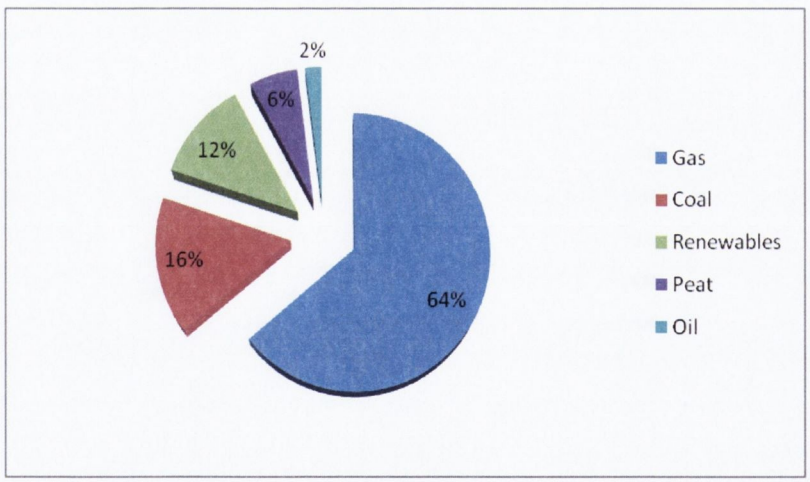


Fig. 2.6: All-Island Single Electricity Market Fuel Mix

These underlying generation portfolio and system characteristics proposed in SONI (2011) are evident for numerous studies attempting to model and simulate the future SEM generation portfolio. DCENR and DETI (2008) focused on producing feasible wind penetration scenarios for high renewable energy penetration by the year 2020. Six portfolios with differing combinations

of renewable and conventional technologies were proposed. Wind energy penetration was the predominant renewable resource in each portfolio. SEI (200) stipulate for 2020 the principal areas of growth are in natural gas and renewables, both observing significant increases in installed capacity with forecasts for gas powered plants contributing 71% to the generation fuel mix by 2020. A synchronous generator is a device that converts kinetic energy to electrical energy whilst non-synchronous is composed of wind generation and interconnection imports.

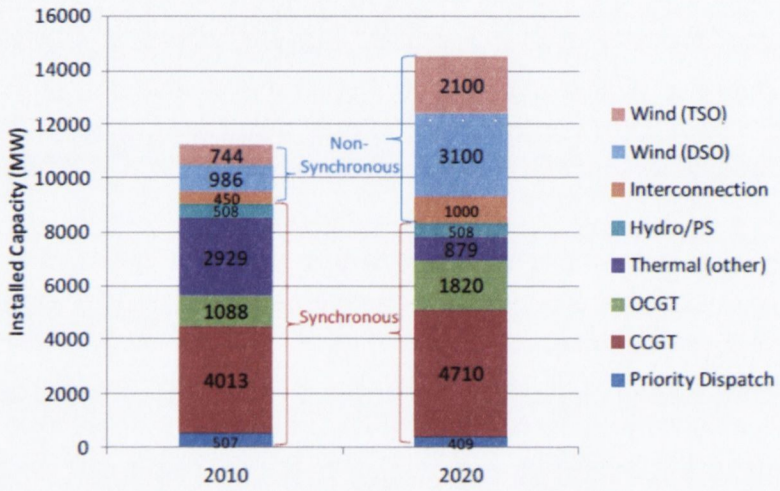


Fig. 2.7: All-Island Portfolio by Generation Type 2010-2020 SONI (2011)

2.4.4 Interconnection within the SEM

A single integrated EU market for electricity is a stated aim of the European Union. The EU has lobbied that electricity markets should be more interconnected creating regional markets, as opposed to ones limited by state borders. In 2006, the European Regulators Group for Electricity and Gas (ERGEG) launched the Electricity Regional Initiative (ERI) with the premise of accelerating the integration of Europe's national electricity markets[10]. The ERI created seven regional electricity markets in Europe, as an interim step to established a single-EU electricity market (ERGEG, 2006). The Irish electricity system is a component of the FUI region. Prior to 1995, the respective ROI and NI electricity systems operated in isolation, since then a single synchronous system has formed connected by a number of Alternate Current (AC) lines - two 275kV circuits, each with capacity of 600MW, length 50km and a further two 110kV circuits, with a capacity of 120MW each located along the interface between the ROI and NI (Lalor, 2005; Eirgrid, 2011-2017).

The purpose of these circuits is to provide support to either system for certain conditions or in the event of an unexpected circuit outage. A 400kV electricity transmission link connect-

[10]Roadmap papers (Creation of regional electricity markets, Consultation Paper of June 2005 and Conclusions Paper of February 2006) are available on www.ergeg.org.

ing Tyrone in NI and Meath in the ROI is being developed by EirGrid and NIE. It is expected to be operational from 2017, adding to system security and the flexible operation of the SEM. At present, the Irish electricity market is only lightly interconnected and as such the market is considered a small isolated system on the periphery of Europe. A single High Voltage Direct Current (HVDC) link between NI and Scotland connects the all-island SEM and the NGUK. This 500MW interconnector entitled the "Moyle interconnector" is limited by contractual arrangements and technical issues to 80MW export capacity, 450MW of imports in the winter, 400MW imports in the summer and accounts for 4.8% of total SEM generation capacity (Foley, 2010; Eirgrid, 2009, 2011*a*). A second HVDC the East West Interconnector (EWIC) owned and operated by Eirgrid with 500MW capacity commenced operation in late 2012. The construction of the EWIC between Dublin in the ROI and North Wales in GB at a cost of €600million provides numerous benefits to the all-island SEM in the form of i) enhanced security of supply ii) encourages the growth of renewable energy sources iii) facilitates increased competition in the electricity sector and iv) allows the export and import of surplus electricity (Eirgrid, 2010, 2009). OFGEM (2010) states two further interconnectors between the SEM and GB are planned, each with a capacity of 350MW.

Numerous studies have been conducted to establish the effects, impacts, benefits and drawbacks of added interconnection between the SEM GB and other electricity systems (Lynch et al., 2011; Eirgrid, 2009; Diffney et al., 2009). DCENR and DETI (2008) establish six future 2020 generation portfolios for investigation comprising of a range of different renewable and conventional technologies in varying compositions. The construction of a second interconnector between the SEM and the GB systems is a precondition for the feasibility of the portfolios. Malaguzzi Valeri (2009) examines interconnection between the SEM and GB in terms of welfare and competition concluding a number of points i) Ireland gains GB loses with interconnection with Irish consumers being the group that gains the most whilst Irish producers lose the most, ii) the socially optimal level of interconnection is higher than the level of interconnection likely to be delivered by market forces and iii) in order to establish a single Ireland GB market adopting the Residual Supply Index (RSI) developed by Sheffin (2002) requires 1,700MW of interconnection.

Nepal and Jamasb (2012) state current levels of electricity market integration between SEM and GB is just 17% indicating considerable potential to improve market integration via added interconnections. The findings indicate benefits of downward pressure on domestic electricity prices in the island due to increased cross-border electricity trade, increased security of supply and reduced price volatility. The study by Eirgrid (2009) researches and investigates the economic feasibility of interconnection between the all-island SEM and GB or France in terms of production cost savings and capacity benefits. The findings indicate a compelling economic argument for the EWIC, and a further third and fourth 500MW capacity interconnectors between the SEM and GB up to 2020 and even more so for 2025 particularly when a high renewables

scenario is contemplated. Also added interconnection between the SEM and France is economically viable in terms of capacity and production cost reductions.

2.4.5 Regulation within the SEM

In the absence of competition, regulation of the naturally monopolistic activities of transmission and distribution is required to ensure fair prices for generators, customers and improve efficiency of electricity markets (Jamasb and Pollitt, 2003). The all-island SEM is regulated by the SEM Committee, consisting of the CER in ROI and the NIAUR in NI and an independent member. The CER regulates in the ROI whilst NIAUR regulates in NI and both are also known as Regulatory Authority (RA). The Regulatory Authority's (RA) employ price and revenue cap incentive regulation based on the RPI-X formulae[11]. This form of regulation is intended to replicate the discipline of competitive market forces. In the ROI the CER conducts a periodic revenue review every five years to determine the revenues that Eirgrid the Transmission System Operator (TSO) and ESB networks the Distribution System Operator (DSO) may earn in order to cover the costs of providing the network service.

The prices are refined annually with the latest Price Review 3 (PR3) extending from 2011 to 2015 setting the total allowed revenues for the TSO and DSO over the period. Each year CER stipulates the tariffs and charges placed on generators, customers in the form of Transmission use of System (TUos) and Distribution use of System (DUos) (CER, 2010). The NIAUR regulates by setting price controls which are typically reviewed every five years with the next price control Regulatory Period 5 (RP5) extending from 2012-2017. The current and future price structure implements an RPI-X type regulation control, designed to incentivise NIE Transmission and Distribution to manage its Operating Expenditure (OPEX) and Capital Expenditure (CAPEX) costs efficiently. RPI-X is a form of incentive regulation which sets a base revenue allowance for NIE transmission and distribution to cover efficiency costs while delivering required outputs (NIAUR, 2012).

2.4.6 Wind Power Generation within the SEM

FESTA (2004) state in relation to its population, Ireland has significant renewable energy potential, more than any other country in the EU. In both the ROI and NI government policy exists which targets the amount of electricity sourced from renewables. RESs in electricity in the all-island SEM is effectively driven by policy in the ROI (Diffney et al., 2009). Energy Policy in the ROI commenced with the governments White Paper on energy in 2007 which focused on three core elements i) security of supply ii) environmental sustainability and iii) economic competitiveness (DCMNR, 2007). Renewable Energy targets were established to generate 13.2% of

[11] RPI-X regulation: CPI-X, or, RPI-X refers to the form of price cap regulation developed in the U.K. and utilised in many countries. The price automatically adjusts for the previous year's Consumer Price Index (CPI) or Retail Price Index (RPI) and for expected efficiency improvements (X) during the time period the price adjustment formula is in place.

electricity from RES by 2010 extending to a further target of 33% by 2020. The latter target was subsequently revised upwards to a share of 40% of RESs contributing to electricity by 2020. The 2010 target was exceeded with a 14.8% RES figure. This growing trend is expected to extend into the coming decades (SEAI, 2012). In the NI context, (DETI, 2004, 2008, 2010) state the target for electricity consumption from RES is 12% by 2012 extending to 40% by 2020. The adopted policy renewable support mechanisms to achieve these stated targets are Renewable Energy Feed in Tariff (REFIT) in the ROI and Northern Ireland Renewables Obligation (NIRO) in NI which will be discussed in depth in the forthcoming Section 2.4.7.

For both jurisdictions the ROI and NI wind energy power will provide the pivotal contribution to achieving stated RES targets, which will require between 3,500MW and 4,000MW of installed wind capacity in the ROI and 1,342MW in NI by 2020 (SONI, 2011). Climate change and environmental policy, both domestic and EU, will drive the extensive deployment of wind energy generation on the all-island SEM in the coming decade. The share of electricity generated from renewable energy sources in 2011 was 17.6% with wind energy contributing 13%, hydro 2.6% and the remaining 2% from bio-energy sources (SEAI, 2012). The installed capacity of wind power generation in the ROI has seen extensive growth in the last two decades increasing from 145MW at the end of 2002 to 1,631MW in 2011 whilst NIs installed wind capacity has risen from 37MW to 398MW for the same period (SONI, 2011). Of the installed wind capacity in the SEM, 767MW and 860MW of wind farm capacity are connected to the ROI transmission and distribution systems respectively[12]. 370MW of wind power capacity is connected to the distribution system in NI and only 27MW connected to the NI transmission system (Davy, 2012). Figure 2.8 depicts the growing share of electricity generated from wind since 1997. Electricity generated from wind in 2011 was 438,025GWh representing an increase of 56% on 2010. The is due to increasing installed capacity.

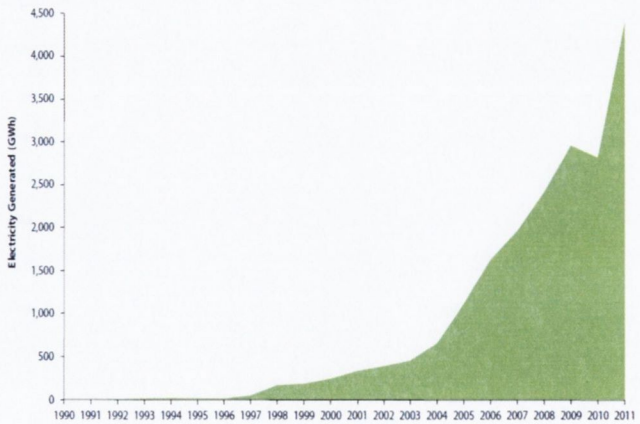
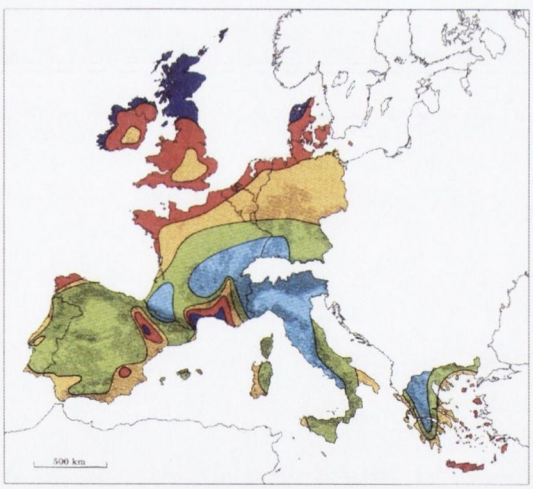


Fig. 2.8: Electricity Generated from Wind Energy (SEAI, 2012)

[12]Transmission system is electricity produced by electrical generating stations, either by fossil fuels or renewable energy generation onto the distribution system. Distribution is the movement of that electricity through power lines, substations and small transformers to the consumer.

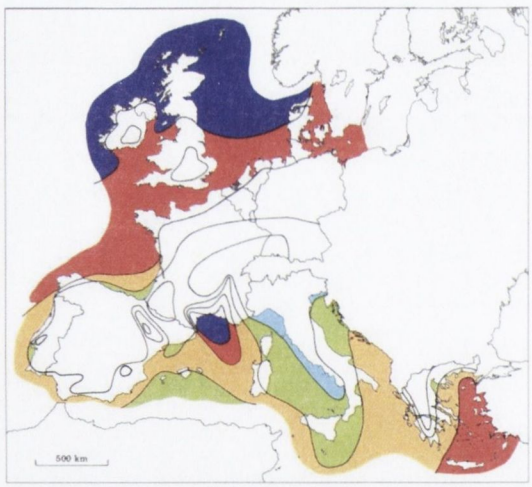
Wind energy power represented 15.7% of gross electrical consumption in 2011. Electricity generated from wind in 2011 was 438,025GWh representing an increase of 56% on 2010. The is due to increasing installed capacity. Wind energy power represented 15.7% of gross electrical consumption in 2011. Observing the graph, it is evident a slowdown in wind farm development occurred in 2007 and 2008, primarily due to uncertainty regarding the REFIT scheme and access to wind farm finance (SEAI, 2012). Numerous factors exist that are conducive to wind power growth i) technology advancements reducing the cost of wind power by 80% over the past 30 years ii) renewable energy support mechanisms and ii) favourable exogenously defined wind resource (Wiser and Bolinger, 2006). Significant research has been conducted to estimate Ireland's wind resource, ESBI and ETSU (1997) estimated that the feasible wind energy resource in Ireland is in the range of 8 to 12GW. Others state the available all-island wind energy resource is estimated based on technological constraints to be 613TWh/year SEI (2004*a*) with approximately 55.5 TWh/year economically viable by 2020 (DETI, 2000).

Foley (2010) states the Irish wind resource is 20GW. SEAI (2011*b*) state with favourable wind development policy and infrastructure, Ireland can achieve deployment of between 11GW - 16GW of onshore wind and 30GW of offshore wind by 2050 reflecting a potential economic value of €15 billion. Figure 2.9 clearly indicates Ireland's strong, favourable, relatively under utilised onshore and offshore wind energy resource, particularly along the west coast of Ireland. Acknowledging the optimistic renewable energy targets in Europe and particularly ROI, extensive research has focused on the implications for the all-island SEM of increased wind power penetration levels (CER, 2009).



Wind resources[1] at 50 metres above ground level for five different topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400



Wind resources over open sea (more than 10 km offshore) for five standard heights

	10 m		25 m		50 m		100 m		200 m	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Fig. 2.9: European Wind Atlas - Onshore and Offshore (Troen and Petersen, 1989)

Advocates for increased wind power penetration levels argue it is the resounding answer to depleting fossil fuel resources (Brown, 2006). Whilst opposition arguments centre on the high costs imposed on the power system threatening stability with added wind generation (Etherington, 2006). According to SEI (2004*c*) accessible, feasible wind energy generation penetration levels for Ireland could reach 10000MW of installed capacity by 2020.

2.4.7 Renewable Support Mechanisms within the SEM

Foley (2010) states levies, taxes and other charges are imposed on consumers to support the employment of renewable energy sources and the burden the balancing costs. The technique adopted to incentivise electricity production from renewable energy sources is a system of support payments. The cost of the support scheme is then passed on to Irish consumers in the form of a PSO levy (Devitt and Malagauzzi Valeri, 2011). The PSO levy relates to the purchase of peat generated electricity output, in the interests of security, diversity of supply, and the output of renewable energy generating stations (DETI, 2005*a*). The PSO levy is designed to support the national policy objectives of security of energy supply, the use of indigenous fuels (e.g. peat) and of the use renewable energy sources in electricity generation (SEAI, 2011*a*). The proceeds of the levy are used to recoup, inter alia, the additional costs incurred by suppliers in sourcing a proportion of their electricity supplies from such generators. For the 2012/2013 PSO levy period CER propose a PSO levy amounting to €146.81 million, an increase of approximately €54.7 million from the previous year,which has been brought about primarily by lower forecast SEM market price (CER, 2012). The following market support mechanism exist to promote electricity generation from renewable energy sources.

1. **Alternative Energy Requirement (AER) Scheme**
   The Alternative Energy Requirement (AER) scheme commenced operation in 1996 incorporating a competitive formal application tendering process for prospective renewable energy generators to supply electricity to the ESB under a Power Purchasing Agreement (PPA) of up to 15 years in duration. The ESB was compensated for additional costs incurred from a PSO levy funded by consumers. The programme as a whole performed poorly with less than expected electricity production from renewables (O'Gallachoir et al., 2006). The AER accounted for about 532MW of wind investment support, designed to last 15 year. The last round of competitive tendering under the AER was in 2005 (Devitt and Malagauzzi Valeri, 2011) .

2. **Renewable Energy Feed in Tariff (REFIT) Scheme**
   The REFIT scheme was launched in 2006 replacing the sub-optimal AER programme. It represents the primary support mechanism to foster investment in new renewable electricity generation in Ireland. Renewable generators in the form of wind, hydro and biomass adopt Power Purchasing Agreement (PPA) with any licensed electricity supplier (i.e. not just ESB) under 15 year fixed price payment conditions for the production of renewable electricity. As in the AER programme suppliers are compensated by way of a balancing

payment for the net additional costs incurred by means of the PSO levy support mechanism. Numerous older established wind farms in the ROI are still supported under the terms of the older Alternative Energy Requirement (AER) Scheme. The REFIT 1[13] prices per megawatt hour DCENR (2012) are provided in Table 2.2. There is currently 1,380MW of REFIT renewable generation capacity supported in the 2012/2013 PSO levy.

Table. 2.2: REFIT Prices per Megawatt Hour

Year	Inflator	Large Wind (€s)	Small Wind (€s)	Hydro (€s)	Biomass Landfill Gas (€s)	Other Biomass (€s)
2008	1.049	63.739	65.976	80.513	78.276	80.513
2009	1.041	66.353	68.681	83.814	81.485	83.814
2010	1	66.353	68.681	83.814	81.485	83.814
2011	1	66.353	68.681	83.814	81.485	83.814
2012	1.026	68.078	70.467	85.993	83.604	85.993

3. **Northern Ireland Renewables Obligation (NIRO) Scheme**
   Since 2005, the NIRO scheme is the main policy support mechanism for developing and encouraging added renewable electricity generation capacity in NI. NIRO incorporates a legal obligation on all licensed NI electricity suppliers to source an increasing proportion of electricity from RES. Obligations are determined as a percentage of total electricity supplied. Compliance with stated obligations is attained through Renewable Obligation Certificates (ROC)s which are green certificates issued by the Office of Gas and Electricity Markets (OFGEM) to generators for each MWh of renewable energy production. Obligations not covered by ROCs require a buy-out price per each MWh of the obligation not met by a ROC, for 2011/12 this is £38.69 (DETI, 2005*b*; OFGEM, 2012). The cost of the NIRO is borne by electricity consumers.

As installed wind power increases, the PSO levy will rise resulting in higher REFIT costs to electricity consumer end users. Also REFIT payments are variable and linked to increases in Consumer Price Index (CPI) whilst ROC payments are adjusted in line with the Retail Price Index (RPI) reflect the state of the economy. Foley (2010) states for these reasons perhaps the redefining and redesigning of the REFIT, the PSO levy support mechanism and the SEM structure is warranted.

[13]Two further schemes have been operational since early 2012, REFIT 2 is designed to incentivise the addition of 4,000MW of new renewable electricity capacity to the Irish grid from onshore wind, hydro and biomass landfill gas technologies whilst REFIT 3 is designed to incentivise the addition of 310MW of renewable electricity capacity to the Irish grid (SEAI, 2012).

2.5 Summary

The issues related to the global energy challenge and global warming are now firmly entrenched in the political domain and policy makers worldwide have acknowledge the importance of mitigating GHG emissions. As such the EU and the island of Ireland have embarked on ambitious 2020 energy efficiency programmes to curb the detrimental effects i) of climate change, ii) of increased GHG emissions, and iii) of fossil fuel dependency. The programmes most importantly focus on increased energy efficiency competition in the electricity sector. The merits and observed effects of electricity market reform in the European and Irish contexts are discussed. The recently formed all island SEM encompassing two jurisdictions the ROI and NI is presented along with the energy demand, supply, underlying structure and regulation characteristics of the SEM. The added benefits of further interconnection within the FUI electricity market region are outlined and all island SEM renewable energy policies driven by environmental, security, and social concerns are discussed, in the context of achieving stated ROI and NI energy efficiency objectives through added installed wind capacity.

This chapter provides the underlying dynamics and impacting policies objectives on the all-island SEM which forms the test system for the DEA efficiency application. The complexity and significant challenge facing EPS of the 21st century can not be understated. Societal obligations stipulate this pervasive technological system must transform into an efficient, reliable, sustainable and environmentally conscious system. This will require a shift from the present centralised, base loaded, fossil fuel paradigm towards a dispersed, multi generation technological, renewables supported energy efficient EPS of significantly greater complexity. This complex issue will require a multi-faceted technological approach supported by forward thinking energy efficient incentive frameworks. This forms the basis of the current research and the focus on the all island SEM system.

CHAPTER 3

Economic Efficiency and Data Envelopment Analysis (DEA)

3.1 Introduction

The focus of this Chapter is to provide a background to economic efficiency measurement and emphasise the primary motivations for employing DEA in attempting to achieve the research objectives. The Chapter defines the concepts of economic efficiency and productivity, the techniques for their evaluation and reviews the main literature contributions to their evaluation. A comprehensive review of the literature relating to DEA applications to EPS is presented. Stochastic Frontier Analysis (SFA) as an alternative to the adoption of DEA is also introduced and the merits of both frontier production techniques are defined and discussed.

3.2 Comparison of Appraisal Techniques

This section presents three economic appraisal techniques i) Cost Benefit Analysis (CBA), ii) Multi Criteria Analysis (MCA), and iii) DEA. A brief definition and the salient capabilities and limitations of each technique follows. Table 3.1 presents a brief summary of the contrasting appraisal techniques. DEA addresses the significant limitations associated with CBA and MCA and as such has been adopted in this thesis for the economic efficiency measurement of the EPSs.

CBA is rooted in applied welfare economics and entails organising and analysing data as an aid to decision making. The underlying rationale for CBA is rational choice i.e. a rational agent will weigh up the costs and benefits of any proposed activity and will only undertake the activity if the benefits outweigh the costs (Clinch, 2003). These costs and benefits are monetised and the ratio of total benefits to overall cost is investigated i.e the Benefit Cost Ratio (BCR). CBA is predominately employed for public decision making policy proposals, programs, and projects, (e.g. include dams, bridges, traffic circles, libraries, drunk driving laws). Tudela et al. (2006) states MCA is a an alternative appraisal technique which deals with the limitations of CBA.

Table. 3.1: Capabilities and Limitations of Appraisal Techniques

Appraisal Technique	Capabilities	Limitations
Data Envelopment Analysis (DEA)	Facilitates multiple input and multiple output models, relevant for electricity power sector; DEA software assigns weights for each input and output to maximise the efficiency of each DMU, therefore avoiding the MCA pitfall of selecting weights and deciding how these weights are combined to give an overall efficiency score; DMUs (i.e different power plants) are directly compared against a peer or combination of peers; Inputs and outputs can have different units of measurement, therefore avoiding the CBA pitfall of evaluating monetary values for impacts that are difficult to ascertain; and Identifies how inefficient each DMU is and stipulates corrective measures to become efficient.	There are a number of potential pitfalls and errors associated with using DEA see Dyson et al. (2001) e.g limitations on the number of inputs and outputs depending on the number of DMUs, important that the DEA software is used correctly and the inputs -outputs are valid and true; Can establish how well each DMU is performing compared to other DMUs being analysed but not compared to "theoretical maximum"; and DEA software creates a separate linear program for each DMU hence large problems can be computational intensive.
Cost Benefit Analysis (CBA)	Gives a clear and transparent evaluation in a manner that is easy to understand i.e benefit cost ratio; Compares all costs and benefits using a single unit value (money); and It can be used to show the economic efficiency i.e establish which is most profitable;	Very difficult to monetise all the impacts of electricity power systems in particular benefits and costs that do not have economic values e.g mean site elevation, customers, customer density; Values are open to interpretation and bias and are often misrepresented leading to unrealistic evaluation of particular benefits and costs; and Difficulties defining appropriate time horizons over which costs and benefits are measured and a suitable discount rate.
Multi Criteria Analysis (MCA)	Can incorporate quantitative and qualitative analysis of economic, environmental and social impacts and, therefore, the results can be more informative than quantitative analysis alone; Avoids the pitfall of evaluating monetary values for impacts that are difficult to ascertain i.e. exogenous impacts; and Objectives led - Output is an overall project score reflecting how well the alternative has met the project objectives;	Can be difficult identifying and defining the impacts to be included; Difficulties in specifying the measurement method and how each will impact will subsequently be assigned a score; Issues surrounding the use of weights and how these might be obtained in practice - can lead to biased results; and Variations in how the scores and weights are combined to give an overall project score;

The significant difference is the MCA incorporates qualitative and quantitative parameters and is objectives led whereas CBA only analyses monetised values of costs and benefits Nijkamp et al. (2002); Tudela et al. (2006). DEA is a non-parametric linear programming technique that provides an objective assessment of the relative efficiency of similar DMUs and will be

discussed in detail in the forthcoming sections. This section is intended to be summative rather than exhaustive. For more on the capabilities and limitations of each appraisal technique see (Cooper et al., 2007; Browne and Ryan, 2011; Grant-Muller et al., 2001; Nijkamp et al., 2002). The current research is evaluating the efficiency of existing operating entities/firms and thus ex-ante assessment techniques such as CBA or MCA do not belong to the scope of the research Kovacs and Bona (2009).

3.3 Economic Efficiency and Productivity

Economic literature accepts the assumption that firms[1] operating in the same industry do not perform equally well and that underlying differences exist between a firms actual and theoretical potential levels of technical efficiency. The measurement of a firms level of efficiency necessitates the calculation of the maximum possible output, and literature has evolved that attempts to estimate a frontier production function, with the word "frontier" emphasising the notion of maximality which it embodies (Schmidt, 1985). Production analysis, firm performance and efficiency measurement has received extensive attention in operations research and economic literature as firms strive to improve productivity and efficiency (Forsund and Sarafoglou, 2005; Emrouznejad et al., 2008). Reasons for this body of research were pertinently summarised fifty years ago:

"The problem of measuring the productive efficiency of an industry is important to both the economic theorist and the economic policy maker. If the theoretical arguments as to the relative efficiency of different economic systems are to be subjected to empirical testing, it is essential to be able to make some actual measurements of efficiency. Equally, if economic planning is to concern itself with particular industries, it is important to know how far a given industry can be expected to increase its output by simply increasing its efficiency, without absorbing further resources" (Farrell, 1957).

Productivity and efficiency are key entwined concepts underpinning the foundations of economic theory. The terms productivity and efficiency frequent the public domain and are often thought of as interchangeably terms. However, this can be misleading. Although closely related terms, they have two distinct interpretations. Productivity is an absolute concept that incorporates efficiency. It is a descriptive measure of performance technically defined as a ratio of outputs to inputs, it can alter through time due to technological change (new technologies) and efficiency change (improvement of existing technologies). Thus, productivity measurement incorporates efficiency measurement (Kortelainen, 2008).

Efficiency conversely is a relative concept, that relates to the comparison of the observed and optimal value of productivity or other performance measure (such as cost or profit). This implies

[1] Hereafter, "firm" refers to production units in general, without discriminating between private enterprises and other type of production organizations such as public sector firms and non-for-profit firms.

that in contrast to productivity, efficiency is adjudged to be a relative performance measure that requires one to stipulate how to measure the optimal level of performance (Mukherjee, 2008). (Farrell, 1957) introduced the first modern literature on efficiency measurement and the estimation of production frontiers[2]. The research focus on growth and productivity intensified in the immediate decade after World War II, culminating in (Solow, 1957)[3] influential paper at macro level. Simultaneously, at micro level, Farrell transformed efficiency and productivity analysis.

3.4 Concept and Measurement of Technical Efficiency

In his seminal paper "The Measurement of Productive Efficiency" Farrell (1957) pioneered an ingenious approach to efficiency and productivity analysis at the micro level[4], that focused on two considerations: (i) how to define efficiency and productivity, and (ii) how to calculate the benchmark technology and efficiency measures. Central to Farrell's approach was the possibility of inefficient operations, indicating an adoption of a frontier production function[5] concept as the benchmark, as opposed to the conventional assumption of average performance underlying the production function (Forsund and Sarafoglou, 2005).

Farrell (1957) surmised that a firms Economic Efficiency[6] could be dichotomised into two components i) *Technical component* reflecting the physical efficiency of the input output production transformation and ii) *Allocative component* reflecting the economic efficiency of optimal factor allocation (price efficiency) (Kopp, 1981; Coelli et al., 1998). Quantification of these components is paramount to efficiency analysis in three ways. One, as measures per se, they facilitate comparisons across similar economic units, i.e. indicate relative efficiency. Secondly, when measurement reveals variations in efficiencies among economic units, further analysis can be undertaken to identify the factors causing such variations. Thirdly, such analyses contain policy implications for the improvement of efficiencies (Kalirajan and Shand, 1999). Farrell (1957) acknowledges the contributions and influence of Koopmans (1951)[7] formal definition and Debreu (1951)[8] measure of technical efficiency but fails to recognise the impact of (Shephard,

[2]A production frontier (PF) is a curve or a boundary which shows the combinations of two or more goods that can be produced whilst using all of the available factor resources efficiently.

[3]Robert Solow investigated economic growth and acknowledged the importance of technological progress by attempting to decompose Gross Domestic Product (GDP) growth into growth attributable to inputs into the aggregate production function (aggregate capital and labour)

[4]In microeconomic theory a production function is defined in terms of the maximum output that can be produced from a specified set of inputs, given the existing technology available to the firms involved

[5]Also known as production technology and production possibility set

[6]Modern economic literature allows the term Economic Efficiency to interchange with total overall efficiency, productive efficiency or cost efficiency.

[7]Koopman's (1951) presents a definition of technical efficiency: A producer is technically efficient if an increase in any output requires a reduction in at least one other output or an increase in at least one input, and if a reduction in any input requires an increase in at least one other input or a reduction in at least one output. Thus, a technically inefficient producer could produce the same outputs with less of at least one input or could use the same inputs to produce more of at least one output.

[8]Farrell's measurement of technical efficiency is closely linked to Debreu's (1951) concept of "coefficient of resource utilisation". Because of this numerous authors refer to it as the Debreu-Farrell technical measure of efficiency

1953, 1970) distance functions. Farrell's input-output oriented technical efficiency measures equate to the mathematical input-output distance functions employed by (Shephard, 1953). For more on this the reader is referred to (Lovell, 1993; Fare, 1975). The model adopted by Farrell to analyse efficiency is graphically represented by Figure 3.1. Farrell's approach to estimating a measurement of technical efficiency is applied extensively in this thesis.

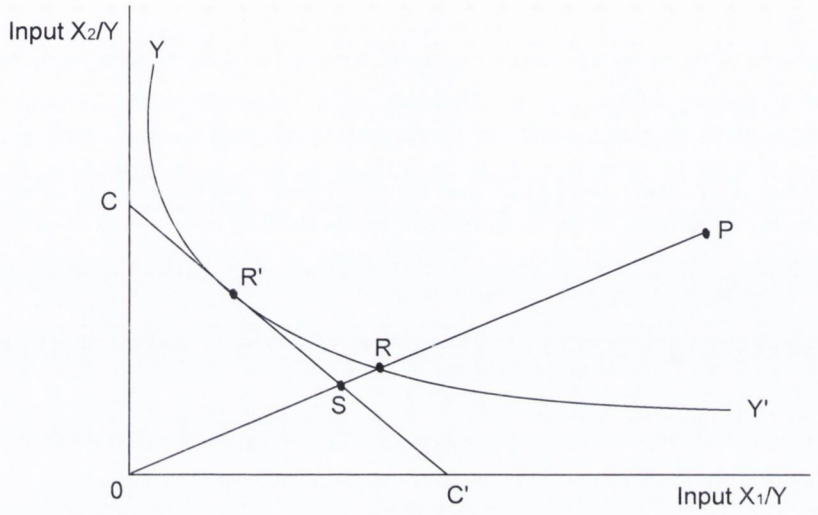


Fig. 3.1: Technical and Allocative Efficiency

Constant Returns to Scale (CRS) are assumed and a set of economic units consume two inputs (X_1 and X_2) to produce a single output (Y). The production technology of fully efficient units is represented by the unit isoquant YY' that allows the measurement of technical efficiency. Any unit operating on this unit isoquant is achieving technically efficient production whilst point P (unit P) defines technically inefficient operation. Technical inefficiency of unit P is given by the distance RP which represents the amount inputs can be proportionally reduced whilst maintaining current output levels. The technical inefficiency of unit P can be expressed in terms of the ratio RP/OP, and therefore unit P's Technical Efficiency (TE) is measured by the ratio OR/OP which is equal to (1-RP/OP).

$$\textbf{Technical Efficiency: } TE_I{}^{9} = OR/OP = 1 - RP/OP. \tag{3.4.1}$$

If market prices are known then allocative efficiency can be obtained from Figure 3.1. The slope of the isocost line, CC' represents the input price ratio. Allocative inefficiency of unit P is shown by the distance SR or in ratio terms SR/OR. That is, SR represents the reduction in production costs available to unit P by moving along the isocost line from point R (position of technical efficiency and allocative inefficiency) to point R' (both technically and allocative efficient). Allocative Efficiency (AE) of unit P is measured by OS/OR.

$$\textbf{Allocative Efficiency: } AE_I = OS/OR. \tag{3.4.2}$$

[9]The subscript 'I' is used on the technical efficiency measure to indicate input-orientated measure.

Having defined technical and allocative efficiency, Overall Efficiency (OE) of a unit is described by the ratio OS/OP, where the line segment SP can be considered in terms of cost reduction. All three measures are bounded by zero and one.

$$\textbf{Overall Efficiency: } OE_I = TE_I \, x \, AE_I = OR/OP \, x \, OS/OR = OS/OP. \tag{3.4.3}$$

Farrell (1957) establishes a radial input-oriented measure of technical efficiency in the single output multiple input technology case, that can be extended to incorporate an output oriented measure of technical efficiency in the single input multiple output case. The output oriented measure is not derived in Farrell's seminal paper but both orientations are attributed to him as they are similar concepts (Fare, Grosskopf and Lovell, 1985; Lovell, 1994). Farrell measures inefficiency as the extent to which a firm's actual input consumption (output production) can be radially contracted (expanded) towards the boundary of the production function (frontier) whilst allowing the firm to maintain current output levels (maintain current input consumption).

The technical efficiency measures under input and output oriented environments equate only when CRS is apparent, otherwise technical efficiency will differ in the presence of increasing or decreasing returns to scale (Fare and Lovell, 1978). The production technology that economic theory associates with the fully efficient firm is not known and in practice the efficient isoquant must be estimated from observations on a sample of firms in the industry concerned. Farrell advocates two methodologies for this: i) a non- parametric piece-wise linear convex isoquant constructed such that no observed unit should lie to the left or below it Figure 3.2, ii) a parametric function be fitted to the data, again such that no observed unit should lie to the left of below it (Hartwich and Kyi, 1999).

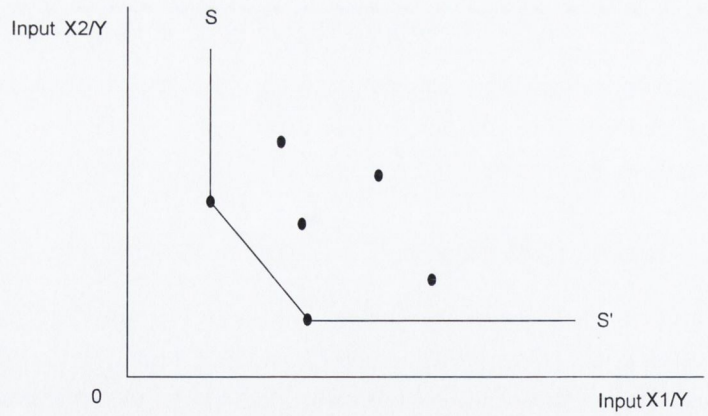


Fig. 3.2: Piece-wise Linear Convex Unit Isoquant

The fundamental concept of technical efficiency originates in neo-classical economics but the estimation of a frontier production function commenced with Farrell. Farrell's contribution to economic literature was so profound that academics and researchers invested time over the sub-

sequent decades developing, discussing and questioning aspects of his paper. The specification of a production technology can take the form of isoquants, production functions, cost, revenue and profit functions.

3.5 Frontier Estimation Techniques

The methods for efficiency and productivity measurement can be classified into two differing approaches: those based on average practice and those based on best practice or non-frontier and frontier estimation techniques (Doraisamy, 2004). Non-frontier estimation techniques are not addressed in this thesis[10]. Frontier models differ from non-frontier models in the assumption that observed production units do not fully utilise their existing technology. In the presence of inefficiency, productivity measurement is affected and so will be productivity change, unless inefficiency does not vary over time. Frontier models are capable of disentangling the two main sources of productive growth: technological change and technical efficiency change. Technological progress pushes the frontier of potential production upward, while efficiency change reflects the capability of productive units to improve production with a set of given inputs and available technology. A distinct advantage of frontier models is that they can provide vital information to the policy makers for the design of productivity enhancing policies (Del Gatto et al., 2010). Figure 3.3 illustrates and input-output model of a set of units to be analysed and the application of three different approaches to the estimation of a production function, i) average practice production function using least squares estimators, ii) a frontier function using maximum likelihood (SFA approach), and iii) an envelope function employing linear programming (DEA approach).

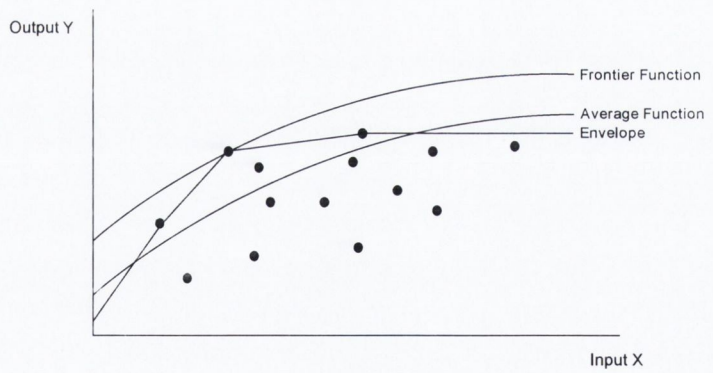


Fig. 3.3: Approaches to Frontier Estimation

Farrell's efficient unit isoquant was the precursor of the frontier production functions of today, frontier estimation techniques can be dichotomized into two research strands, parametric or non-parametric in nature. That is the contrasting distinction between these two techniques is where the functional form of the efficient frontier is pre-defined or imposed a priori and those where

[10]For a comparison of non-frontier and frontier estimation techniques see (Del Gatto et al., 2010)

no functional form is pre-established but one is calculated from the sample observations in an empirical way (Murillo-Zamorano, 2004). The two main exponents of the frontier estimation approach to efficiency measurement are the linear programming deterministic non-parametric technique of Data Envelopment Analysis (DEA) and the econometric parametric technique of Stochastic Frontier Analysis (SFA). The non-parametric deterministic assumption stipulates that all deviations from the theoretical maximum (efficient frontier) is solely attributed to the inefficiency of the firm. In contrast, parametric frontier functions require a specific functional form for technology and for the inefficiency error term which can lead to specification and estimation problems. The choice of frontier estimation technique has been an issue of controversial debate, with Berger (1993) preferring the parametric technique and Seiford and Thrall (1990) preferring the non-parametric approach. A discussion on the merits of both DEA and SFA follows in subsequent sections. Figure 3.4 graphically represents the two parametric and non-parametric approaches to economic efficiency measurement.

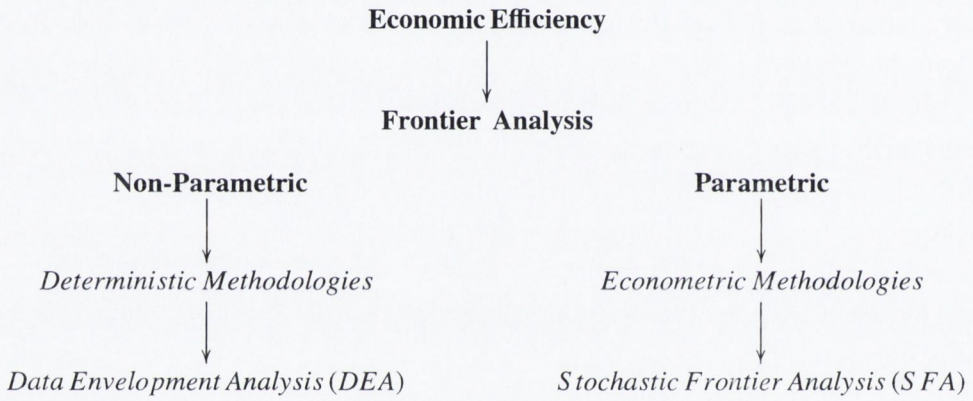


Fig. 3.4: Parametric and Non-Parametric Techniques

DEA establishes a systematic methodology framework for analysing productive efficiency. Numerous bibliographies exist documenting the extensive applications of DEA among researchers in the fields of Economics, Applied Economics, Econometrics and Operations Research (OR)/ Management Science (MS), as well as practitioners in the business community, government institutions and many sectors of the economy. The reader is referred to (Emrouznejad et al., 2008; Zhou et al., 2008; Cook and Seiford, 2009; Emrouznejad and Banker, 2010*a*). An extensive description of the mathematical notation underpinning DEA and the models employed in this thesis is reserved for Chapter 4. As with the DEA technique, the models linked to stochastic frontiers have evolved in multiple directions, increasing the possibilities of analysis and research (Kumbharkar and Knox Lovell, 2003).

3.6 DEA as a Tool to Evaluate Electricity Power Systems (EPS)

European Energy market liberalisation has entailed the restructuring of electricity power markets through the unbundling of electricity generation, transmission and distribution, supply activities and introducing competition into electricity generation. The main tenets of electricity market liberalisation have been i) restructuring ii) regulation and iii) privatisation. Under these new electricity market regimes, it is important to have an evaluation tool that is capable of examining the impacts of these market changes. Chapter 2 stresses the changing electricity market regime of the all island SEM. Implementing benchmark performance measurement and assessing the technical efficiency of EPS has seen extensive research in recent years with DEA at the forefront of this research. DEA has long been established as an advanced mathematical methodology for benchmarking and measuring the efficiency of a set of homogeneous entities. Electricity is an indispensable part of modern social and economic life. A well functioning, reliable and efficient EPS is crucial for economic growth, development and competitiveness.

Early research into the efficiency performance in EPS focused attention on the nature of generation returns to scale (Johnston, 1960; Komiya, 1962; Nerlove, 1963; Barzel, 1964; Dhrymes and Kurz, 1964). Most observers agree that there exist economies of scale in electricity generation. However, there is disagreement about the range over which economies persist. The pioneering application of DEA to EPSs was that of (Fare et al., 1983). The authors evaluated the relative efficiency of electricity generating utilities in Illinois, United States of America (USA) between 1975 and 1979, in order to relate the efficiency scores obtained to the regulation of the sector. Their findings indicate that regulation does not automatically result in efficient operation of electric utilities, nor does it result in consistent performance across plants.

Subsequently, DEA research and efficiency performance measurement has been extensively applied to all four functions of EPSs (Generation, Transmission, Distribution and Retail Supply). The comprehensive adoption of DEA to EPSs research can be attributed to the fact that it accommodates the employment of multiple inputs and multiple outputs without pre-assigned weights and where no functional form is pre-established but one is calculated from the sample observations in an empirical way (Murillo-Zamorano, 2004). These characteristics are particularly relevant when investigating, evaluating and modelling the efficiency performance of EPS. Sections 3.7 and 3.8 details the literature concerned with DEA applications in the electricity generation and distribution research fields. The generation function comprises of the production and conversion of electric power whilst the distribution function relates to the transportation of low voltage electricity through local networks, consisting of overhead lines, cables, switchgear, transformers, control systems and meters, necessary to transfer electricity from the transmission system to end users (domestic, industrial and commercial) (Jamasb and Pollitt, 2007).

3.7 Applications of DEA to Electricity Generation

The electricity generating sector has been the focus of considerable attention for productivity efficiency measurement for at least three decades. (Pollitt, 1995; Zhou et al., 2008) provide a comprehensive review of the research literature related to this field of interest. Wilson (2002) postulates power concerns a flow of energy, of which the variable demand cannot be perfectly monitored and met by a given supply capacity. Storing potential energy is extremely expensive, hence, it becomes critically important to efficiently and effectively transmit power from generation plants to distribution networks and end users, without a cascading power failure (Iimi, 2003). Generation of electric power is at the core of the production process, and efficiency is of the utmost importance, as it is closely related to security and adequacy of the EPS. The primary function of generating units, is to convert energy from various sources into electricity. From the literature, the modelling of the electricity generation production process centres on incorporating all or a combination of four inputs (capital, fuel, energy, labour), and a single homogeneous output (annual production). This generation production framework is adopted and applied extensively to thermal, hydro and wind generating units. Harrison (1979) state the electricity generation process is extremely capital intensive and dependent on rigid technological requirements.

There is a substantial body of empirical work focused on estimating economies of scale in electricity generation. Early influential works include (Nerlove, 1963; Christensen and Greene, 1976; Dhrymes and Kurz, 1964). The sector is thought to be characterised by substantial economies of scale and the available evidence lends firm support to this view (Knittel, 2002; Hisnanick and Kymn, 1999). Considerable research contributions by (Fare et al., 1990; Fare, Grosskopf, Logan and Lovell, 1985; Fare et al., 1989) must be acknowledged relating to the production of electricity. DEA was employed to analyse the technical and scale efficiency, technological progress and effects of regulation on the production of electricity in the USA. Appendix A.1 illustrates the extensive empirical DEA applications to electricity generation efficiency performance. Table A.1 contains information concerning the author, year of publication, models employed, sample dataset, input-output specification and the contribution to knowledge. Studies investigate the impacts of privatisation on the efficiency of decentralised electricity generation include (Abbott, 2006) Australia, (Nakano and Managi, 2008) Japan, (Bunn, 1994) UK.

A growing number of DEA applications assess the operational efficiency of coal-fired power plants. Shrivastava et al. (2012) analyse sixty coal-fired thermal power plants in India. Research findings indicate poor performance of power plants due to over use of input resources, efficiency of small power plants is lower compared to the medium and large category and also the efficiency performance also performance of state owned power plants is comparatively lower than central and privately owned Fare et al. (1990) employ the Malmquist productivity index to study the productivity growth of nineteen coal-fired generating plants in Illinois from 1975 to 1981, concluding that the average rates of productivity growth were relatively stable, except

during a productivity slowdown from 1976 to 1977. Sueyoshi and Goto (2010) analysed the performance of USA coal-fired power plants and results suggest that plant managers need to find a balance between their operational efficiency and environmental performance. Numerous researchers have focused on analysing the electricity generation of coal-fired power plants (Behera and Dash, 2010) USA, (Fang et al., 2009) India, (Olatubi, 2000) USA, (Coelli, 1997), Australia.

Another research strand relates to thermal power plant efficiency. Sozen et al. (2010) conducted an efficiency analysis of fifteen Turkish state-owned thermal power plants employed in electricity generation. Operational efficiency and environmental performance evaluation are defined and pursued. The study emphasised the need to incorporate environmental effects when analysing thermal power plants. Lam and Shiu (2001) investigated the technical efficiency of China's thermal power generation for 1995 to 1996. The municipalities and provinces along the eastern coast of China achieve the highest levels of technical efficiency with productivity growth over 2.1% primarily due to technological change. Fuel efficiency and capacity factor are found to significantly affect the technical efficiency of plants. Another study by Liu et al. (2010) evaluated nine thermal power generating plants with all power plants achieving acceptable overall efficiencies, with combined cycle power plants the most efficient. Other studies focusing on thermal power plants include (Chien et al., 2007) Taiwan, (Jain et al., 2010) and (Chitkara, 1999) India. Several studies have concentrated on investigating productivity growth before and after electricity generation sector reform. Abbott (2006) adopted the DEA technique to measure the productivity and efficiency of Australia's electricity supply industry over a thirty year period, finding productivity efficiency improvements of electricity supply over the time period. Coelli (1997) measure the Total Factor Production (TFP) change of 13 coal-fired plants in Australia from 1981 to 1991. The empirical results suggested a TFP growth over the period of 10 years of up to 16%. Other productivity studies in the literature include (Nakano and Managi, 2008) Japan, (Chien et al., 2007) Taiwan and (Lam and Shiu, 2001) China.

Some research has focused not only on establishing an efficiency measure by DEA but also incorporating other objectives such as assessing targets, forecasting efficiency, allocation of resources and determining the main factors responsible for increasing efficiency (Golany, 1988; Thanassoulis and Dysosn, 1992). Vaninsky (2006) estimated the relative efficiency of electric power generation in the USA from 1991 through to 2004 and make future technical economic forecasts. Athanassopoulos et al. (1999) developed the concept of target setting and scenario planning as a means of supporting decision making in multi-unit organisations in the UK. Thakur et al. (2006) present a framework for accessing the comparative efficiencies of Indian State Owned Electric Utilities (SOEU). The results indicate that the performance of several SOEUs is sub-optimal, suggesting the potential for significant cost reductions. It was found that bigger utilities display greater inefficiencies and have distinct scale inefficiencies. Exploiting scale efficiencies by suitable restructuring and unbundling of SOEUs is suggested. Other

studies of similar interest include (Golany et al., 1994) Israel, (Jha et al., 2006) Nepal, (Thakur and S., 2009) India. Other noteworthy contributions to the literature on fossil fuel electricity generation efficiency performance include (Meenakumari and Kamaraj, 2008) India, (Diewert and Nakamura, 1999) Canada, (Goto and Tsutsui, 1998) Japan and UK, (Sueyoshi and Goto, 2001) and (Arocena and Waddams Price, 2003) Spain, (Korhonen and Luptacik, 2004) Finland, (Park and Lesourd, 2000) South Korea, (Meibodi, 1998) Iran.

DEA as a efficiency research technique, has been formulated to evaluate the relative efficiency of hydro power plants. Barros and Peypoch (2008) conducted a DEA analysis of the technical efficiency of hydroelectric generating plants in Portugal between 1994 and 2004. The results show that the hydroelectric generating plants are very distinct and therefore, any energy policy should take into account this heterogeneity. It also concludes that competition, rather than regulation, plays a pivotal role in increasing hydroelectric plant efficiency. Also in Portugal, Barros (2008) estimate total productivity change for the period 2001-2004 concluding that a number of plants experienced productivity growth while others experienced a decrease in productivity. An internal benchmarking procedure is proposed along with managerial strategies to curb inefficiencies. (Jha and Shrestha, 2006*a*; Jha et al., 2007) investigate the performance of hydro power plants of the Nepal Electricity Authority (NEA). The average technical efficiency of hydro power plants of NEA was found to be approximately 74% with scale efficiency 71% and average overall efficiency found to be around 50%. Other applications of DEA to hydro efficiency analysis include (Dedoussis et al., 2010) Greece, (Barros and Peypoch, 2007) Portugal.

Renewable energy sources will play an ever increasing role in the electricity generation portfolios of nations and in particular wind energy. However, there exists a gap in the literature related to wind farm DEA efficiency studies, very few exist. Sarica and Or (2007) examine the operational and investment performance of sixty-five thermal, hydro and wind power plants in Turkey. Performance comparisons include public versus private sector plants, and natural gas versus coal versus oil fired plants. Also, the relationships between efficiency scores and various input-output factors are investigated and some interesting trends are identified. Iglesias et al. (2010) estimate the productive efficiency of a group of wind farms employing both frontier methods DEA and SFA. Their results are of interest to regulators, wind farm developers, technology suppliers, operators and other stakeholders in the sector. More recently, Barros and Antunes (2011) analyse ownership and unobserved managerial ability as factors impacting on the performance of Portuguese wind farms and advise the implementation of common policies.

3.8 Applications of DEA to Electricity Distribution

The relative efficiency performance of electricity distribution has seen extensive research worldwide in the last decade due to the restructuring of EPS (Santos et al., 2010). Performance measurement, optimisation, and policy making of electricity distribution are important issues for regulators in the electricity restructuring and reform, with efficiency scores of various tech-

niques setting x-factors in the incentive regulation methods such as price cap and revenue cap regulation (Azadeh et al., 2009). The incentive regulation techniques are discussed in (Hill, 1995; Jamasb and Pollitt, 2000; Joskow and Schmalensee, 1986).

Performance measurement is a key component of price cap regulation as efficiency and productivity are essential input parameters determining the revenue that firms are allowed to absorb under this type of regulation. This form of regulation prevents the abuse of monopolistic power and is adopted to protect and promote the welfare of both consumer and producer (Olemez, 2008). If the regulatory regime is efficacious, then both producers and consumers become better off. Efficiency and productivity in electricity generation are primarily determined by technological factors, whilst the electricity distribution sector is mainly determined by efficient management and labour utilisation (Kumbhakar and Hjalmarsson, 1998). Performance measurement is the fundamental concept underpinning incentive regulation and is increasingly being adopted by many countries. The underlying interest in measuring efficiency is the desire to compare performance of different units and to identify sources of efficiency or inefficiency (Lovell, 1993). The DEA literature on electricity distribution efficiency and productivity analysis, both theoretical and empirical, is now vast and associated benchmarking techniques have been applied in a wide variety of settings (Doraisamy, 2004; Perez-Reyes and Tovar, 2009; Jamasb and Pollitt, 2001; Santos et al., 2010; Haney and Pollitt, 2009).

Since Fare et al. (1983) pioneering DEA application to EPS, electricity distribution efficiency analysis has primarily focused on establishing a measure of efficiency and productivity, and more recently accounting for differences in electricity distribution performance due to inhibiting operational characteristics and their surrounding environment. Appendix A.2 illustrates the empirical DEA applications to electricity distribution efficiency performance. The Appendix Table contains information concerning the author, year of publication, models employed, sample data set, input-output specification and the contribution to knowledge. The following is a list of topics related to DEA efficiency distribution literature:

1. The effect of average and frontier specifications on efficiency estimates;
2. The specification of inputs and outputs and the sensitivity of efficiency results to variable specification;
3. Economies of scale;
4. The effects of power sector reforms;
5. The effects of ownership on efficiency performance;
6. International inter-country Comparisons; and
7. Effect of differing operational environments on efficiency performance.

Jamasb and Pollitt (2001) provide an extensive literature survey on the differing regulatory regimes employed around the world. Virtually all the regulatory regimes are based on "benchmarking" that is measuring a firms productive efficiency namely technical and cost efficiency against a reference performance (Filippini et al., 2005). In Section 3.5, techniques to measure efficiency can be dichotomised into two categories: non-parametric linear programming techniques such as DEA, and parametric econometric technique such as SFA. Both techniques have advocates but DEA has proved a more popular technique, perhaps reflecting the opinion amongst researchers and regulators that DEA as a benchmarking technique is more appropriate for modelling the efficiency performance of electricity distribution. However, numerous studies have focused on adopting both parametric and non-parametric techniques to the same dataset (Estache et al., 2004; Jamasb and Pollitt, 2003; Farsi and Filippini, 2004, 2005; Kumbhakar and Hjalmarsson, 1998; Whiteman, 1999; Pollitt, 1995; Cullmann and Von Hirschhausen, 2008*a*). The empirical evidence in the electricity sector analysis suggest that the efficiency estimates attained are sensitive to the chosen benchmarking technique. For a critique on benchmarking analysis in electricity sector the reader is referred to Shuttleworth (2005).

Efficiency analysis of electricity distribution units has focused on establishing technical or cost efficiency measures rather than allocative efficiency. The difficulty arises in the form of valuing service quality for inclusion in regulatory models. The regulatory concern is that technical efficiency can be achieved at the expense of service quality measures as well as allocative efficiency. Electricity distribution utilities may operate at sub-optimal quality and social cost level in the absence of regulation, in order to counteract this and prevent inefficient allocation of resources, service quality measures and incentives need to be incorporated in to regulatory models. Recent studies have attempted to bridge this gap in the research (Goto and Tsutsui, 1998; Yu et al., 2007; Cullmann and Von Hirschhausen, 2008*a*; Giannakis et al., 2005). Cambini et al. (2012) state that a number of recent studies indicate a clear trade-off between quality and technical efficiency (companies with higher cost structures present higher levels of quality and vice versa) (Giannakis et al., 2005; Growitsch, Jamasb and Pollitt, 2010), however (Coelli et al., 2008; Growitsch, Jamasb, Muller and Wissner, 2010) find the introduction of quality does not have a significant effect on the technical efficiency scores estimated.

The selection of input-output variables to be employed is an important step in DEA. However, there is no firm consensus on which variables best describe the operational characteristics of electricity distribution utilities (Giannakis et al., 2005). Keeney and Raiffa (1993) state a desirable set of measurement factors should be complete, decomposable, operational, non-redundant, and minimal. According to Jamasb and Pollitt (2001) the most extensively employed inputs are operating costs, number of employees, transformer capacity, and network length. The most widely used outputs are units of energy delivered, number of customers, and the size of service area. The benchmarking of electricity distribution utilities employing physical quantities of input measures highlight the potential for efficiency improvements in terms of reductions in

physical units. The majority of DEA benchmarking applications use physical measures of inputs as proxies for the operating and capital costs, with the exception of (Hougaard, 1994; Burns and Weyman-Jones, 1994; DTe, 2000; Jamasb and Pollitt, 2003; Hattori et al., 2002). However from a regulatory viewpoint, it is preferable to focus on costs (monetary measure) rather than adopting physical measures since the primary aim of regulators is to promote cost savings in utilities and subsequently achieve lower prices for consumers (Doraisamy, 2004). Jamasb and Pollitt (2003) state relative performance measured on the basis of physical inputs bears an indirect relationship with cost savings potential as the basis for setting RPI X-factors. An extensive review of the input and outputs adopted in electricity distribution studies is reserved for Chapter 5.

Many research publications have explored the economies of scale related to electricity distribution. Early influential studies include (Neuberg, 1997; Meyer, 1975; Huettner and Landon, 1978), indicating evidence of initial scale economies in distribution among USA electric utilities. Recent years have seen research focus on distribution economies in countries other than the USA (Hjalmarsson and Veiderplass, 1992), (Kumbhakar and Hjalmarsson, 1998) Sweden, (Giles and Wyatt, 1993) New Zealand, (Korhonen and Syrjanen, 2003) Finland, (Salvanes and Tjotta, 1994) Norway, (Filippini, 1996) Switzerland, (Von Hirschhausen et al., 2006) Germany and (Yatchew, 2000) Canada. These studies find evidence of scale economies in electricity distribution but differ in some aspects with certain systems exhausting their economies at relatively modest scale, while others have persistent economies. It is important to distinguish between *Returns to Network Density (RND)*, i.e., the economies of increasing electricity supply when the network is held constant and *Returns to Scale (RTS)* i.e., the economies of increasing both electricity supplied and the network (Gulledge and Lovell, 1992). For independent distributors there is clear evidence of RND but less indication of RTS. Salvanes and Tjotta (1994) in Norway, find significant evidence of economies of density but no evidence of economies of scale above small outputs. Hjalmarsson and Veiderplass (1992) Sweden, indicate that the primary source of productivity growth is returns to network density.

Since the 1980s, reforms have altered the institutional framework, development and operational environment of power sectors throughout the world (Jamasb and Pollitt, 2003). The central focus of these power sector reforms has been improving the efficiency of the sector. The reforms have entailed the adoption of competition into electricity generation, design of organised power markets, and unbundling of the electricity generation, transmission, distribution, and retailing activities Jamasb and Pollitt (2000), coupled with ownership transfers and privatisation of existing assets Joskow (1998). The consensus from the literature states power sector reform improves efficiency (Perez-Reyes and Tovar, 2009) Peru, (Nakano and Managi, 2008) Japan, (Pombo and Taborda, 2006) Columbia, (Chunbo et al., 2011) China, (Abbott, 2006) Australia, whilst others argue a negative impact (Ramos-Real et al., 2009) Brazil and some retain inconclusive results (Cullmann and Von Hirschhausen, 2008*b*) Germany. However, there is a gap in the literature investigating the impact of reforms on quality of service.

There has been an increased research focus to investigate the implications of power sector reform that entails some form of private involvement, that is the effects of ownership on efficiency performance of electricity distribution utilities (i.e private and publicly owned) (Newberry, 1999). The results from this research strand have been conflicting. For instance, numerous authors such as (Pollitt, 1995) USA and UK, (Hjalmarsson and Veiderplass, 1992) and (Hjalmarsson and Veiderpass, 1992) Sweden conclude that there exists no significant difference between public and privately owned electricity distribution utilities in terms of technical efficiency. In contrast to this, (Bagdadioglu et al., 1996) Turkey, (Hougaard, 1994) Denmark, (Kumbhakar and Hjalmarsson, 1998) Sweden and (Berry, 1994) USA, find private ownership of electric utilities leads to greater efficiency performance as opposed to public ownership. However, other authors (Estach et al., 2002) South America, (Pombo and Taborda, 2006) Columbia, (Mota, 2004) Brazil and USA and (Sanhueza, 2003), Chile have focused on less developed countries (mainly Latin America) concluding that power sector reform and privatisation has a positive effect on electricity distribution efficiency performance. Perez-Reyes and Tovar (2009) posited that these results in electricity distribution efficiency performance are attributed to inhibiting operating environments prior to reform. These factors include political influence, capital constraints, complicated and corruptive behaviour concerning procurement. Several studies have argued (Zhang et al., 2002; Jamasb et al., 2004; Mota, 2004) that private ownership and privatisation in the context of market-oriented infrastructure reforms is inconclusive and only when effective regulation is present will privatisation achieve efficiency improvements.

Prior to the 1990s the employment of DEA as an economic evaluation tool was confined to electricity generation plants. Weyman-Jones (1991) was the initial single country DEA application to electricity distribution utilities, in which the technical efficiency of twelve Area Electricity Boards (AEB)s in the UK electricity distribution industry was studied. The findings indicate a wide divergence in efficiency among the Area Electricity Boards (AEB)s. Subsequently, single country efficiency evaluation has been widespread. Pahwa et al. (2003) benchmark the performance of the fifty largest electric distribution utilities in the USA. The results indicate inefficient utilities can adopt and develop strategic plans to improve performance. Kumbhakar and Hjalmarsson (1998) find evidence of economies of scale, technical progress, and relative efficiency of private utilities when investigating distribution utilities in Sweden. Other intuitive single country studies enhancing the DEA benchmarking literature include (Economics, 1999) New South Wales, (Korhonen and Syrjanen, 2003) Finland, (Miliotis, 1992) Greece, (Bagdadioglu et al., 1996) Turkey, (Grifell-Tatje and Lovell, 2003*a*) Spain, (Forsund and Kittlesen, 1998) Norway, (Meibodi, 1998) Iran, (Hjalmarsson and Veiderplass, 1992) Sweden, (Tsutsui and Goto, 2009) USA, (Cullmann and Von Hirschhausen, 2008*b*) Poland, (DTe, 2000) Netherlands.

Coinciding with single country research, inter-county comparisons have become more prominent in recent years. Jamasb and Pollitt (2003) stipulate this growing trend is because i) regu-

lators can assess the performance of national utilities within the larger context of international practice, ii) international comparators to a sample can improve the validity of the research and iii) international comparisons allow regulators to measure efficiency of the utilities by the standards of international best practice. Pollitt (1995) was one of the first to implement a comparative electricity efficiency study across fourteen countries concluding that there is no strong evidence that performance is affected by ownership. Cullmann and Von Hirschhausen (2008*a*) investigated the technical efficiency of electricity distribution in four Eastern European countries concluding that technical efficiency has improved through privatisation. Hattori et al. (2005) ascertained productivity gain from 1985-1998 was more prominent in the UK electricity distribution sector as opposed to Japan's. Numerous astute inter-country DEA electricity distribution applications can be found in the literature (Yunos and Hawdon, 1997; Whiteman, 1995; Goto and Tsutsui, 1998; Whiteman, 1999; Jamasb and Pollitt, 2003; Cullmann and Von Hirschhausen, 2008*a*; Jamasb and Pollitt, 2001; Mota, 2004; Edvardsen and Forsund, 2003; IPART, 1999).

However, efficiency estimates from international inter-country benchmarking need careful consideration as Zhang and Bartels (1998) show as the sample size increases the estimated mean technical efficiencies decrease generally. Other research focuses on analysing the performance of distribution systems by evaluating operational efficiency and the possible reorganisation of electricity distribution utilities (Lo et al., 2001; Chien et al., 2003) Turkey and (Jha et al., n.d.) Nepal. In most cases higher efficiency is attainable through reorganisation. Another strand of research focuses on the comparison of electricity distribution utilities in an urban versus rural setting, concluding the presence of higher efficiency in urban areas as opposed to sparsely populated regions (Miliotis, 1992) Greece, (Yang and Lu, 2006) (Chen, 2002) Taiwan and (Hjalmarsson and Veiderplass, 1992) Sweden.

The classical DEA models allow almost total flexibility in the selection of weights for electricity distribution utilities. However, applications of employing weight restrictions in electricity distribution efficiency analysis have grown in recent times (Jha et al., 2011) Nepal, (Bjorndal et al., 2008; Migueis et al., 2011) Norway, (Pahwa et al., 2003) USA, and (Santos et al., 2010) Portugal. These extended classical DEA models are referred to as "weight-restricted" DEA models, which are intended to enhance discriminatory power and reflect the details of the underlying technology of production. Arguments in favour of adopting weight restrictions can be found in (Chaparro et al., 1997).

The UK electricity market has seen extensive applications of DEA to establish technical, cost and productivity measures of efficiency whilst also incorporating service quality research (Weyman-Jones, 1991; Burns and Weyman-Jones, 1994; Weyman-Jones, 1995; Giannakis et al., 2005; Yu et al., 2009, 2007; Hattori et al., 2003, 2005; Yunos and Hawdon, 1997; Pollitt, 1995). The main theme in the majority of studies centres on establishing the productive efficiency of Area Electricity Boards (AEB)s in England and Wales before and after their privatization. The

results indicate the existence of productive growth, technical efficiency in half of the area boards and the existence of wide divergences in their performance. Other research literature examining productive growth include (Hjalmarsson and Veiderplass, 1992; Kumbhakar and Hjalmarsson, 1998) Sweden, (Forsund and Kittlesen, 1998) Norway. In all cases the primary source of productive growth was technological progress. Thus, the effect of reforms on efficiency and productivity growth in electricity sectors is positive. Individual electricity distribution firms operate in different regions with various environmental and network characteristics that are only partially observed, it is crucial for DEA benchmarking models to distinguish between inefficiency and such exogenous heterogeneity.

A growing number of applications employ exogenous variables[11] (i.e. variables beyond the firms control) in electricity distribution analysis to account for differences in terms of the characteristics of distribution utilities and their operating environment (e.g. countries, regulatory system, geographic region, differing ownership, electricity demand and consumption characteristics) (Ramos-Real et al., 2009) Brazil, (Pombo and Taborda, 2006) Columbia, (Estache et al., 2004) South America, (Weyman-Jones, 1995) UK, (Korhonen and Syrjanen, 2003) Finland, (Agrell et al., 2005) Sweden, (Hattori et al., 2005) UK. Extensive discussion on environmental variables employed in distribution analysis is reserved for Chapter 5.

Doraisamy (2004) state the value of modelling for policy analysis can be enhanced by accurately establishing the technological realities of the underlying production process to obtain accurate, reliable and realistic results. The comprehensive review of the literature related to the applications of DEA in electricity generation and distribution efficiency measurement conclude that it has been an effective, exhaustive and prolific technique, represented by the number of publications in the literature.

3.9 Capabilities and Limitations of DEA

DEA models accumulate information on the efficiency of each unit, not only relative to the efficiency frontier they formulate but also to specific efficient units that can be identified as role models or comparators (Hawdon, 2003). It is a non-parametric mathematical programming model applied to observed data that provides a way to construct production frontiers as well as calculate the efficiency scores relative to those constructed frontiers (Murillo-Zamorano, 2004). DEA accommodates the efficiency measurement of multiple inputs and multiple outputs without pre-assigned weights and where no functional form is pre-established but one is calculated from the sample observations in an empirical way. The capabilities and limitations of DEA are well documented in literature (Kalirajan and Shand, 1999; Daraio and Simar, 2007; Fried et al., 2008). A comprehensive list outlining the capabilities of DEA is provided by (Charnes et al., 1994) below:

[11] Introducing exogenous variables into the production function specification assumes that these variables affect technology rather than computed efficiency scores, and generates net efficiency measures

1. The focus is on individual DMUs in contrast to population averages.
2. Each DMU has single aggregate measure for the utilisation of input factors (independent variables) to produce desired outputs (dependent variables).
3. DEA can simultaneously utilise multiple outputs and multiple inputs with each being stated in different units of measurement (Unit invariance).
4. Adjustments can be made for extraneous variables.
5. Categorical (Dummy) variables can be included.
6. Computations are value-free and do not require specification of knowledge of a priori weights of prices for the inputs or outputs.
7. There is no restriction on the functional form of the production relationship.
8. DEA can accommodate judgement when desired.
9. DEA can produce specific estimates for desired changes in inputs and/or outputs for projecting DMUs below the efficient frontier onto the efficient frontier.
10. Results are Pareto optimal.
11. Focus is on revealed best-practice frontiers rather than on central-tendency properties of frontiers.
12. It satisfies strict equity criteria in the relative evaluation of each DMU.

The characteristics that make DEA a powerful technique for performance measurement can be inverted to reveal certain limitations, which have been discussed in the literature (Manzoni, 2007; Ramanathan, 2003; Trick, 1996; Charnes et al., 1994).

1. The non-parametric nature of DEA means it does not allow the application of inferential statistics and traditional mechanism such as hypothesis testing.
2. Applications of DEA require separate Linear Programme (LP) solutions for each DMU under investigation, thus resulting in numerous LP iterations. Hence, the application of DEA to problems with many DMUs can be computationally intensive and demanding, and sometimes beyond the capabilities of some but not all programs.
3. As DEA is an extreme point technique, the efficiency frontier obtained relates to the actual performance of the best performing DMUs. A direct consequence of this aspect is DEA can be significantly influenced by outliers and is susceptible to 'noise' (even symmetrical noise with zero mean) such as measurement error. This makes sensitivity analysis an important component of post-DEA procedure.

4. DEA is good at estimating "relative" efficiency of a DMU but poor with absolute values. It converges slowly to "absolute" efficiency only allowing for comparisons with peers but not with a "theoretical maximum".

5. DEA literature fails to establish definitive operational parameters, albeit rules-of-thumb[12] exist but there appears to be a lack of a definitive boundary. For example, due to the nature of DEA, inserting more variables not only inflates DEA efficiency scores but also potentially conceals the actual extent of inefficiencies (Liu et al., 2010). Cooper et al. (2007) adduce a simplistic solution of "trial and error" by combining small sets of input and output variables and gradually increase the number, whilst observing the effects.

Successful applications of DEA can be inhibited by the limitations discussed but acknowledging, understanding and alleviating their possible impact can lead to a parsimonious DEA model for investigation. Dyson et al. (2001) identify the pitfalls encountered in DEA application and suggest protocols to avoid them, necessary for the successfully application of the methodology.

3.10 Parametric Frontier Analysis

Parametric frontier analysis are methods that impose a functional form on the frontier using estimation for production or cost functions. They require more knowledge about the production or cost functions and also about the distribution of errors. The initial framework on parametric frontier analysis commenced with Farrell (1957) cross-sectional model where goal programming techniques were adapted to estimate the production function. In an early influential study Aigner and Chu (1968) considered the estimation of a parametric frontier production function of Cobb-Douglas[13] form. Their dilemma in acquiring "estimates" of parameters depicting the production function frontier was twofold. The first problem was a Linear Programming (LP) problem, the second was quadratic in nature, and both were deemed goal programming problems, where the goal is to select a non-negative parameter vector that minimizes the sum of deviations beneath the parametric frontier, and the method is mathematical programming (Fried et al., 1993).

Aigner and Chu (1968) models are referred to as "goal programming" approaches to parameter estimation of prescribed (and explicitly stated) functional forms with only one sided deviations permitted. Goal programming techniques calculate the technology parameter vector by solving deterministic optimisation problems. Since Aigner and Chu (1968) seminal paper, variations of their concept, adopting the Cobb-Douglas assumption have been implemented by (Timmer, 1971; Forsund and Hjalmarsson, 1979). The main limitation of goal programming is

[12]Boussofiane et al. (1991) stipulate the minimum number of DMU observations must be equal to, or larger than, the product of the number of inputs and outputs, Golany and Roll (1989) suggest that the number of DMUs should be at least twice the sum of the number of input and output factors whereas Cooper et al. (2000) state the number of DMUs should exceed the combined number of inputs and outputs

[13]A standard production function which is applied to describe much output two inputs into a production process make. It is used commonly in both macro and micro examples. For capital K, labour input L, and constants a, b, and c, the Cobb-Douglas production function is: f(k,n) = $bk^a n^c$

that the parameters are calculated using mathematical programming techniques rather than being estimated in any statistical sense (using regression techniques). This complicates statistical inference concerning the calculated parameter values (Kumbhakar and Knox Lovell, 2000).

3.11 Stochastic Frontier Analysis (SFA)

SFA is a parametric frontier analysis technique that attempts to estimate an efficient production or cost frontier that does incorporate the possibility of measurement error or chance factors in the estimation of the efficient frontier. SFA is an alternative efficiency estimation technique to DEA. SFA is based on the simultaneously proposed pioneering contributions of (Aigner et al., 1977; Meeusen and Van de Broeck, 1977). Due to the limitations and inadequacy of goal programming models and the deterministic econometric approach to accurately measure the productive structure, in the parametric context Stochastic Frontier Models (SFM) have egressed as the only viable econometric parametric technique for the measurement of economic efficiency. The stochastic production frontier is motivated by the notion that deviations from the production "frontier" may not be entirely under the control of firm under analysis resulting in sub-optimal performance of firms. In the context of technical efficiency, it concerns the production function that indicates the maximum attainable output given particular inputs. Any below par performances can be attributed to random noise (beyond the manager's control) as well as inefficiency (Behr and Tente, 2008). For the log linear Cobb-Douglas form, single output case, t the estimation of the stochastic production frontier model can be written as:

$$ln\, Y_i = \beta_0 + \sum_n \beta_n ln\, X_n i + v_i - u_i \tag{3.11.1}$$

where the term $v_i - u_i$ is the composed error term, with v_i represents randomness (or two-sided statistical noise) component and u_i represents the non-negative technical inefficiency component. The random statistical noise component encompasses the effects of exogenous shocks beyond the control of the analysed unit. That is both uncontrollable factors directly affecting the "actual" production function (such as differing operating environments) and econometric errors (such as noise, misspecification and measurement error). External influences impacting on efficiency measurement include uncertainty, luck, geographic location, weather, socio-economic and demographic factors, regulatory-competitive environments. For more on the SFA approach see (Kumbharkar and Knox Lovell, 2003).

The statistical noise component v_i is assumed to be identical independent, symmetric and identically distributed independently of u_i. Thus the error term is $\varepsilon_i = v_i - u_i$ is asymmetric, since $u_i \geq 0$. The assumption with two-component error structure is that inefficiencies follow an asymmetric half-normal distribution and the random errors are normally distributed. Most often the half normal assumption is applied to ensure non-negativity is satisfied, but the exponential, truncated normal and gamma cases are also discussed in specific literature (Murillo-Zamorano, 2004; Behr and Tente, 2008). Similar to the DEA technique, the models linked to SFA have

evolved in multiple directions, increasing the possibilities of research and analysis (Kumbharkar and Knox Lovell, 2003).

SFA applications to electricity generation include (Jain et al., 2010) India, electricity distribution efficiency analysis (Burns and Weyman-Jones, 1996) UK, (Farsi et al., 2006) Switzerland. Numerous application employ both employ techniques DEA and SFA to efficiency analysis (Whiteman, 1999), Australia (Mota, 2004), Brazil (Meibodi, 1998), Iran (Simaba and Haghifama, 2011). Evaluating Ordinary Least Squares (OLS) residuals provides a test for the presence of technical inefficiency in the data. If the residuals are centered at zero, $u_i = 0$, then $\varepsilon_i = v_i$, the composed error term is symmetric, then there is little support for evaluating the technical inefficiency of the data. However, if the residuals are not centered at zero, $u_i > 0$, then $\varepsilon_i = v_i - u_i$ is negatively skewed suggesting evidence of technical inefficiency of the data (Kumbharkar and Knox Lovell, 2003). Coelli (1995) propose a test statistic to estimate technical efficiency. The test statistic is $\frac{m_3}{(6m_2^3/N)^{\frac{1}{2}}}$, where N is equal to the number of observations. under the null hypothesis of zero skewness in the OLS residuals, $m_3 = 0$, the third moment of OLS residuals is asymptotically distributed as a normal random variable with mean zero and variance $\frac{6m_2^3}{N}$. This implies that the test statistic is asymptotically distributed as a standard normal random variable $N(0,1)$.

If negative skewness exists and if statistically significant, there is evidence of technical inefficiency in the data and the problem is estimating this parameter. The motivation behind efficiency analysis is to estimate maximum feasible frontier and accordingly measure the efficiency scores of each DMU relative to that frontier. This estimation process was initially originated with different versions of Ordinary Least Squares (OLS) as shown in 3.5 through which average-practising frontier was estimated and shifting up by Gabrielsen (1975) (i) maximum amount of residuals (Corrected Ordinary Least Squares (COLS)) (ii) mean of the residuals (Modified Ordinary Least Squares (MOLS)) (Richmond, 1974). The drawback of these applications are that average producer efficiency performance is adopted as the benchmark instead of best-practice and they are based on asymptotic theory, and many samples are relatively small.

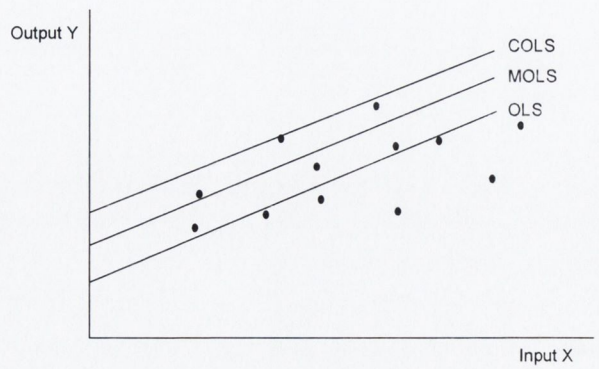


Fig. 3.5: OLS Production Frontier Estimators

In lieu of adopting OLS, Maximum Likelihood Estimation (MLE) is proposed by Greene (1980) to estimate technology parameters as well as residuals which are decomposed into statistical noise and inefficiency term by (Jondrow et al., 1982). To estimate the technical efficiency of each firm, it is necessary to separate the composed error term and make distribution assumptions.

3.11.1 Estimation of efficiency for SFA Half Normal Model

Jondrow et al. (1982) postulate that if technical inefficiency is assumed to be distributed as a half-normal random variable independent from the random noise, then the distribution assumptions for the error terms are i) $v_i \sim N(0, \sigma_v^2)$ ii) $u_i \sim N^+(0, \sigma_u^2)$ that is, as non-negative half normal iii) v_i and u_i are distributed independently of each other, and of the regressors. The expected value of u_i conditional on the composed error term is:

$$E[u_i \mid e_i] = \frac{\sigma\lambda}{(1+\sigma^2)} \left[\frac{\phi(e_i\lambda/\sigma)}{\Phi(-(e_i\lambda/\sigma)} - \frac{e_i\lambda}{\sigma}\right] \tag{3.11.2}$$

where $\phi(.)$ is the density of the standard normal distribution, $\Phi(.)$ the cumulative density function, $\lambda = \sigma_u/\sigma_v, e_i = v_i - u_i$ and $\sigma = (\sigma_u^2 + \sigma_v^2)^{\frac{1}{2}}$. For each productive unit under analysis, when the conditional estimates of u_i have been acquired, the technical efficiency can be calculated as:

$$TE_i = 1 - E[u_i \mid e_i] \tag{3.11.3}$$

In the estimation of the technical inefficiency term, assuming that u is non-positive and numerous density functions can be specified for u (Kalirajan and Shand, 1999). Aigner et al. (1977) and Stevenson (1980) produce results for a truncated distribution as opposed to half-normal distribution. Meeusen and Van de Broeck (1977) adopt an exponential distribution for u along with a normal distribution for v. Jondrow et al. (1982) provide the expected value of u_i when the asymmetric error term follows an exponential distribution:

$$E[u_i \mid e_i] = (e_i - \theta\sigma_v^2) + \frac{\sigma_v\phi[(e_i - \theta\sigma_v^2)/\sigma_v]}{\Phi[(e_i - \theta\sigma_v^2)/\sigma_v]} \tag{3.11.4}$$

where $\theta = 1/\sigma_u$ Greene (1980) proposed the adoption of maximum-likelihood estimation of a stochastic frontier with gamma-distributed errors. The complexities incurred in adopting the correct estimation procedure outweigh their associated benefits and consequently the adoption of half normal density functions have dominated the empirical literature of stochastic frontier (Murillo-Zamorano, 2004). The SFA literature presented here is intended to be summative rather than exhaustive, for an extensive review on the SFA methodology see (Del Gatto et al., 2010; Kalirajan and Shand, 1999; Kumbharkar and Knox Lovell, 2003; Van Fulton, 2005; Murillo-Zamorano, 2004).

3.12 Capabilities and Limitations of SFA

SFA has been extensively employed as methodology for frontier estimation and efficiency measurement, the main capabilities and limitations are outlined below.

1. SFA allows the incorporation of an error term representing noise, measurement error and exogenous shocks beyond the control of the firm under analysis.
2. Modelling production functions following SFA conforms with production theory.
3. SFA reduces influence of extreme observations and is easily adapted to work with panel data.

The limitations of SFA include:

1. SFA imposes considerable structure on data in stringent parameter form (functional form) and distribution assumptions.
2. SFA is susceptible to collinearity[14] through misspecification errors and the requirement of monotonicity of relationships.
3. SFA requires the careful selection of input and output variables.

3.13 Comparison of DEA and SFA Attributes

The non-parametric DEA and the parametric SFA adopt the concept of a frontier to define firm specific technical efficiency performance that employ similar technologies.

"....non-statistical approaches such as Data Envelopment Analysis (DEA) have the disadvantage of assuming no statistical noise, but have the advantage of being non-parametric and requiring few assumptions about the underlying technology. Stochastic Frontier Analysis (SFA) models on the other hand have the attraction of allowing for statistical noise, but have the disadvantage of requiring strong assumptions as to the form of the frontier" (Jacobs, 2000).

Numerous research has focused on clarifying the trade-off of employing the "correct" estimation technique. Gong and Sickles (1992) state that if the employed functional form is close to the given underlying production technology SFA exceeds DEA but as mis-specification of the chosen functional form becomes more apparent, the case for adopting DEA becomes more compelling. Hence, DEA is more appropriate when knowledge about underlying technologies is weak (Kalirajan and Shand, 1999).

[14]Collinearity is a linear relationship between two explanatory variables

Mortimer (2002) investigate the capabilities and limitations of adopting these competing frontier estimation techniques for efficiency measurement. A literature review of fourty-one real world DEA versus SFA comparisons, conclude that neither technique has and absolute advantage over the other. The adoption of one efficiency measurement technique over another will always lead to an opportunity cost of some description. It should be emphasized that the mathematical programming technique DEA and the econometric approach SFA address different questions, serve different purposes, and have different informational requirements and as such, the choice of estimation technique should be research specific, which best fits the aims and objectives of the analysis. Further, the SFA approach in its most common form only considers a single output. Hence, where electricity generation and distribution are most characterised by multiple outputs, the efficiency estimation may result in bias when assuming a single output. It is therefore appropriate and prudent to employ DEA when constructing models related to the efficiency performance benchmarking of electricity generation and distribution in EPSs.

3.14 Summary

This Chapter provides a systematic review of the literature in all fields that are germane to this research. The terms efficiency and productivity are discussed and the seminal contributions of Farrell (1957) to economic efficiency measurement are acknowledged and illustrated. The evolution of frontier estimation and the contrasting parametric SFA and non-parametric DEA techniques to efficiency measurement are defined, presented and interpreted. A comprehensive literature review relating to applications of DEA to the electricity generation and distribution functions of EPSs is introduced. The capabilities and limitations associated with DEA and SFA techniques are discussed, concluding that the employment one technique over another is research specific and should reflect the aims and objectives of the research. The non-parametric technique DEA is more applicable when constructing models to reflect the underlying characteristics of EPS. This is evident from the successful applications of DEA to EPS efficiency research and consequently a DEA technical efficiency evaluation methodology is applied to the all island SEM.

The research conducted in this thesis adds to the field of research in evaluating the technical efficiency of EPSs. The input-output parameters, alternative combinations and constructed DEA models are the salient contributions to knowledge in this thesis. The research contributes to knowledge by advancing DEA applications to electricity distribution by incorporating a new diagnostic parameter industrial output to account for differences across regions in terms of electricity distribution characteristics as opposed to incorporating traditional exogenous variables extensively employed in the literature. The three tier methodological efficiency framework, DEA models, parameters employed and methods developed are generic and applicable to other EPS worldwide for efficiency performance measurement. The concept of the three tier methodological efficiency framework is transferable and applicable to other sectors of a countries economy.

CHAPTER 4

Data Envelopment Analysis (DEA) Methodology

4.1 Introduction

The purpose of this Chapter is to provide a technical and analytical framework for the empirical analysis of the Irish EPS that will be presented in Chapter 6. The chapter exhibits the theoretical underpinnings of the adopted DEA models. DEA is a non-parametric technique employing piecewise linear programming to calculate the relative efficiency of as set of comparable entities entitled DMUs[1]. The mathematical notation concerning the fundamental Charnes Cooper Rhodes (CCR) Constant Returns to Scale (CRS) and Banker Charnes Cooper (BCC) Variable Returns to Scale (VRS) DEA models are presented along with extensions to these models for efficiency analysis.

4.2 Data Envelopment Analysis (DEA)

Research is never done in isolation. In the non-parametric context, Farrell (1957) proposed a piecewise-linear convex hull technique to estimate the frontier production function whilst the academics, (Boles, 1967; Afriat, 1972)[2] advocated that mathematical programming techniques could form the basis of the estimation. The non-parametric approach to frontier estimation is attributed to the influential paper "Measuring the Efficiency of Decision Making Units" by (Charnes et al., 1978). They adopted a non-parametric piecewise linear programming technique to measure technical efficiency, referring to the process as "Data Envelopment Analysis". This term has been firmly established in the literature, and is extensively used. DEA is a technique

[1]In the literature on productivity and efficiency analysis the term "Decision Making Unit" (DMU) is used to describe a productive entity in instances when the term "firm" may not be entirely appropriate. Examples of DMUs include power plants, electricity distribution zones, schools, hospitals, universities and police forces.

[2]Boles (1967) theorised how a multiple output case could be formulated. Afriat (1972) contributed to the non parametric framework by formulating and extending Farrell's model with Variable Returns to Scale (VRS) in single output case. Neither academic received recognition for their contributions to the non-parametric framework.

to measure the relative technical efficiency of DMUs. The generic term DMU describes the collection of firms, departments, or divisions which have multiple incommensurate inputs and outputs that are being assessed for efficiency. Charnes et al. (1978) proposed a model which subsequently became known as the CCR model that:

"generalised the single output-input ratio measure of efficiency for a single DMU in terms of a fractional linear-programming formulation transforming the multiple output-input characterisation of each DMU to that of a single "output and virtual input" (Charnes et al., 1994).

DEA is a linear programming model applied to observed data that provides a way to construct production frontiers as well as calculate the efficiency scores relative to those constructed frontiers (Murillo-Zamorano, 2004). It is a multi-factor productivity analysis model for measuring the relative efficiencies of a homogeneous set of DMUs. DEA measures the holistic efficiency of a DMU by comparing it with other homogeneous DMUs that transform the same measurable positive inputs into the same measurable positive outputs (Brooks and Cuillinane, 2007). This homogeneity constitutes a fundamental underlying assumption upon which the veracity of DEA research is established. DEA models produce detailed information on the efficiency of each DMU, not only relative to the efficiency frontier they formulate but also to specific efficient DMUs that can be identified as role models or comparators (Hawdon, 2003).

DEA accommodates the efficiency measurement of multiple outputs and multiple inputs without pre-assigned weights and where no functional form is pre-established but one is calculated from the sample observations in an empirical way. Since Charnes et al. (1978) pioneering CCR DEA model, numerous academics and scholars have developed, enhanced and extended its application (Banker et al., 1984; Seiford and Thrall, 1990; Seiford, 1996; Tone, 2001). DEA is a non-parametric technique extensively adopted primarily for performance measurement, target setting and benchmarking of DMU by academics and practitioners worldwide. Evidence of this fact is given by the extended applications of DEA to varying fields of research. The reader is referred to (Emrouznejad et al., 2008; Cook and Seiford, 2009; **?**; Emrouznejad and Banker, 2010*b*). There are multiple formulations of DEA models, two of the most frequently utilised DEA models in economic literature are the CCR and the BCC models (Charnes et al., 1978; Banker et al., 1984).

The mathematical notation underpinning these two fundamental DEA models and their extensions is presented. Assume that the relative efficiency of a set of comparable DMUs is to be investigated (e.g thermal power plants), there exists a sample of n DMUs where each DMU consumes j input resources to produce r outputs. Economic efficiency research focuses on comparing DMUs by a measure of productivity. A measure of productivity is a relationship of real outputs to real inputs. The ratio of output to input measures the efficiency of a selected DMU in the sample as:

$$E_i = \frac{u_1 y_{1i} + u_2 y_{2i} + ... + u_m y_{mi}}{v_1 x_{1i} + v_2 x_{2i} + ... + v_j x_{ji}} = \frac{\sum_{r=1}^{m} u_{ri} y_{ri}}{\sum_{j=1}^{n} v_{ji} x_{ji}} \tag{4.2.1}$$

Where Efficiency of:$DMU_i = \frac{Weighted\ sum\ of\ DMU_i\ Outputs}{Weighted\ sum\ of\ DMU_i\ Inputs}$

DMU_i = the efficiency of DMU_i
u_r = the weight given to output r
y_{ri} = the amount of output r from DMU_i
v_j = the weight given to input j
x_{ji} = the amount of input j to DMU_i

Within the DEA framework, multiple inputs and multiple outputs are reduced to a single virtual input and a single virtual output, culminating in a single relative efficiency score. DEA establishes that each DMU be allowed to adopt a set of weighted factors that portray it in the most favourable light in comparison to the other DMU (Dyson et al., 1990). The weights (multipliers)[u,v] corresponding to the outputs and inputs selected are to achieve Pareto efficiency for each DMU. Pareto efficiency is attained by a DMU, if and only if none of its inputs or outputs can be improved without worsening some of its other inputs or outputs (Cooper et al., 2007).

4.3 Charnes Cooper and Rhodes (CCR) Models

The DEA model was first introduced by (Charnes et al., 1978). The CCR model assumes a set of input-output variables are established for a set of DMUs, DEA constructs a Production Possibility Set (PPS)[3] containing all input-output vector correspondences that are feasible. Simultaneously, it estimates the maximum feasible radial expansion of the output or radial contraction of the input levels of each DMU operating within PPS. Within this framework one can stipulate that the CCR model, analysing DMU efficiency performance to be either input or output oriented. *Input oriented models* are models whose objective is to minimise inputs while producing at least the given output levels. *Output oriented models* are models that attempts to maximize outputs while using no more than the observed amount of any input (Cooper et al., 2007). As in Charnes et al. (1978) a input orientated CCR model is assumed.

The CCR model imposes three constraints; 1) that the PPS exhibits CRS; 2) convexity of the set of feasible input-output combinations; and 3) strong disposability of inputs and outputs (Murillo-Zamorano, 2004). An assumption of technical efficiency of each DMU is formed by the ratio of virtual weighted outputs to virtual weighted inputs. When the above stated assumptions and constraints are present, the formulation of the *primal* form of the CCR linear programming model to measure technical efficiency for each DMU is given as:

[3]PPS is defined as the set of feasible activities. DEA models implicitly use PPS to evaluate relative efficiency of DMUs.

$$Max\ DMU_k = \theta_k = \frac{\sum_{r=1}^{m} u_{rk} y_{rk}}{\sum_{j=1}^{n} v_{jk} x_{jk}} \tag{4.3.1}$$

$$\text{Subject to:} \quad \frac{\sum_{r=1}^{m} u_{rk} y_{rz}}{\sum_{j=1}^{n} v_{jk} x_{jz}} \leq 1; \qquad z = 1, ..., s;$$

$$u_{rk}, v_{jk} \geq 0;\ r = 1, ..., m;\ j = 1, ..., n;$$

In this formulation, there are m outputs produced, n input resources, and z DMUs. k is the DMU being evaluated in the set of $z = 1, ..., n\ DMUs$, θ_k is the efficiency measure of DMU "k" rated relative to all the other DMUs. The output data y_{rk} is the value of output r for DMU_k, while x_{jk} is the input j for DMU_k during the period of observation. u_{rk} is the coefficient or weight assigned to outputs r computed in the solution to the DEA model, similarly v_{jk} is the coefficient or weight assigned to inputs j computed by the DEA model solution. These weights can be 1) fixed in advanced or 2) derived from the data (Cooper et al., 2000). All weights are restricted to be non-negative. Thus, the weighted sum of the DMU outputs must be less than or equal to the weighted sum of the DMU inputs $\sum_{r=1}^{m} u_{rk} y_{rk} \leq \sum_{j=1}^{n} v_{jk} x_{jk}$. The measure of efficiency is defined as the maximisation of the ratio of weighted linear combinations of outputs to the weighted linear combinations of inputs, subject to the constraint that the efficiency score obtained for each DMU cannot exceed one. The efficiency score is bounded between zero and one. (Note: the mathematical program is run z times for each DMU to determine efficiency. That is, the parametric approach optimizes over all observations as opposed to the non-parametric DEA optimisation of each observation).

The formulation of Equation 4.3.1 is non-linear. It is a fractional linear program where the numerator has to be maximised and the denominator minimized simultaneously (an infinite number of solutions). The objective function will become linear if either the denominator or numerator of the ratio is forced equal to one (Onut and Soner, 2007). A transformation developed by Charnes and Cooper (1962) for fractional programming introduces a constraint $\sum_{j=1}^{n} v_j x_{jz} = 1$ stipulating the sum of all inputs is one which provides:

$$Max\ DMU_k = \theta_k = \sum_{r=1}^{m} \mu_{rk} y_{rk} \tag{4.3.2}$$

$$\text{Subject to:} \quad \sum_{r=1}^{m} \mu_{rk} y_{rz} - \sum_{j=1}^{n} v_{jk} x_{jz} \leq 0; \qquad z = 1, ..., s;$$

$$\sum_{j=1}^{n} v_{jk} x_{jk} = 1$$
$$\mu_r, v_j \geq \varepsilon > 0;\ r = 1, ..., m;\ j = 1, ..., n;$$

where the notation changes from u and v to μ and v reflects the transformation. ε is an infinitesimal positive number, which constrains the input and output coefficients to be positive, eliminating the possibility that they will be given a zero relative value in the DEA results (Cooper et al., 2004; Arnold et al., 1998). This form is known as the *multiplier* form of the linear programming problem. Computation of an efficiency score is done with the dual of primal model. Employing the duality theorem[4] in linear programming, one can derive an equivalent *dual or envelopment* form of the problem:

$$Min\ \theta_k - \varepsilon(\sum_{j=1}^{n} s_{jk}^{-} + \sum_{r=1}^{m} s_{rk}^{+}) \tag{4.3.3}$$

$$\text{Subject to:} \sum_{z=1}^{s} x_{jz}\lambda_z + s_{jk}^{-} = \theta x_{jk} \quad j = 1, 2, ..., n;$$
$$\sum_{z=1}^{s} y_{rz}\lambda_z - s_{rk}^{+} = y_{rk} \quad r = 1, 2, ..., m;$$
$$\lambda_z, s_{jk}^{-}, s_{rk}^{+}, \geq 0 \qquad z = 1, 2..., s.$$

where θ_k is the scalar efficiency measure of DMU "k" rated relative to all the other DMUs, s_{jk}^{-} slack variables[5] for input constraints, which are constrained to be non-negative, s_{rk}^{+} slack variables output constraints, which are non-negative, and λ_z is the dual coefficient or weight assigned to DMUs. Slacks will be examined in greater detail in Section 4.6. This envelopment form has fewer constraints than the multiplier form, and hence is the generally preferred form to solve[6]. It will satisfy $\theta \leq 1$, with technically efficient DMUs scoring unity, indicating the point of PPS, while inefficient DMUs will score less than unity. The performance of a DMU_k (the DMU being evaluated relative to the performance of all DMUs) is said to be (100%) technically efficient if and only if the following two conditions are both satisfied (Cooper et al., 2000, 2004):

$$(i)\ \theta^* = 1$$
$$(ii)\ \text{All slacks are zero } (s^{-^*} = s^{+^*} = 0)$$

A DMU is referred to as "weakly efficient" if and only if, *(i)* $\theta^* = 1$ and *(ii)* ($s_i^{-} \neq 0$ and/or $s_r^{+} \neq 0$) occur for some r and j in some alternate optima. The fulfillment of conditions *(i)* and *(ii)* define "Pareto-Koopmans"[7] or "strong efficiency", which can be verbalized as: PK efficiency

[4]Duality Theorem: (i) In a primal-dual pair of linear programmings, if either the primal or the dual problem has an optimal solution, then the other does also, and the two optimal objective values are equal. (ii) If either the primal or the dual problem has an unbounded solution, then the other has no feasible solution. (iii) If either problem has no solution then the other problem either has no solution or its solution is unbounded Cooper et al. (2000)

[5]The presence of slacks reveals the scope for further non-radial reduction in inputs or expansion in the case of outputs once an inefficient DMU is projected on to the production frontier.

[6]The forms defined by equation are introduced here for expository purposes.

[7]PK efficiency refers to the Pareto concept of welfare efficiency employed in "welfare economics" and extended to "production economics" by Koopmans (1951)

can be attained if and only if it is not possible to improve any input or output without worsening some other input or output (Cooper et al., 2007).

4.3.1 Two Inputs One Output Case

To provide clarity, an illustration to establish the relative performance of six DMUs for a single output multiple (two) input case is outlined in this section (Mullarkey et al., 2011). An input oriented model is assumed and considers the performance of six thermal power plants (A-F), which each have the following inputs and outputs: Fuel Consumption X_1 TeraJoules (TJ), Unit Rate Export Capacity X_2 MW, and output of Annual Energy Production Y_1 Megawatt-hour (MWh). Efficiency of an individual DMU (or thermal power plant) is equal to output/two inputs. For illustration purposes the numerical values employed are simplistic. Table 4.1 presents these values.

Table. 4.1: Two Input and One Output Numerical Example

Thermal Power Plants DMU	Fuel Consumption X_1	Export Capacity X_2	Annual Production Y_1	Input X_1/Y_1	Input X_2/Y_1
A	2	5	1	2	5
B	2	4	2	1	2
C	6	6	3	2	2
D	3	2	1	3	2
E	6	2	2	3	1
F	10	2	2	5	1

The input-output ratios for this example are shown in Figure 4.1. The DEA frontier corresponds to the solution of the DEA model defined and is obtained by running six separate linear programming problems - one for each of the six thermal power plants. Figure 4.1 illustrates that points F, B and E employ less inputs resources and as such form the *efficiency frontier*. If all the data is "Enveloped" within this region the area where operations are feasible is entitled the piecewise linear PPS delineated by points F, B and E. The thermal power plants operational in this area are not on the frontier and as such are inefficient. Thermal power plants A, C and D are inefficient to the extent that they need to move to A', C', D' respectfully to become efficient. Note the technical efficiency of C is 0.833%, interpreted as thermal power plant C could possibly reduce consumption of all inputs by 16.7% without reducing output. This technical efficiency score is calculated by projecting a ray from the origin 0 through C' to point C, and then obtain C's efficiency as: $0C'/0C=0.83$. This implies production at point denoted C'.

Focusing on its current inefficient state, DMU C, consumes inputs of 2TJ of fuel consumption/annual production in 2MW of export capacity/annual production. It can maintain current annual production of 3MWh and adopt strategies to the coordinates of the efficiency projec-

tion point C'. This is achieved by reducing both fuel consumption and export capacity by 0.833x(2,2)= (1.666,1.666). Graphically this is the shortest possible distance to the efficiency frontier. Thus firm C should produce its 3 units of output with 3x(1.666,1.666)=(5,5) units of the two inputs. This projection point C' lies between the line joining thermal power plants B and E and are therefore referred to as the *peers* of thermal power plant C. The same calculation process applies to the other inefficient thermal power plants, establishing efficiency scores for A of 0.5% and for D of 0.714%. The power plants F, B and E all have a technical efficiency score of 1 as they lie on the efficiency frontier.

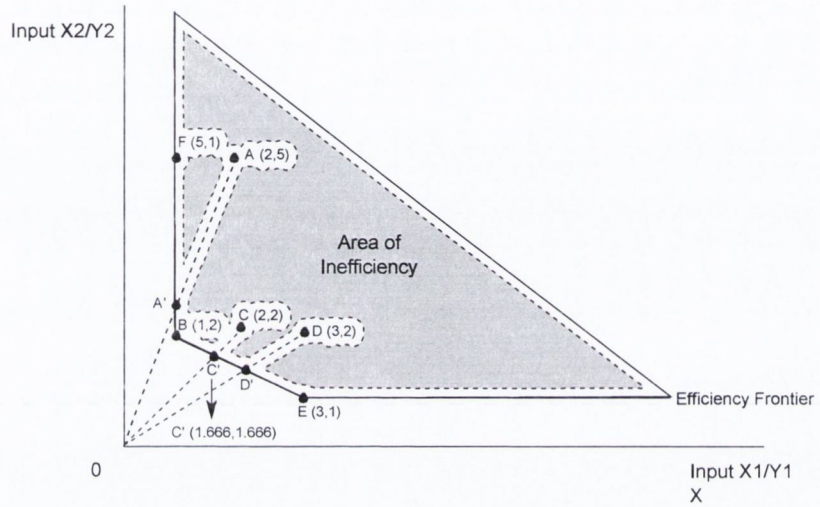


Fig. 4.1: Efficiency Frontier Two Inputs One Output Case

4.4 Input and Output Orientation

A key attribute of DEA research is it's ability to project inefficient DMUs onto production frontiers. There are three possible corrective measures that can be adopted to achieve this: 1) *Input orientation* - reduce input amounts by as much as possible whilst keeping present output levels constant; 2) *Output orientation* - maximise output at the current input consumption levels; 3) A combination of 1 and 2. The first two approaches are classified as "radial[8]" models and require a distinction between input and output orientation. The third approach is represented by the Additive and Slacks Based Measure (SBM) models that employ non-radial measures of efficiency where the focus is analysing the existence of slacks by addressing input excesses and output shortfalls. Slack analysis is discussed in Section 4.6. These efficiency formulations can enhance resource based decisions (Van Fulton, 2005).

[8]"Radial" means that a proportionate change in input-output values is the main concern and hence neglects the existence of slacks (input excesses and output shortfalls remaining in the model) as secondary or freely disposable, whereas Non-Radial deals with slacks directly and does not stick to a proportionate change of input/output (Cooper et al., 2007).

The preceding fundamental DEA CCR model is *Input orientation* and corresponds to Farrell's input based measure of technical and allocative inefficiency outlined Section 3.4. However, this *Input orientation* approach can be extended to illustrate the Farrell technical and allocative *Output orientation* efficiency measure, by considering the case where production involves a single input (X1) and two outputs (Y1 and Y2) represented in Figure 4.2 (Fare, Grosskopf and Lovell, 1985).

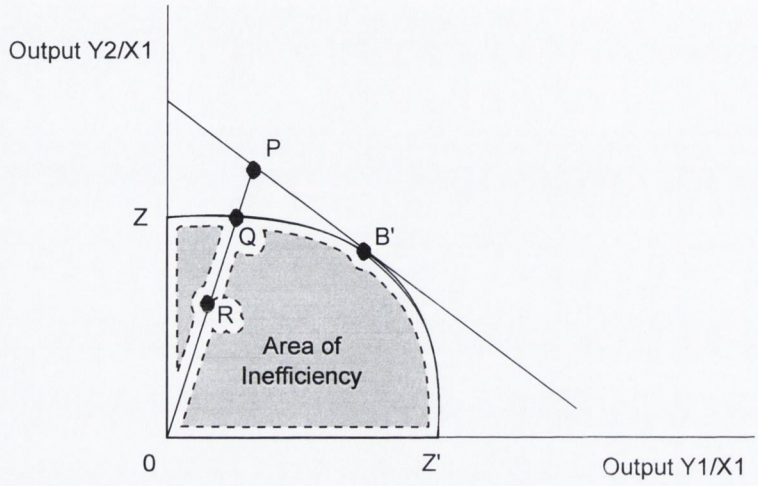


Fig. 4.2: Technical and Allocative Efficiency Output Orientation

4.4.1 One Input Two Outputs Case

In the DEA context consider the relative performance of seven DMUs for a single input multiple (two) output case. The output oriented model is assumed and considers the performance of seven Electricity Distribution Counties (EDC)s[9] (Mullarkey et al., 2012) (A-G).

Table. 4.2: One Input and Two Output Numerical Example

Electricity Distribution Counties (EDC)s	Network Length (km) X_1	Electricity Consumed (MWh) Y_1	Number of Customers Y_2	Output Y_1/X_1	Output Y_2/X_1
A	1	1	5	1	5
B	1	2	7	2	7
C	1	3	4	3	4
D	1	4	3	4	3
E	1	4	6	4	6
F	1	5	5	5	5
G	1	6	2	6	2

[9]EDCs are responsible for medium and low voltage electricity distribution in a particular geographical regions of Ireland. Each EDC region, or municipality is considered as a DMU under DEA investigation.

Each have the following input and outputs: Network Length X_1 km and outputs Electricity Consumed Y_1 MWh, Number of Customers Y_2 (Numerical Number). Efficiency of an individual DMU is equal to two outputs/one input. Figure 4.3 depicts an output-oriented DEA model, with the aim of maximising output levels whilst holding input quantities constant, the underlying technology is represented by the production possibility curve line ZZ'. The efficiency frontier consists of lines connecting the DMU points B, E, F and G as shown. The production possibility set is the region bounded by the axes and the efficient frontier, noting the observations A, C and D lie below the piece-wise linear production possibility curve ZZ' and are inefficient.

Efficiency can be by referring to the frontier lines, the efficiency of electricity distribution zone D is evaluated by $\frac{d(O,D)}{d(O,D')} = 0.75$ where $d(O,D)$ and $d(O,D')$ relate to the "distance from the origin to point D" and the "distance from the origin to point D' ". DMU D must increase both its outputs by 1.33 to become efficient, that is 1.33x(4,3) projects point D onto the efficiency frontier D' represented by the coordinates (5.33,4). Point D' shows the possible improvement available and 0.75% refers to the proportion of inefficiency in both outputs of DMU D. The corrective measure is to increase both outputs without altering their proportions - until point D' on the efficiency frontier is obtained. This is referred to as *"technical inefficiency"*.

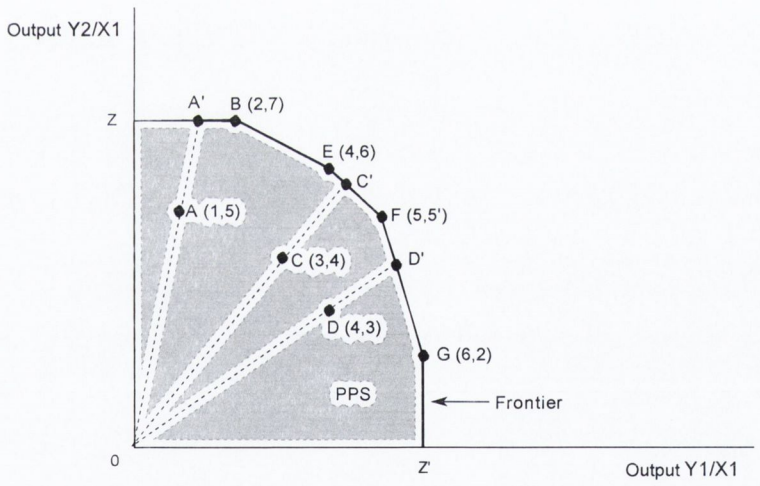


Fig. 4.3: Efficiency Frontier One Input Two Outputs Case

Another defined source of inefficiency is "mix inefficiency" and it occurs when some (but not all) outputs (or inputs) are identified as exhibiting inefficient behaviour. The corrective measure alters the proportions in which outputs are produced (or inputs are utilised) Cooper et al. (2007). An illustrative example is represented by the observation A which lies below the piece-wise linear production possibility curve. Point A is projected onto the frontier at point A', however this is not on the *efficient frontier*. It lies outside the DEA efficiency (production) frontier delineated by the B, E, F and G. The improvement in technical efficiency of DMU A to point A' does not remove all inefficiencies. This is due to the fact that Y1 production could be increased

by $A'B$ without consuming any more inputs. Thus there exists slacks in the production of Y1 represented by $A'B$. The examples given in Sections 4.4.1 and 4.3.1 achieve the same objective, projection onto the efficiency frontier and only differ in their direction to achieve this. Section 4.4.1 illustrates that efficiency is attained by progressing towards the origin and efficiency frontier *(Input-orientation)* whilst Section 4.3.1 achieves efficiency by progressing away from the origin to achieve the same objective of efficiency *(Output-orientation)*. The choice of particular orientation is case and industry specific, for example in electricity generation, DMUs must meet stated demand, hence input oriented model are appropriate as minimising input resources whilst meeting demand is the primary objective. An example in the output oriented sense could be applications to the hotel industry. Adopting either orientation should reflect which quantities (inputs and outputs the DMU managers retain most control over). The input-oriented CCR definition of DEA efficiency can be modified to exhibit the output-oriented version. Table 4.3 presents the CCR model in both the input and output oriented versions, each in the form of a pair of dual linear programs.

Table. 4.3: DEA Charnes Cooper Rhodes (CCR) Models

Input oriented	
Multiplier Model	Envelopment model
$Max\theta_k = \sum_{r=1}^{m} \mu_{rk} y_{rk}$	$Min\ \theta_k - \varepsilon(\sum_{j=1}^{n} s_{jk}^{-} + \sum_{r=1}^{m} s_{rk}^{+})$
Subject to:	Subject to:
$\sum_{r=1}^{m} \mu_{rk} y_{rz} - \sum_{j=1}^{n} v_{jk} x_{jz} \leq 0;\ z = 1, ..., s;$	$\sum_{z=1}^{s} x_{jz}\lambda_z + s_{jk}^{-} = \theta x_{jk} \quad j = 1, 2, ..., n;$
$\sum_{j=1}^{n} v_{jk} x_{jk} = 1$	$\sum_{z=1}^{s} y_{rz}\lambda_z - s_{rk}^{+} = y_{rk} \quad r = 1, 2, ..., m;$
$\mu_r, v_j \geq \varepsilon > 0;\ r = 1, ..., m;\ j = 1, ..., n;$	$\lambda_z, s_{jk}^{-}, s_{rk}^{+}, \geq 0 \qquad z = 1, 2..., s.$
Output-oriented	
Multiplier model	Envelopment model
$Min\theta_k = \sum_{j=1}^{n} v_{jk} x_{jk}$	$Max\ \phi + \varepsilon(\sum_{j=1}^{n} s_{jk}^{-} + \sum_{r=1}^{m} s_{rk}^{+})$
Subject to:	Subject to:
$\sum_{j=1}^{n} v_{jk} x_{jz} - \sum_{r=1}^{m} \mu_{rk} y_{rz} \geq 0;\ z = 1, ..., s;$	$\sum_{z=1}^{s} x_{jz}\lambda_z + s_{jk}^{-} = x_{jk} \quad j = 1, 2, ..., n;$
$\sum_{r=1}^{m} \mu_{rk} y_{rk} = 1$	$\sum_{z=1}^{s} y_{rz}\lambda_z - s_{rk}^{+} = \theta y_{rk} \quad r = 1, 2, ..., m;$
$\mu_r, v_j \geq \varepsilon > 0;\ r = 1, ..., m;\ j = 1, ..., n;$	$\lambda_z, s_{jk}^{-}, s_{rk}^{+}, \geq 0 \qquad z = 1, 2..., s.$

(Coelli et al., 2005, 1998) stipulate an important point that *"the input and output oriented DEA models will estimate exactly the same frontier and therefore, by definition, identify the same set of firms as being efficient. It is only the efficiency measures associated with the inefficient firms that may differ between the two methods"*. Input and output orientation under constant returns to scale yields the same efficiency scores and Coelli and Perelman (1996) states the choice of any particular orientation rarely has more than a minor influence upon the efficiency scores obtained.

4.5 Banker Charnes and Cooper (BCC) Models

The fundamental CCR model assumes CRS, which is arguably less appropriate for evaluation of EPS, because there should be no assumption of constant returns to scale (Nerlove, 1963). Nerlove (1963) focused on the issue of economies of scale by modelling the nature of production under a cost function specification and concluded that economies of scale were exhausted at relatively modest firm size (Hisnanick and Kymn, 1999). The CRS assumption is only appropriate when all DMUs are operating at an optimal scale. However, imperfect competition, government regulations, constraints of finance, among others may inhibit a firm from operating at optimal scale (Margaretio and Romero, 2004; Coelli, 1996).

The CCR model can be altered to incorporate a more general VRS environment. The CCR model exhibits CRS assumption and evaluates the Total Technical Efficiency (TTE) for each DMU, specifically by aggregating Pure Technical Efficiency (PTE) and Scale Efficiency (SE) into one value. The BCC model with VRS can differentiate between PTE and SE, and determine if Increasing Returns to Scale (IRS), Decreasing Returns to Scale (DRS), or CRS possibilities are present[10].

The BCC model differs from the CCR by incorporating the condition $\sum_{j=1}^{n} \lambda_j = 1$ which is also written as $e\lambda = 1$ where e is a row vector with all elements unity and λ is a column vector with all elements of non negative. Together with the condition $\lambda_j \geq 0$ for all j, this imposes a convexity condition on allowable ways in which the observations for the n DMUs may be combined. This added constraint introduces an additional variable into the (dual) of the multiplier problems. The envelopment form is given as:

$$Min\ \theta_k - \varepsilon(\sum_{j=1}^{n} s_{jk}^{-} + \sum_{r=1}^{m} s_{rk}^{+}) \tag{4.5.1}$$

$$\text{Subject to:} \quad \sum_{z=1}^{s} x_{jz}\lambda_z + s_{jk}^{-} = \theta x_{jk} \quad j = 1, 2, ..., n;$$

$$\sum_{z=1}^{s} y_{rz}\lambda_z - s_{rk}^{+} = y_{rk} \quad r = 1, 2, ..., m;$$

[10]Term returns to scale relates to a firms production function and relates to changes in output resulting from proportional change in all inputs. 1) If output increases by that same proportional change then CRS prevails, 2)If output increases by less than that proportional change there are DRS, 3) If output increases by more than that proportional change there is IRS

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_z, s_{jk}^-, s_{rk}^+, \geq 0 \qquad z = 1, 2..., s.$$

Coelli et al. (2005) state that incorporating the convexity constraint ensures that an inefficient firm is only benchmarked against firms of a similar size. A comparison of the fundamental CCR and BCC models is illustrated in Figure 4.4. A one input, one output VRS production technology is depicted exhibiting four DMU, A, B, C and D (e.g. four thermal power plants). The efficient frontier of the CCR model under CRS assumptions is illustrated by the continuous line from the origin passing through point B. DMU B can be extrapolated to points on this line, such that the change in input level causes an equally proportional change in the output level. The efficient frontier of the BCC model under VRS assumption is depicted by the bold lines linking points A, B and C. It consists of convex combination of the extreme points lying on the production surface.

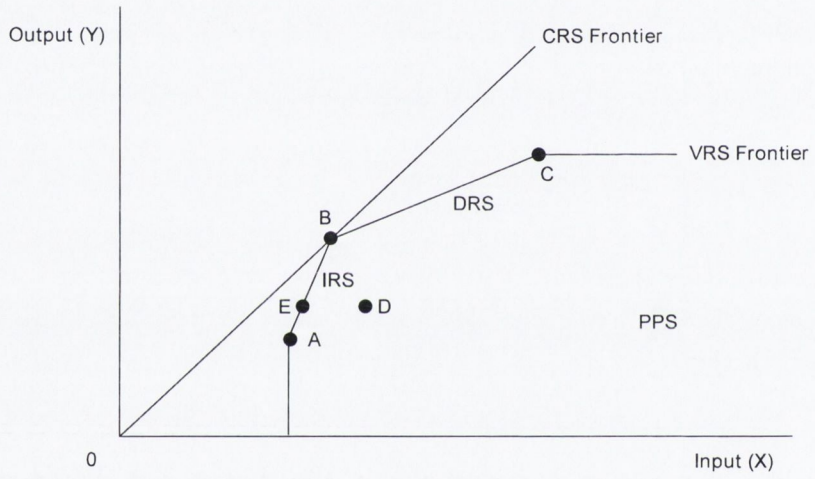


Fig. 4.4: Technical and Scale Efficiency Measures

The PPS is the area between the VRS production frontier and the x-axis, inclusive of these bounds. It consists of the frontier together with observed or possible activities with a surplus of inputs and/or a shortfall in output compared with the frontier. The firms A, B and C are all operating technically efficiently (i.e. BCC efficient) as they lie on the production frontier. However, only firm B is CCR efficient. If the underlying technology is assumed to be VRS then a scale efficiency measure can be obtained for each individual firm. Returning to Figure 4.4, it can be observed that firm A is operating in the increasing returns to scale portion of the production frontier and can enhance productivity by increasing its scale of operation approaching point B.

Point C is operating in the decreasing returns to scale portion of the production frontier and can enhance productivity by decreasing its scale of operation approaching point B. The firm positioned at point B, cannot become more productive by altering its scale of operation. It is noted, firm B is operating at the "optimal" (feasible) production point that maximises productiv-

ity, also entitled the *Most Productive Scale Size (MPSS)* or equivalently the *Technically Optimal Productive Scale (TOPS)* (Fried et al., 2008; Coelli et al., 2005; Cooper et al., 2007). To conceptualise a scale efficiency measure, note the technically inefficient firm operating at point D. It is clearly evident that productivity of firm D could be enhanced by progressing to point E on the VRS frontier (i.e. eliminating technical inefficiency), and further enhancement can be obtained by moving from point E to point B (i.e. eliminating scale inefficiency). The distance of the scale size of a DMU from MPSS is reflected in its scale efficiency. This is defined as in either an input or output orientation as the ratio TTE (i.e. CRS) and PTE (i.e. VRS) expressed as:

$$\textit{Total Technical Eff (TTE)} = [\textit{PureTechnical Eff (PTE)}]\, X\, [\textit{Scale Eff (SE)}] \tag{4.5.2}$$

with the scale efficiency measure defined as:

$$SE = \frac{\theta_{\text{CCR}^*}}{\theta_{\text{BCC}^*}} \tag{4.5.3}$$

Note: the technical efficiency of a particular firm or DMU will not exceed its pure technical efficiency irrespective of orientation. Hence, from the above formulae, it can be concluded that scale efficiency will always be ≤ 1. The mathematical formulation of the input and output oriented BCC models are expressed in Table 4.4. In summation, the fundamental DEA models can be represented by classification in the following pictorially figure adopted from Charnes et al. (2000).

Table. 4.4: DEA Banker Charnes Cooper BCC Model

Input oriented	
Multiplier Model	Envelopment model
$Max\theta_k = \sum_{r=1}^{m} \mu_{rk} y_{rk}$	$Min\ \theta_k - \varepsilon(\sum_{j=1}^{n} s_{jk}^{-} + \sum_{r=1}^{m} s_{rk}^{+})$
Subject to:	Subject to:
$\sum_{r=1}^{m} \mu_{rk} y_{rz} - \sum_{j=1}^{n} v_{jk} x_{jz} \leq 0;\ z = 1, ..., s;$	$\sum_{z=1}^{s} x_{jz}\lambda_z + s_{jk}^{-} = \theta x_{jk} \quad j = 1, 2, ..., n;$
$\sum_{j=1}^{n} v_{jk} x_{jk} = 1$	$\sum_{z=1}^{s} y_{rz}\lambda_z - s_{rk}^{+} = y_{rk} \quad r = 1, 2, ..., m;$
	$\sum_{z=1}^{s} \lambda_z = 1$
$\mu_r, v_j \geq \varepsilon > 0;\ r = 1, ..., m;\ j = 1, ..., n;$	$\lambda_z, s_{jk}^{-}, s_{rk}^{+}, \geq 0 \quad z = 1, 2..., s.$
Output-oriented	
Multiplier model	Envelopment model
$Min\theta_k = \sum_{j=1}^{n} v_{jk} x_{jk}$	$Max\ \phi + \varepsilon(\sum_{j=1}^{n} s_{jk}^{-} + \sum_{r=1}^{m} s_{rk}^{+})$
Subject to:	Subject to:
$\sum_{j=1}^{n} v_{jk} x_{jz} - \sum_{r=1}^{m} \mu_{rk} y_{rz} \geq 0;\ z = 1, ..., s;$	$\sum_{z=1}^{s} x_{jz}\lambda_z + s_{jk}^{-} = x_{jk} \quad j = 1, 2, ..., n;$
$\sum_{r=1}^{m} \mu_{rk} y_{rk} = 1$	$\sum_{z=1}^{s} y_{rz}\lambda_z - s_{rk}^{+} = \theta y_{rk} \quad r = 1, 2, ..., m;$
	$\sum_{z=1}^{s} \lambda_z = 1$
$\mu_r, v_j \geq \varepsilon > 0;\ r = 1, ..., m;\ j = 1, ..., n;$	$\lambda_z, s_{jk}^{-}, s_{rk}^{+}, \geq 0 \quad z = 1, 2..., s.$

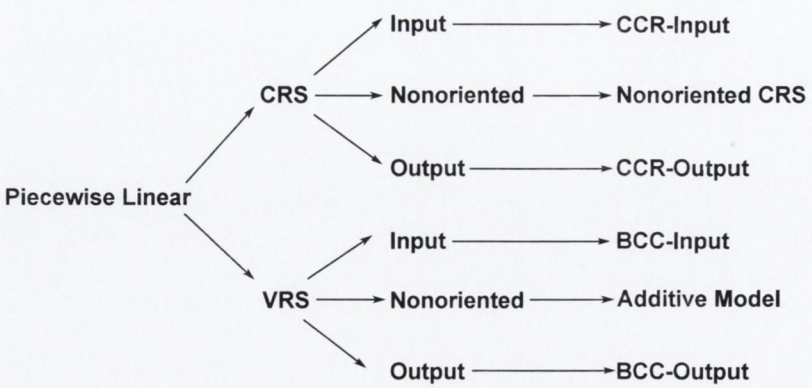


Fig. 4.5: Classification by Returns to Scale and Orientation

4.6 Peer Firms and Slacks Affiliated with Inputs and Outputs

The presence of slacks reveals the scope for further non-radial reduction in inputs or expansion in the case of outputs once an inefficient DMU is projected on to the production frontier. DMUs that are 100% efficient and operating on the efficiency frontier have zero slacks, conversely those DMU not operating on the efficiency frontier are inefficient and present slacks. Slacks relate to degree of inefficiency exhibited by DMU operating inefficiently and stem from the poor performance of inputs, outputs or both. If inputs are being utilised ineffectively and inefficiently, then there is input slack present or *input excesses*. Conversely, a similar situation unfolds if outputs are being utilized in an ineffective and inefficient manner, there is output slack or *output shortfall* in production.

For DEA models the assumption of convexity applies to the PPS P, which states that for any two points that are feasible, their convex combination is also feasible. That is, if two DMU lie on the efficiency frontier, then every point on the line segment connecting these two points belongs to P. As a result, DEA compares actual firms to virtual firms that are the weighted combinations of actual firms (Pasupathy, 2002). Peers or the "composite set" are the DMU firms that are operating on the efficiency frontier or the best-performing frontier. It is the existence of this *reference set* or *peer group* of efficient DMUs that forces inefficient DMUs to become efficient. Figure 4.6 depicts the relative efficiency of Six DMU in an input oriented environment. Firms C, D and E are operating on the efficiency frontier and are efficient whilst firms A, B, F lie north east of the efficiency frontier and are inefficient.

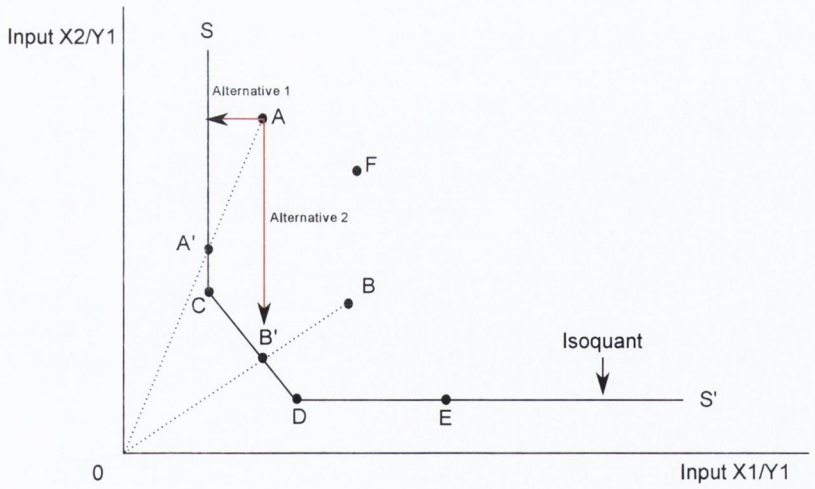


Fig. 4.6: Peer, Slack Identification and Improvement Potential

For DMU B, projection onto the efficiency frontier is observed to be point B′. This efficient DMU B′ lies on the line segment connecting the two efficient DMU C and D. Hence, both C and D are the peers of B and firm B is compared to the weighted combination of C and D. The technical efficiency of DMU A could be enhanced by progressing to point A′. The efficiency

of A is the ratio 0A′/OA, so the slack value is obtained by subtracting (1- 0A′/OA). In order to facilitate the progression of A to point A′, the ratio of inputs/outputs must be altered to achieve this but alternative strategies exist. These strategies where A achieves efficiency are represented by Alternative 1, progression towards the vertical axis (X2/Y1) or towards the horizontal axis (X1/Y1). In these cases the slack values obtained will differ and there acceptability will depend on the optimizing strategy adopted (Manzoni, 2007). Observing firm E, it lies on the efficiency frontier parallel to DMU D and as such is efficient. However, Firm E produces the same quantity as D in terms of output production, consumes the same resources as input X2 but more of input X1 for each unit of Y production. The distance DE is the excess of input X1 consumed by firm F and as such this existence of slack input should be acknowledge when determining its efficiency score.

4.7 Classification Proposal for DMUs

DEA identifies sources and estimates the extent of inefficiencies contained in the outputs and inputs generated by DMUs. Charnes and Cooper (1986) proposed an efficient-inefficient classification scheme relative to the unit isoquant. Kabnurkar (2001) states all DMUs can be dichotomized into two differing sets - Efficient (RE) and Inefficient (N). Figure 4.7 presents a the visually representation of the classification scheme.

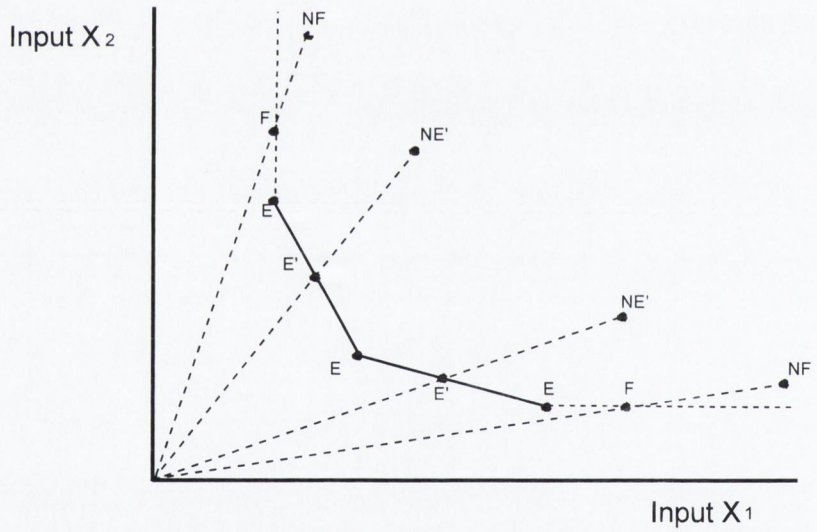


Fig. 4.7: Efficient and Inefficient Classification of DMUs

Figure 4.7 illustrates efficient (RE) DMUs can be sub-divided further into sets E E′ and F. Points designated by E are extremely efficient DMUs and form the vertices of the efficient frontier, E′ DMUs are not extremely efficient because they can be represented as a convex combination of extremely efficient E DMUs. Both E and E′ are on the PK efficient frontier of K. The points F are on the extended efficiency frontier and are characterised as being efficient DMUs with slacks. All points E E′ and F are scale efficient. The defined Inefficient set (N) is composed

of NE, NE′ and NF. Stipulating inefficient DMUs NE, NE′ and NF according to whether they relate to E E′ and F on the efficiency frontier provides a way to identify the scale efficiency properties and separate them from technical inefficiencies in any non-zero slacks that may be present (Charnes and Cooper, 1986). The classification proposals presented lay the foundations for the calculated and presented slack discussion of DMU's in Chapter Six.

4.8 Non Increasing Returns to Scale (NIRS)

If the underlying technology is thought to be VRS then a scale efficiency measure can be obtained for each DMU under analysis. This is achieved by employing the previously explained fundamental DEA CCR and BCC models to the same data set. Numerous research studies have decomposed the technical efficiency score obtained from the DEA CCR CRS model into two components, one attributed to scale efficiency and the other due to pure technical inefficiency (Coelli et al., 2005; Onut and Soner, 2007). If discrepancies exist between the CCR CRS and BCC VRS technical efficiency scores then one can conclude the presence of scale inefficiency. If a DMU is fully efficient (100%) in both the CCR and BCC efficiency scores, then it is operating in the Most Productive Scale Size (MPSS). If a DMU is BCC efficient but inefficient in the CCR model, then it is locally efficient but not globally and this is due to its scale size (Cooper et al., 2007). The calculation of a scale efficiency measure can be illustrated in Figure 4.8 for the one input one output case with the CRS and VRS DEA production frontiers included.

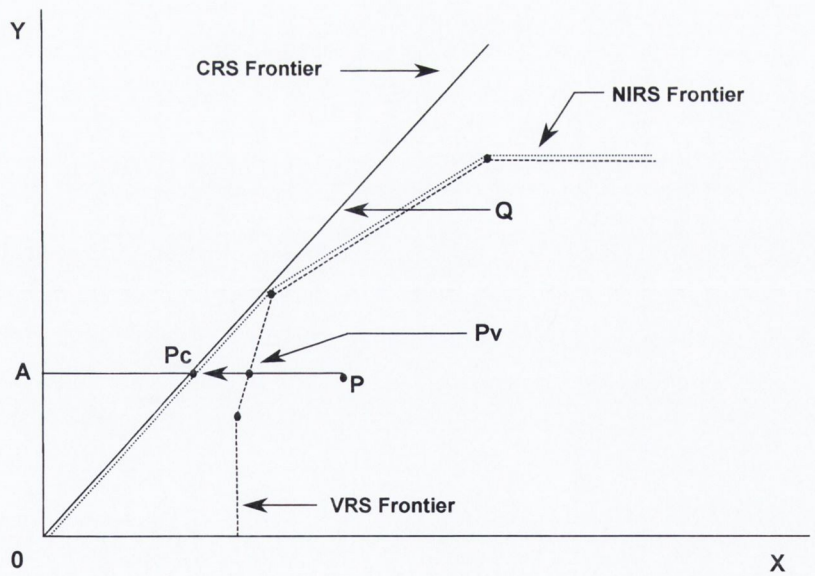


Fig. 4.8: Scale Economies

The technical inefficiency of point P is represented by the distance PPc under CRS input-orientation whilst the technical inefficiency of point P under the assumption of VRS would be PPv, with the difference between the two attributed to scale efficiency. This relationship can

be expressed in ratio efficiency measures as:
$TE_{I,CRS}$ = APc/AP
$TE_{I,VRS}$ = APv/AP
SE_I = APc/APv

where all these ratio measures are bounded by zero and one. This is also represented by: $TE_{I,CRS}$ = $TE_{I,VRS}$ x SE_I because of the relationship:
APc/AP = (APv/AP)x(APc/APv).

This example is adopted from (Coelli et al., 2005, 1998) and is graphically represented in Figure 4.8. The SE measure discussed, whilst alerting the analyst to the presence of scale inefficiency, fails to stipulate if the DMU in question is operating in the increasing or decreasing returns to scale area of the production function. This can be resolved by solving a linear programming problem where Non Increasing Returns to Scale (NIRS) are assumed. This is warranted to establish if the DMU in question needs to increase or decrease its scale of operation. By altering the fundamental BCC DEA model in Equation 4.5.1 by substituting $\sum_{j=1}^{n} \lambda_j = 1$ for $\sum_{j=1}^{n} \lambda_j \leq 1$ to obtain :

$$Min\ \theta - \varepsilon(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+) \tag{4.8.1}$$

$$\text{Subject to:} \quad \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{io} \quad i = 1, 2, ..., m;$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{ro} \quad r = 1, 2, ..., s;$$

$$\sum_{j=1}^{n} \lambda_j \leq 1$$

$$\lambda_j, s^-, s^+ \geq 0 \qquad j = 1, 2..., n.$$

By imposing a restriction forcing $\sum_{j=1}^{n} \lambda_j$ to be equal to or lower than one, a technical efficiency score can be obtained for the NIRS environment. The nature of the scale inefficiencies of the DMU in question can be determined by contrasting the technical efficiency scores of the NIRS and VRS DEA models. If they are unequal, increasing returns to scale exist for that DMU (NIRS TE ≠ VRS TE = IRS). If they are equal, then decreasing returns to scale applies (NIRS TE = VRS TE = DRS) (Coelli et al., 2005). An empirical application of this approach can be found in (Fare, Grosskopf and Logan, 1985).

4.9 Extensions to the fundamental DEA Models

DEA researchers have acknowledged external influences and other non-discretionary (sometimes causal) factors on DEA efficiency. Exogenous factors are variables that impact on the efficiency performance level of DMUs and are not under the control of the firm management. These factors are not inputs consumed nor outputs produced, but affect the level of inputs and

outputs exogenously. The previously discussed fundamental DEA models make no allowances for the presence of exogenous and non-discretionary fixed variables. The terms *exogenous*, and *non-discretionary* variables will be used interchangeably throughout this thesis. The fundamental DEA models are referred to as Discretionary models. Discretionary models of DEA implicitly assume that all inputs and outputs are discretionary variables, i.e., controlled by the management of each DMU and varied at its discretion (Saen, 2005). However, in any realistic situation, there may exist "exogenously fixed" or non-discretionary factors (variables) inputs and outputs that are beyond the management control of a particular DMU[11] which also need to be considered. Banker and Morey (1986*a*) in their analysis of sixty restaurants in a fast food chain refer to such variables as "exogenously fixed" or not under the control of firm management. They illustrate the impact of exogenous inputs in their study.

Instances of such non-discretionary variables from DEA literature include snowfall, soil characteristics, topography of different farms, age of facilities in different universities (Saen, 2005). Environmental variables related to benchmarking studies of electricity distribution include inverse density index, losses MWh, network length, and customer density (Mota, 2004). Failure to explicitly account for exogenously fixed variables will result in the adopted model returning unrealistic suggestions in order to improve efficiency performance. The reader will acknowledge that altering exogenous variables like the "mean site elevation, wind speeds, topography or level of rainfall" of a given region is an unrealistic suggestion. There are a number of techniques that can be employed to incorporate exogenous variables into DEA efficiency analysis. The techniques can be dichotomised somewhat loosely into one-stage models and two-stage models[12]. Single-stage techniques were established by (Banker and Morey, 1986*a*,*b*) whilst Timmer (1971) pioneered the two-stage technique. The first two of the following four techniques are adopted when the exogenous factors present can not be measured.

i If the exogenous factor can be ordered from the least favourable to the most favourable effect upon efficiency, then firms can be classified according to there favourability level and as such firms operating under the same environment are compared with each other or those firms operating in a less favourable environment.

ii If the exogenous variable can not be measured or no natural ordering is prevalent then the technique introduces categorical variables that restrict the comparison set to other DMUs in the same of higher (or the same or lower) categories. The exogenous variable must be a categorical variable. Both methods one and two can only incorporate one exogenous variable and suffer from the effect of a reduction in the comparison set, thereby reducing

[11] Ray (1988)states that a failure to incorporate all relevant non-discretionary variables simply results in technical inefficiency

[12] One-stage models use data on inputs, outputs and observable exogenous variables all at once, whilst two-stage models use data on inputs and outputs in the first stage, and use data on observable exogenous variables in the second stage.

the discriminatory power of the model. The final two techniques are employed when the exogenous factors present can be measured.

iii This approach to non-discretionary variables is to include them directly in the linear programming formulation along with the traditional inputs and outputs, but restrict the optimisation to either inputs or outputs. A prerequisite of this technique is that the direction of influence of the exogenous variable (upon efficiency) must be known a priori. If a "positive-effect" on efficiency is anticipated then it should be included in the linear program in the same way as a non-discretionary input would be included, conversely an exogenous variable with a "negative-effect" should be included in the linear program the same way a non-discretionary output would be included (Coelli et al., 2005). The formulation of Non-Discretionary (NDSC) is given in the next Section 4.9.1.

iv The two-stage technique incorporates a first stage DEA solution involving only the traditional inputs and outputs whilst the second stage regression analysis seeks to explain the variation in the first stage efficiency scores in terms of a vector of observable exogenous variables (Fried et al., 2002). The signs of the coefficients of the exogenous variables indicate the direction of influence whilst hypothesis testing can indicate the strength of relationships.

In this thesis, techniques ii), iii) and iv) are employed at various stages. The focus of interest is to investigate whether the source of inefficiency in a DMU is caused by the inefficient operation of the DMU itself or by the disadvantageous conditions under which the DMU is operating.

4.9.1 Non-Discretionary Model (NDSC)

NDSC models are an extension of the fundamental CCR and BCC models designed to incorporate exogenous parameters in DEA models. Figure 4.9 depicts an output-oriented model illustrating the relative efficiency of six DMUs (A-F) each having a normalised consolidated input and two outputs.

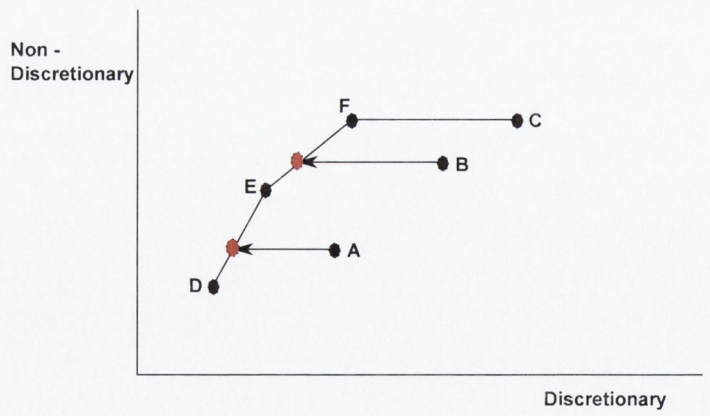


Fig. 4.9: Example of Exogenous Variables

Of the two outputs one is discretionary and the other is non-discretionary or exogenous, the red

diamonds show the way in which the inefficient DMUs A and B can alter the production process to become efficient. The movement is possible only along the direction of the discretionary variable, which is the horizontal axis, whilst the non-discretionary or exogenous variable is kept fixed. Banker and Morey (1986*a*) pioneer the formulation of the first DEA model for evaluating efficiency in the presence of "exogenously fixed" inputs. There efficiency model is a modification of the fundamental CCR model, differing in that it does not suggest any changes (increase of the output or decrease of the inputs) for any variable that is not within the discretionary control of the decision maker or manager. Equation 4.9.1 provides the formulation of the NDSC model.

$$Min\ \theta - \varepsilon(\sum_{i\in I_D} s_i^- + \sum_{r=1}^{s} s_r^+) \tag{4.9.1}$$

$$\begin{aligned}
\text{Subject to:} \quad & \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{io} \quad i \in I_D; \\
& \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{io} \quad i \in I_N; \\
& \sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{ro} \quad r = 1, 2, ..., s; \\
& \lambda_j \geq 0 \qquad j = 1, 2..., n.
\end{aligned}$$

where all variables (except θ) are constrained to be non-negative and $\epsilon > 0$ is a non Archimedean infinitesimal constant to assure strongly efficient solutions. The symbols $i \in I_D$ and $i \in I_N$ refer to the sets of discretionary and non-discretionary inputs, respectively. The non-discretionary variables do not enter directly into the efficiency measures being optimised but they can nevertheless affect the efficiency evaluations by virtue of their presence in the constraints (Cooper et al., 2007). The model formulation for the NDSC input-output CRS and VRS are given in Table 4.5.

Table. 4.5: DEA Non-Discretionary (NDSC) Model

Non-Discretionary (NDSC) Constant Returns to Scale	
Input Oriented	Output Oriented
$Min\ \theta - \varepsilon(\sum_{i\in I_D} s_i^- + \sum_{r=1}^{s} s_r^+)$	$Max\ \phi + \varepsilon(\sum_{i=1}^{m} s_i^- + \sum_{r\in O_D} s_r^+)$
subject to	subject to
$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{io} \quad i \in I_D;$	$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = \phi y_{ro} \quad r \in O_D;$
$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{io} \quad i \in I_N;$	$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{ro} \quad r \in O_N;$
$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{ro} \quad r = 1,2,...,s;$	$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{io} \quad r = 1,2,...,s;$
$\lambda_j \geq 0 \qquad j = 1,2...,n.$	$\lambda_j \geq 0 \qquad j = 1,2...,n.$
Non-Discretionary (NDSC) Variable Returns to Scale	
Input Oriented	Output Oriented
$Min\ \theta - \varepsilon(\sum_{i\in I_D} s_i^- + \sum_{r=1}^{s} s_r^+)$	$Max\ \phi + \varepsilon(\sum_{i=1}^{m} s_i^- + \sum_{r\in O_D} s_r^+)$
subject to	subject to
$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{io} \quad i \in I_D;$	$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{io} \quad r = 1,2,...,s;$
$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{io} \quad i \in I_N;$	$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = \phi y_{ro} \quad r \in O_D;$
$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{ro} \quad r = 1,2,...,s;$	$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{ro} \quad r \in O_D;$
$\sum_{j=1}^{n} \lambda_j = 1$	$\sum_{j=1}^{n} \lambda_j = 1$
$\lambda_j \geq 0 \qquad j = 1,2...,n.$	$\lambda_j \geq 0 \qquad j = 1,2...,n.$

4.10 Comparison of Attributes for CCR, BCC and NDSC Models

A synopsis of the attributes pertaining to the fundamental DEA models and their extensions is presented. The assumption of a positive data set for DEA models can be relaxed by alternating between *Semi-p-* non-negative with at least one positive element in the data for each DMU, and *Free-* permits negative values, zero or positive data. Incorporated into performance analysis and DEA models are two important properties of a reliable measure of efficiency; 1) *Translation Invariance* - that it be independent of an affine translation of the input and output variables Floudas and Pardalos (2001); Knox Lovell and Pastor (1995). This property is

of critical importance when data contain zero or non negative and must be translated prior to analysis (these transformations are to ensure that data are strictly positive prior to logarithmic transform). The Additive model is translation invariant only when the convexity constraint is added. 2) *Units Invariance* - that it is independent of the units in which the input and output variables are measured. This property has its origins in classical mathematics, an application called "dimensionless" (Bridgeman, 1933).

All the models presented produce as single scalar measure of efficiency θ^* with the exception of the additive model, a serious limitation. CRS and VRS relate to constant and variable returns to scale, respectfully. Based upon the literature, when researching EPS VRS models should generally be adopted. Careful consideration of the varying DEA models capabilities and limitations is paramount, before definitively concluding which DEA models are to be employed. The model characteristics discussed are adopted from (Cooper et al., 2007).

Table. 4.6: Comparison of Model Characteristics

Model	CCR-I	CCR-O	BCC-I	BCC-O	ADD	NDSC-I-O
Data Inputs	Semi-p	Semi-p	Semi-p	Free	Free	Semi-p
Outputs	Free	Free	Free	Semi-p	Free	Free
Translation Inputs	No	No	No	Yes	Yes	No
Invariance Outputs	No	No	No	No	Yes	No
Units invariance	Yes	Yes	Yes	Yes	No	Yes
Efficiency Score	[0, 1]	[0, 1]	(0, 1]	(0, 1]	No	[0, 1]
Returns to Scale	CRS	CRS	VRS	VRS	Both	Both

4.11 Summary

This chapter details the DEA models employed in the research and of links the computation of technical efficiency with production frontiers to (Farrell, 1957). The measurement of DEA efficiency is defined and explained. The mathematical notation underpinning the fundamental CCR VRS and BCC VRS DEA models are presented and illustrative examples are employed to present the application of these formulations. The calculation of an efficiency frontiers, peer reference DMUs and slacks, and input-output orientation are illustrated. The classification of efficient and inefficient DMUs and RTS properties are investigated. Extensions to the fundamental CCR and BCC DEA models in the form of NDSC models are illustrated. The NDSC models propose methodological formulations to account for exogenous variables that are out of the control of the DMUs but impact upon the efficiency scores obtained. The comparative attributes of the all the models employed in the DEA efficiency evaluation of the SEM are discussed. The Chapter presents the DEA methodology employed to conduct the efficiency evaluation of the all island SEM.

CHAPTER 5

Data Sources and Models

5.1 Introduction

DEA and its appropriate applications are dependent on the data set employed in the efficiency evaluation model being accurate, valid, precise and veritable. This thesis develops DEA models based on real world data in order to test the proposed models, methodology and define targets for efficient DMUs. This form of analysis is paramount to improving the operational efficiency of the Irish electricity system and achieving stated energy and emission reduction targets. This Chapter presents the conceptual framework for the application of DEA, emphasising certain necessary acceptable data characteristics and requirements that may ease the execution of the DEA models and the interpretation of the results. The appropriate selection of input-output variables and the astute development of models pertaining to this research thesis are presented, discussed and interpreted in this Chapter. Finally, issues relating to the process of validating the adopted models and research conducted are proposed and justified. A three tier generation and distribution efficiency analysis of the Irish EPS is defined and discussed. The core issue in modelling the electricity generation and distribution processes is to ensure that the models adopted represent and capture all the resources consumed and the outputs delivered are well specified. The modelling is conducted by DEA software programme SAITECH.

5.2 Conceptual Research Framework

Efficiency analysis and productivity are core managerial control tools for assessing the degree to which inputs are utilised in the process of obtaining desired outputs. As outlined in sections 3.7 and 3.8 DEA literature has expanded rapidly, reporting further conceptual and theoretical developments as well as numerous applications. Norman and Stroker (1991) state *"the value of DEAs contribution will depend on how well the efficiency analysis is meticulously planned and how well the results are integrated with other elements of management information"*.

Norman and Stroker (1991) explain the complete process of setting up the DEA performance measurement system highlighting the benefits management gains from a better understanding of the process within each unit of organisation and knows when and where action is needed to improve efficiency performance. Golany and Roll (1989) present a systematic research application procedure of the DEA methodology in its various stages. Attention is focused on defining the DMUs, the role of the units and the units primary objectives. Golany and Roll (1989) stipulate that DEA efficiency applications consists of three phases:

1. Definition and selection of DMUs to enter the analysis;
2. Determination of input and output factors which are relevant and suitable for assessing the relative efficiency of the selected DMUs, and;
3. Application of the DEA models and analysis of outcomes.

Each of these phases incorporates several steps which include heuristic, rule of thumb, selections of appropriate number of DMUs, physical organisational boundaries, and the time horizon for the application. The DEA research application framework in its entirety is presented in Figure 5.1. The salient issues relating to the correct application of Figure 5.1 are discussed extensively in this section.

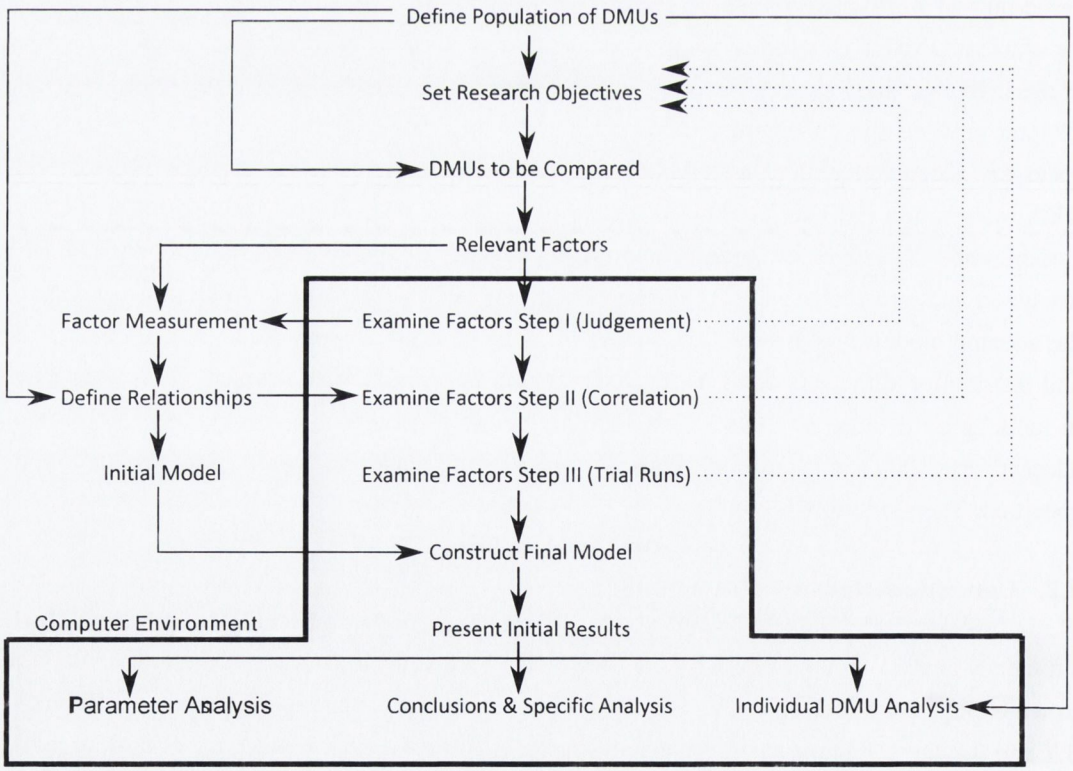


Fig. 5.1: DEA Application Framework

The employment of DEA mathematical programming models as an efficiency diagnostic tool relies significantly on the value of the data being true and valid. If there are legitimate concerns about the quality of the data being employed, the underpinnings of the adopted models become questionable and the research findings invalid and untenable. Jamasb et al. (2005) postulate that data should be readily available at realistic and reasonable levels of cost and effort, and sources should be reliable and ideally cross-checked whilst also ensuring that consistency and continuity of the dataset is maintained. For this research study several criteria exist to aid in the selection process of the input and output variables for the three tier efficiency study.

Firstly, an empirical criterion is data availability. Secondly, the literature review is a way of ensuring validity of the research and thus represents another criterion to be taken into account. The last criterion for measurement selection is the professional opinion of relevant individuals (Barros, 2008). Literature survey being the most important guideline in selecting input and output variables. The present research thesis conforms to these criteria by: 1) ensuring a full, valid dataset is available for analysis; 2) acknowledging and developing on concepts established in the literature review: 3) only employing relevant and pertinent indicators for assessing the efficiency of the SEM.

The selection of inputs (resources) and outputs (transformation of resources) indicators are dependent upon the research being conducted. It is imperative that the input-output selection factors should reflect the type of efficiency being assessed. For this reason researchers invest significant time, effort and resources in the optimal selection of input-output variables acknowledging what is postulated by theory and completed research. The discriminatory power of a particular model can be greatly enhanced by being parsimonious in the selection and number of factors. The optimal selection of efficiency performance indicators for research has seen extensive discussion and focus in recent years, with the primary arguments centreing on whether the efficiency indicators are measurable, comparable and consistent (Jamasb and Pollitt, 2001; Jamasb et al., 2004; Vaninsky, 2006; Jamasb et al., 2005).

Jamasb et al. (2005) suggests efficiency performance indicators whether physical, monetary or qualitative should be clearly definable, easily measurable and if consistent in definition then are comparable over time. The variables employed in efficiency analysis should be finalised after extensive consultation, help, guidance and advice from expert industry professionals, government and educational institutes. Keeney and Raiffa (1993) state a desirable set of measurement factors should be complete, decomposable, operational, non-redundant, and minimal. Thanassoulis (2001) states that:

"The relationship of exclusivity and exhaustiveness between inputs and outputs in a DEA assessment means that subject to the exogenity of factors involved, the inputs and they alone must influence the output level, and only of the outputs being used in the assessment".

Epstein and Henderson (1989) state all variables incorporated into the model have equal opportunity to influence the calculated efficiency performance. Golany et al. (1994) provide an extensive framework for factor analysis and adoption. The initial list of variables to include in the model should be comprehensive, extensive, exhaustive and inclusive reflecting the relevant and suitable variables affecting efficiency performance and must be strongly related to the underlying production function objectives of the DMUs under analysis (Ozbek et al., 2009). Golany and Roll (1989) postulate a framework to reinvestigate, reformulate and refine the initial list of variables and only to retain the most relevant and important variables. This framework process is necessary to establish the variables included in the three tier efficiency evaluation framework employed in this thesis. It incorporates three stages:

1. **Judgement Process:** This process entails judgement guidelines for the incorporation of factors that determine efficiency discrepancies. The factor judgement screening process may be implemented *inter alia* along the following line:

   (a) Is the factor related to , or contributing to, one or more of the objectives set for the application?;

   (b) Is the factor conveying pertinent information not included in other factors?;

   (c) Does the factor contain elements (e.g. price) which interfere with the notion of technical efficiency?; and

   (d) Are data on the factor readily available and generally reliable?.

2. **Quantitative Methods:** Certain quantitative methods exist that help refine the list of relevant indicators. Some variables can be aggregated into one variable (e.g number of people, gallons of fuel) reducing the number of variables. Regression analysis identifying correlations between variables and/or statistical analysis aids eliminating redundancies and reducing the number of variables.

3. **DEA Based Methods:** The remaining variables can be employed by the DEA models. By running DEA with a series of combinations of these variables, one can eliminate variables consistently being assigned small weights indicating little impact on the efficiency scores and having a low discriminatory power. These techniques further reduce the number of applicable valuable variables.

Most research studies do not describe the selection of factors or the process exhaustively. A few exceptions exist in the literature, Kittelsen (1993) adopt a stepwise procedure employing statistical tests of model specification to arrive at the set of included variables. Korhonen and Syrjanen (2003) select factors or efficiency indicators based on the correlation, regression analyses and graphical examination of variables. (Miliotis, 1992; Bagdadioglu et al., 1996) examine the robustness, strength and coherence of model specifics by incorporating and omitting inputs and outputs from the chosen model. Numerous rules of thumb relating to input-output selection and DMU requirements have been proposed in the literature to ensure the fundamental efficiency

models have more discriminatory power. Data selection, model validation and attaining high discriminatory power according to Boussofiane et al. (1991) is achieved when the minimum number of DMU observations is equal to, or larger than, the product of the number of inputs and outputs. Golany and Roll (1989) propose that the number of DMUs should be at least twice the number of inputs and outputs considered. Bowlin (1998) state the requirement to have three times the number of DMUs as there are input and output variables. Dyson et al. (2001) propose the number of DMUs needs to be twice the product of the number input and output variables employed in the analysis. There is an extensively adopted expression in the DEA literature, which relates the number of units evaluated to the number of input and output parameters considered:

$$n \geq max\, m\, s,\ 3(m+s) \tag{5.2.1}$$

where n is number of units evaluated and m, s is the relevant number of input and output parameters. With classical DEA models, selection of inputs and outputs affects the discriminatory power of DEA as the number of variables selected needs to be sufficiently small compared to the number of DMUs for effective discrimination (Kabnurkar, 2001; Pahwa et al., 2003). The reason for this is clear: it is evident that if the number of DMUs under investigation is small and the input-output variables selected for the analysis is close to the number of DMUs, the classical model losses discriminatory power and almost all the DMU will be deemed efficient (Charnes et al., 1994).

The efficiency scores obtained from DEA are only relative in magnitude among the units being investigated. It should be noted that efficiency is measured with respect to the DMUs and factors selected. The efficiency scores are strongly influenced by the selection of the number of DMUs and input-output variables. Due to the nature of the DEA approach, inserting more variables not only inflates DEA efficiency scores but also potentially conceals the actual extent of inefficiency (Liu et al., 2010).

5.3 Synopsis of Variable Selection for DEA

The DEA application framework outlined in Section 5.2 was stringently adhered to. DEA is a "data oriented" approach for evaluating the performance of a set of peer entities called DMUs which convert multiple inputs into multiple outputs (Cooper et al., 2004). This "data oriented" characteristic is of critical importance as any comparative efficiency evaluation employing inaccurate, erroneous or inconsistent data will lead to spurious and questionable results. Data therefore must be of an accurate and sound nature, meticulously scrutinized for discrepancies. In this thesis considerable time and effort was afforded to data refinement and the extensive validation of the sources and content. The database developed concerning the input-output variables for DEA analysis in this research thesis have been sourced predominately from collaborating and consultation with market system operators, generation and distribution companies, electricity

sector regulators, official meteorological centres and technical industry reports. Numerous parameters were considered for the research analysis. Table 5.1 provides a number of variables considered.

Table. 5.1: Selection of Variable considered for Research

Thermal Parameters	**Wind Parameters**	**Hydro Parameters**
Individual generator data, No. of units, plant type (mid, base, peaker) year of commission, percent fuel usage, forced outage rate %, O&M days per year	Wind Speed, availability factor, No. of wind farms, area km^2, capacity %, wind generation (MW), wind provinces, load factor, average wind generated, average annual production	Head size (m), pump efficiency, turbine efficiency, water inflow volume m^3, year of commission, capacity utilisation

The incorporation of CO_2 emissions into the thermal efficiency analysis was beyond the scope of the present thesis as the primary focus was on the operational efficiency performance of thermal power plants and not environmental efficiency performance. The parameters and datasets employed in the presented research thesis are presented in detail in Tables 5.2, 5.3, 5.4, 5.5, 5.6, 5.7. They relate to the thermal, hydro and wind electricity generation process and the electricity distribution process of the all island EPS and will be discussed in detail in the subsequent sections. Table 5.8 reflects the parsimonious models adopted and the set of variables selected for the three tier efficiency analysis of the Irish EPS.

Table. 5.2: Input and Output Data for Thermal Generating Units

Number	Generating Unit	Location	Plant Description	Unit Rate Export Capacity (MW)	Commission Decommission Year	No.Units Plant	Fuel Type	Heat Value Fuel Used (kCal/kg)	Fuel Consumption Terajoules (TJ)
1	Aghada	Cork	Gas Steam Turbine	258	1980 & 2020	1	Gas	13546	
			OCGT	85	1980	3	Gas/DO	11998	
			OCGT	85	1980	N/A	Gas/DO	11998	
			OCGT	85	1980	N/A	Gas/DO	11998	
			GT	26	2003	3	DO	10450	
			GT	26	1980	3	DO	10450	
			CCGT	430	2009	1	Gas/DO	11998	
				995		**6**		**82438**	**9133.16**
2	Ballylumford	Antrim	CCGT	97	1997 (Gas)	1	Gas/DO	11998	
			CCGT	160	2002	3	Gas/DO	11998	
			CCGT	160		N/A	Gas/DO	11998	
			CCGT	170		N/A	Gas/DO	11998	
			CCGT	170	2003	3	Gas/HFO	11998	
			CCGT	170		N/A	Gas/HFO	11998	
			CCGT	170		N/A	Gas/	11998	
			OCGT	58	1977 & 2020	2	DO	10450	
			OCGT	58		N/A	DO	10450	
				1213		**9**		**104886**	**20939.14**
3	Dublin Bay	Dublin	CCGT	403	2002	1	Gas/DO	11998	
				403		**1**		**11998**	**22956.29**
4	Coolkeeragh	Derry	CCGT	402	2004	1	Gas/DO	11998	
			GT	53	2004	1	DO	10450	
				455		**2**		**22448**	**18321.91**
5	Edenderry	Offaly	Peat Fired Condensed	117.6	2000	1	Peat	3583	
				117.6		**1**		**3583**	**15738.30**

Note: OCGT - Open Cycle Gas Turbine, CCGT - Combined Cycle Gas Turbine, GT - Gas Turbine, HFO - Heavy Fuel Oil, DO - Distillate Oil, N/A - Non Applicable

Number	Generating Unit	Location	Plant Description	Unit Rate Export Capacity (MW)	Commission Decommission Year	No.Units Plant	Fuel Type	Heat Value Fuel Used (kCal/kg)	Fuel Consumption Terajoules (TJ)
6	Great Island	Wexford	Oil Fired Steam Turbines	54	1993 & 2013	2	HFO	9666	
			Oil Fired Steam Turbines	54	1994& 2013	0	HFO	9666	
			Oil Fired Steam Turbines	108	1995& 2013	1	HFO	9666	
			CCGT	430	2013	1	Gas/DO	11998	
				646		**4**		**40996**	**1189.72**
7	Huntstown	Dublin	CCGT	343	2002	1	Gas/DO	11998	
			CCGT	401	2007	1	Gas/DO	11998	
				744		**2**		**23996**	**35797.88**
8	Kilroot	Antrim	Coal/Oil Fired	220	1992	2	Coal/HFO	7832	
			Coal/Oil Fired	220	1992	0	Coal/HFO	7832	
			GT	30		2	DO	10450	
			GT	30		0	DO	10450	
				500		**4**		**36564**	**18718.20**
9	Loughree	Longford	Peat Fired Steam Turbine	91	2004	1	Peat	3583	
				91		**1**		**3583**	**8303.12**
10	Marina	Cork	CCGT	112	2008	1	Gas/DO	11998	
			OCGT	85	2008	1	Gas/DO	11998	
				197		**2**		23996	**4595.49**
11	Moneypoint	Clare	Coal/Oil Fired	305	1985	3	Coal/HFO	7832	
			Coal/Oil Fired	305	1986	0	Coal/HFO	7832	
			Coal/Oil Fired	305	1987	0	Coal/HFO	7832	
				915		**3**		**23496**	**15137.60**
12	Northwall	Dublin	CCGT	150		1	Gas	13546	
			OCGT	90		1	DO	10450	
				240		**2**		23996	**2671.17**

Note: OCGT - Open Cycle Gas Turbine, CCGT - Combined Cycle Gas Turbine, GT - Gas Turbine, HFO - Heavy Fuel Oil, DO - Distillate Oil, N/A - Non Applicable

Number	Generating Unit	Location	Plant Description	Unit Rate Export Capacity (MW)	Commission Decommission Year	No.Units Plant	Fuel Type	Heat Value Fuel Used (kCal/kg)	Fuel Consumption Terajoules (TJ)
13	Poolbeg	Dublin	CGT	120	1971& 2009	2	HFO/Gas	11606	
			GT	120	1971& 2009	0	HFO/Gas	11606	
			GT	271	1978	1	HFO/Gas	11606	
			CCGT	157	1995	2	Gas/DO	11998	
			CCGT	157	1999	0	Gas/DO	11998	
				1005		**7**		**58814**	**21758.75**
14	Rhode Island	Offaly	OCGT	52	2002	2	DO	10450	
			OCGT	52	2002	0	DO	10450	
				104		**2**		**20900**	**63.75**
15	Tarbert	Kerry	Oil Fired Steam Turbines	54		2	HFO	9666	
			Oil Fired Steam Turbines	54		0	HFO	9666	
			Oil Fired Steam Turbines	241		2	HFO	9666	
			Oil Fired Steam Turbines	241		0	HFO	9666	
				590		**4**		**38664**	**11892.55**
16	Tawnaghmore	Mayo	OCGT	52	2002	2	DO	10450	
			OCGT	52	2002	0	DO	10450	
				104		**2**		**20900**	**102.95**
17	Tynagh	Galway	CCGT	384	2006	1	Gas/DO	11998	
				384		**1**		**11998**	**20180.20**
18	West Offaly	Offaly	Peat Fired Steam Turbine	137	2005	1	Peat	3583	
				137		**1**		**3583**	**11905.22**

Note: OCGT - Open Cycle Gas Turbine, CCGT - Combined Cycle Gas Turbine, GT - Gas Turbine, HFO - Heavy Fuel Oil, DO - Distillate Oil, N/A - Non Applicable

Table. 5.3: Input and Output Data for Thermal Power Plants

No.	Generating Unit	Location	Input 1 Fuel Consumption Terajoules (TJ)	Input 2 Unit Rate Export Capacity (MW)	Input 3 Heat Value Fuel Used (kCal/kg)	Output 1 Annual Production (MWh)
1	Aghada	Cork	9133.16	995	82438	770360
2	Ballylumford	Antrim	20939.13	1213	104886	9212000
3	Dublin Bay	Dublin	22956.29	403	11998	6376748.77
4	Coolkeeragh	Derry	18321.91	455	22448	2800000
5	Edenderry	Offalys	15738.29	117.5	3583	812539.5
6	Great Island	Wexford	1189.72	646	40996	78870
7	Huntstown	Dublin	35797.87	744	23996	5179459
8	Kilroot	Antrim	18718.19	500	36564	3640000
9	Loughree	Longford	8303.11	91	3583	685229
10	Marina	Cork	4595.48	197	23996	492772
11	Moneypoint	Clare	15137.60	915	23496	4204890
12	Northwall	Dublin	2671.17	240	23996	890000
13	Poolbeg	Dublin	21758.74	1005	58814	1990000
14	Rhode Island	Offaly	63.74	104	20900	5927
15	Tarbert	Kerry	11892.55	590	38664	1222338
16	Tawaghmore	Mayo	102.95	104	20900	7035
17	Tynagh	Galway	20180.19	384	11998	5 605610
18	West Offaly	Offaly	11905.22	137	3583	951962

Table. 5.4: Input and Output Data for Wind Generating Regions

No.	Generation Unit	Location	Input 1 (I) Full Time Man Hours (O&M)	Input 2 (I) Unit Rate Export Capacity (MW)	Input 3 (I) Wind Availability (%)	Output 1 (O) Annual Production (MWh)
1	Region A	Ulster	1140	190.5	30.79	505711.84
2	Region B	Connaght	420	72.1	30.17	390471.55
3	Region C	Leinster	480	41.6	28.47	750432.5
4	Region D	Munster	300	100.42	28.01	745632.06
5	Region E	Munster	840	243.4	32.78	260915.2
6	Region F	Munster	360	50.86	32.78	690524.2
7	Region G	Leinster	360	101.05	31.47	128381.3
8	Region H	Munster	300	14.45	30.74	34499.3
9	Region I	Leinster	480	127.95	31.2	355834.7

Table. 5.5: Input and Output Data for Hydro Power Plants

No.	Generation Unit	Location	Input 1 (I) Storage Capacity (GWh)	Input 2 (I) Employees/ Unit Rate Export Capacity	Input 3 (I) O & M (OM/MW/YR)	Output 1 (O) Annual Production (MWh)
1	Ardnacrusha	Clare	3.844	57/86=0.66	70000	441000
2	Erne	Donegal	14.273	28/65=0.43	60000	324000
3	Lee	Cork	4.966	19/27=0.7	21000	90000
4	Liffey	Wicklow	11.479	21/38=0.55	30000	46000
5	Turlough Hill	Wicklow	1.431	22/292=0.7	35000	349000

Table. 5.6: Input and Output Data for County Distribution

No.	County Region	Location	(I) Number of Employees	(I) Distribution Network Length (km)	(I) Transformer Capacity (MVA)	(I) Distribution Losses (MWh)	(O) Energy Consumed (MWh)	(O)Number of Customers	(O) Service Area (m^2)	(O) Industrial Output '000s	(O) Customer Density
1	Donegal	Ulster	221	8,691	1013	21357.95	288621	94298	4860.91	803676	11
2	Cavan	Ulster	164	5,334	372	12249.96	165540	40310	1931.77	1434171	8
3	Monaghan	Ulster	95	3,969	153	5490.87	74201	29248	1295.08	913152	7
4	Letrim	Connaght	65	2,404	166	4826.05	65217	17925	1590.03	161190	7
5	Sligo	Connaght	102	3,246	236	9177.25	124017	36268	1837.52	620850	11
6	Roscommon	Connaght	113	4,582	625	9337.616	126184	32631	2548.19	961221	7
7	Mayo	Connaght	235	9,454	505	19234.96	259932	74396	5586.05	2815243	8
8	Galway	Connaght	338	12,246	1853	33132.98	447743	122970	6148.77	2628920	10
9	Clare	Munster	149	5,926	1110	16090.04	217433	56344	3450.04	1223815	10
10	Limerick	Munster	173	6,962	1505	25906.36	350086	93460	2755.91	11526227	13
11	Tipperary	Munster	237	9,772	757	21909.62	296076	85819	4304.72	3940551	9
12	Kerry	Munster	272	9,386	1111	20819.53	281345	91667	4806.89	1709363	10
13	Cork	Munster	545	19,858	3462	67438.64	911333	256391	7499.95	31274436	13
14	Waterford	Munster	88	3,763	662	15303.57	206805	58178	1856.59	2603666	15
15	Carlow	Leinster	76	2,145	343	6990.70	94469	24552	896.55	356536	11
16	Dublin	Leinster	233	9,059	6130	157025.78	2121970	565110	922.27	17611797	62
17	Kildare	Leinster	156	5,465	1884	23820.6	321900	91680	1695.4	4104968	17
18	Kilkenny	Leinster	121	5,355	223	12282.37	165978	41652	2072.89	659275	8
19	Laois	Leinster	56	2,851	153	9378.908	126742	30345	1719.9	490680	11
20	Longford	Leinster	73	2,703	186	5067.07	68474	24371	1091.16	681511	9
21	Louth	Leinster	70	3,299	2154	15162.45	204898	62542	826.13	3361694	19
22	Meath	Leinster	126	5,451	1702	21711.67	293401	58906	2342.07	1217179	11
23	Offaly	Leinster	75	3,245	572	9868.56	133359	38446	2001.17	701095	12
24	Westmeath	Leinster	136	4,332	143	11138.62	150522	43629	1856.59	908824	10
25	Wexford	Leinster	161	6,723	599	18720.89	252985	66357	2366.85	1163037	10
26	Wicklow	Leinster	111	4,637	389	16751.45	226371	49082	2026.62	1571443	11

Table. 5.7: Input and Output Data for Wind Farms

Number	Wind Farm	Location	(I) Installed Capacity (MW)	(I) Wind Turbines	(I) Wind Turbine Model	(I) Hub Height (Metres)	(I) Area Swept (m^2)	(I) Total Surface Area (m^2)	(I) Annual Wind Speed (m/s)	(I) Air Density (kg/m^3)	(I) Wind Fuel (MWh)	(I) Full Time Manhours	(I) Mean Site Elevation	(O) Annual Production (MWh)
Donegal														
1	Golagh	Ulster	15	10	Vestas V39 500	53	1195	11950	7.59	1.24	56234.31	600	320	41401.2
2	Cronaglacht	Ulster	4.98	8	Vestas V39 600	40	1195	9560	9.32	1.24	55241.5	480	300	14321.6
3	Drumlough	Ulster	4.8	8	Vestas V47 660	60	1735	13880	9.07	1.24	78052.79	480	290	11758.4
4	Crockahenny	Ulster	5	10	Enercon E40	67	1276	12760	8.8	1.24	69618.56	600	326	10763.2
5	Cark	Ulster	15	20	NEG Micon 600	46	1451	29020	8.61	1.24	154914.56	1200	339	43588.6
6	Cuillagh	Ulster	11.88	18	Vestas V47 660	49	1735	31230	8.96	1.24	173488.89	1080	353	34899.2
7	Anarget	Ulster	3.1	3	Vestas V47 660	49	1735	5205	7.72	1.24	24913.21	180	40	7000
8	Meenadreen	Ulster	3.4	4	Vestas V52 850	49	2124	8498	7.72	1.24	40674.83	240	255	8000
9	Burtonport	Ulster	0.66	1	Vestas V47 660	55	1735	1735	8.92	1.24	9595.24	60	118	1000
10	Meenanilta	Ulster	5	3	Vestas V52 850	49	2124	6372	7.47	1.24	29511.28	180	200	12000
11	Meentycat	Ulster	72.4	38	Bonus Siemens	68/80	5333/3019	167944	8.58/8.63	1.24	898601.17	2280	295	193032.8
12	Sorne Hill	Ulster	32	16	Enercon E70	64	3959	63344	7.75	1.24	304367.92	960	165	89144.7
13	Beam Hill	Ulster	14	8	Vestas V66	60	3421	27368	9.59	1.24	162724.65	480	285	39216
14	Loughderryduffy	Ulster	7.65	9	Vestas V52 850	49	2124	19116	7.97	1.24	94459.80	540	60	19000
15	Lurganboy	Ulster	5	6	Enercon E44	55	1521	9126	7.13	1.24	40342.39	360	155	14321
16	Killybegs	Ulster	2.55	6	Enercon E70	49	3959	23754	7.97	1.24	117378.01	360	120	6000
17	Meenachullan	Ulster	11.9	6	Enercon E70	60	3959	23754	8.3	1.24	122238.08	360	205	51091.7
Total		**214.34**	**174**				**35248**	**464616**			**2432357.22**	**10440**	**225**	**596538.4**
Cavan														
18	Corneen	Ulster	3	2	GE 1.5s	64.7	3904	7808	7.26	1.24	35145.36	120	250	7000
19	Gartnaneane	Ulster	15.5	10	GE 1.5s	64.7	3904	39040	7.78	1.24	188313.34	620	200	37000
20	Ratrussan/Bindoo	Ulster	48	32	GE 1.5s	64.7	3904	124928	8.03	1.24	621966.54	1920	231	127151.7
21	Snugborough	Ulster	13.5	13	GE 1.5s	64.7	3904	50752	7.52	1.24	236626.12	540	221	33731.4
22	Mountain Lodge I	Ulster	32	21	GE 1.5s	64.7	3904	81984	8.04	1.24	408673.84	1280	230	84958.9
23	Mountain Lodge II	Ulster	3	2	GE 1.5s	64.7	3904	7808	8.04	1.24	38921.31	120	220	7000
Total		**116**	**80**				**23424**	**312320**			**1529646.54**	**4600**	**225.33**	**296842**
Monaghan														
24	Mullananalt	Ulster	7.5	5	GE 1.5	64.7	3904	19520	7.78	1.24	94156.67	300	333	20423.6
Total			**7.5**	**5**			**3904**	**19520**			**94156.67**	**300**	**333**	**20423.6**

Number	Wind Farm	Location	(I) Installed Capacity (MW)	(I) Wind Turbines	(I) Wind Turbine Model	(I) Hub Height (Metres)	(I) Area Swept (m^2)	(I) Total Surface Area (m^2)	(I) Annual Wind Speed (m/s)	(I) Air Density (kg/m^3)	(I) Wind Fuel (MWh)	(I) Full Time Manhours	(I) Mean Site Elevation	(O) Annual Production (MWh)
Letrim														
25	Moneenatieve	Connaght	4.25	5	Gamesa G52850	44	2214	11070	7.31	1.24	50171.45	300	250	12456.8
26	Corrie Mts	Connaght	4.8	8	Vestas V42 600	40	1385	11080	5.74	1.24	39431.50	480	150	14897.5
27	BlackBanks	Connaght	10.2	12	Vestas V52 850	49	2124	25488	5.23	1.24	82647.38	720	370	28567.3
28	Spion Kop	Connaght	1.2	2	Vestas V42 600	53	1385	2770	6.07	1.24	10424.61	480	400	3124.3
Total			**20.45**	**27**			**7108**	**50408**			**182674.96**	**1980**	**292.5**	**59045.9**
Sligo														
29	Kingsmountain	Connaght	25	10	Nordex N80	60	5026	50260	8.56	1.24	73725.75	600	140	66637.8
30	Geevagh	Connaght	5.1	6	Gamesa G52 850	40	2214	13284	7.41	1.24	61029.35	360	285	10745.1
31	Caranne Hill 1	Connaght	3.4	4	Gamesa G52 850	44	2214	8856	7.8	1.24	42827.61	240	430	13000
32	Lacken 1	Connaght	6.6	3	Enercon E70	60	3959	11877	8.56	1.24	63033.61	180	10	18765.3
Total			**40.1**	**23**			**13413**	**84277**			**240616.33**	**1380**	**216.25**	**109148.2**
Roscommon														
33	Kilronan	Connaght	5	9	Vestas V 39 500	40	1195	10755	8.23	1.24	54878.46	200	320	14238
34	Largan Hill	Connaght	5.94	9	Vestas V 47 660	55	1735	15615	6.33	1.24	61282.62	237.6	162	14000.5
35	Altagowan	Connaght	7.65	9	Gamesa G58 850	44	2124	19116	8.83	1.24	104652.45	306	130	19789.2
Total			**18.59**	**27**			**5054**	**45486**			**220813.54**	**743.6**	**204**	**48027.7**
Mayo														
36	Bellacorrick	Connaght	6.5	21	Nordtank 300	31	755	15855	7.5	1.24	73725.75	1260	87	16000
37	Burren	Connaght	2	2	Vestas V47 660	49	1735	3470	8.47	1.24	18222.35	120	170	4125.7
38	Raheen Barr	Connaght	18.7	22	Vestas V52 850	49	2124	46728	7.97	1.24	230901.73	1320	195	52315.7
39	Cuillalea	Connaght	3.4	4	Vestas V52 850	49	2124	8496	8.48	1.24	44668.56	240	210	8765.4
Total			**30.6**	**52**			**6738**	**74549**			**91879.60**	**2940**	**165.5**	**81206.8**
Galway														
40	Inis Mean	Connaght	0.67	3	Vestas V27 225	31	573	1719	8.18	1.24	8718.08	180	15	1000
41	Inverin	Connaght	3.96	5	Vestas V47 660	49	1735	8675	7.96	1.24	42812.86	300	72	6589.2
42	Sonnagh Old	Connaght	7.65	9	Vestas V52 850	49	2124	19116	8.71	1.24	103230.22	540	308	23865
43	Derrybrien	Connaght	60	70	Vestas V52 850	49	2124	148680	7.72	1.24	711641.95	4200	328	150798.5
Total			**72.28**	**87**			**6556**	**178190**			**866403.11**	**5220**	**180.75**	**182252.7**
Clare														
44	Moanmore	Munster	12.6	7	Enercon E70/E4	57	3959	27713	7.96	1.24	136769.19	420	20	38955.6
45	Boultiagh	Munster	19.5	13	GE 1.5s	54.7	3904	50752	7.38	1.24	232220.85	780	170	46296.1
Total			**32.1**	**20**			**7863**	**78465**			**368990.04**	**1200**	**95**	**85251.7**

Number	Wind Farm	Location	(I) Installed Capacity (MW)	(I) Wind Turbines	(I) Wind Turbine Model	(I) Hub Height (Metres)	(I) Area Swept (m^2)	(I) Total Surface Area (m^2)	(I) Annual Wind Speed (m/s)	(I) Air Density (kg/m^3)	(i) Wind Fuel (MWh)	(I) Full Time Manhours	(I) Mean Site Elevation	(O) Annual Production (MWh)
Limerick														
46	Knockawarriga	Munster	22.5	9	Nordex N90	75	6362	57258	8.5	1.24	301749.66	540	277	64713.1
47	Tournafulla	Munster	7.5	5	GE 1.5s	54.7	3904	19520	8.4	1.24	101660.16	300	266	49752.1
Total			**30**	**5**			**10266**	**76778**			**403409.82**	**840**	**271.5**	**114465.2**
Tipperary														
48	Curraghgraigue	Munster	2.55	3	Vestas V52 850	49	2124	6372	7.47	1.24	29511.28	102	135	7685.7
49	Carrig	Munster	2.55	3	Vestas V52 850	65	2124	6372	6.48	1.24	25600.14	102	130	4328.1
50	Skehanagh	Munster	4.25	5	Vestas V52 850	65	2124	10620	8.04	1.24	52938.57	170	167	9567.9
51	Ballinlough	Munster	2.55	3	Vestas V52 850	55	2124	6372	7.85	1.24	31012.52	102	150	6783.3
Total			**12.75**	**15**			**8496**	**29736**			**139062.52**	**476**	**145.5**	**30499.3**
Kerry														
52	Beal Hill	Munster	4.29	4	V66/52850	55	3421/2124	9793	8.91	1.24	54098.49	240	89	4439.6
53	Beenageeha	Munster	3.96	6	Vestas V47 660	49	1735	10410	8.47	1.24	54667.07	360	321	9255.3
54	Tursillagh	Munster	21.8	31	V47/52 660/850	3859	56897	8.71	1.24	307255.17	1860	363	71818.2	
55	Mount Eagle	Munster	5.1	6	Vestas V52 850	49	2124	12744	7.96	1.24	62894.18	360	385	12000.8
56	CoomagearlahyI	Munster	45	15	Vestas V90	65	6362	95430	8.26	1.24	488716.11	900	485	110329.6
57	CoomagearlahyII	Munster	8.5	10	Vestas V52 850	49	2124	21240	8.26	1.24	108774.28	600	470	20187.1
58	Pallas	Munster	40	20	Enercon E70	60	3959	79180	8.9	1.24	436915.24	1200	237	106946
59	Glanlee	Munster	31.6	23	Siemens 1.3	45	3019	69437	8.32	1.24	358183.82	1380	410	90879.5
60	Ballybane	Munster	20	8	Enercon E70	60	3959	31672	8.56	1.24	168089.63	480	310	71009.4
61	Muingnaminane	Munster	15.3	18	Enercon E44/48	55	1521	27378	8.75	1.24	148525.65	1080	260	35193.5
Total			**195.55**	**85**			**30768**	**414181**			**2188119.68**	**8460**	**333**	**532059**
Cork														
62	Gneeves	Munster	9.35	11	Vestas V52 850	55	2124	23364	8.66	1.24	125445.98	660	410	23000
63	Kealkill	Munster	8.5	10	Gamesa G52 850	44	2214	22140	8.29	1.24	113795.17	600	320	21000
64	Milane Hill	Munster	5.94	9	Vestas V47 660	60	1735	15615	9.07	1.24	87809.39	540	260	14345.5
65	Curabwee	Munster	4.92	7	Vestas V47 660	55	1735	12145	8.91	1.24	67091.40	420	230	13457.3
66	Lahanaht Hill	Munster	4.25	3	Vestas V47 660	55	1735	5205	8.15	1.24	26399.86	180	210	4000
67	Coomatalin	Munster	5.95	4	GE 1.5SE	60	3904	15616	8.56	1.24	82877.23	240	230	14000
68	Kilvinane	Munster	4.5	3	G80/52 850	67/40	2214	6642	8.04	1.24	33109.04	180	140	12345.6
69	Taurbeg	Munster	25.3	11	Siemens 2.3	80	5333	58663	9.37	1.24	340796.83	660	405	70232.9
Total			**68.71**	**58**			**20994**	**159390**			**877324.93**	**3480**	**275.6**	**172381.3**

Number	Wind Farm	Location	(I) Installed Capacity (MW)	(I) Wind Turbines	(I) Wind Turbine Model	(I) Hub Height (Metres)	(I) Area Swept (m^2)	(I) Total Surface Area (m^2)	(I) Annual Wind Speed (m/s)	(I) Air Density (kg/m^3)	(I) Wind Fuel (MWh)	(I) Full Time Manhours	(I) Mean Site Elevation	(O) Annual Production (MWh)
Waterford														
70	Beallough	Munster	1.7	2	Vestas V52 850	55	2124	4248	7.09	1.24	18673.35	68	239	4000
Total			**1.7**	**2**			**2124**	**4248**			**18673.35**	**68**	**239**	**4000**
Carlow														
71	Greenoge	Leinster	5.2	4	Nordex N60	60	2828	11312	7.95	1.24	55756.84	208	330	12765.4
72	Cronelea I	Leinster	6.9	3	Enercon E70	60	3959	11877	8.72	1.24	64211.81	276	320	17459.4
Total			**11.2**	**7**			**6787**	**23189**			**119968.66**	**484**	**325**	**30224.4**
Louth														
73	Dundalk IT	Leinster	0.85	1	Vestas V52 850	55	2124	2124	6.58	1.24	8665.07	34	100	1987.8
74	Drybridge	Leinster	1.7	2	Enercon E48	55	1810	3620	8.1	1.24	18179.64	68	223	4346
Total			**2.55**	**3**			**3934**	**5744**			**26844.71**	**102**	**161**	**6333.8**
Meath														
75	Dunmore	Leinster	1.7	2	Vestas V52 850	55	2124	4248	8.36	1.24	22018.23	68	222	3850
Total			**1.7**	**2**			**2124**	**4248**			**22018.23**	**68**	**222**	**3850**
Wexford														
76	Carnsore	Leinster	12	12	Vestas V52 850	49	2124	25488	8.22	1.24	129897.04	480	90	43821.6
77	Ballywater	Leinster	43	21	Enercon E70	64	3959	83139	7.76	1.24	399998.35	1720	80	101004.4
78	Richfield	Leinster	27	18	GE 1.5s	64.7	3904	70272	8.04	1.24	350291.86	1080	100	88196
Total			**82**	**51**			**9987**	**178899**			**880187.26**	**3280**	**90**	**233022**
Wicklow														
79	Cronelea	Leinster	6.9	3	Enercon E70	113	3959	11877	9.83	1.24	72385.56	276	327	17435
80	Arklow Banks	Leinster	25.2	7	GE 3.6	73.5	5346	37422	7.92	1.24	183756.98	1008	75	71417.8
81	Cronelea Upper Leinster	2.55	3	Vestas V52 850	55	2124	6372	8.87	1.24	35042.17	102	280	3735.5	
Total			**82**	**51**			**9987**	**178899**			**880187.26**	**3280**	**90**	**233022**

Table. 5.8: DEA Input and Output Sources and Measures

Variable and Input/ Output Status	Data Sources	Data Measures
Thermal Efficiency Variables		
Fuel Consumption	EPA	Terajoules (TJ)
Unit Rate Export Capacity	EPA \Eirgrid	Megawatt (MW)
Heat Value Fuel Used	KEMA Limited	kCal/kg
Annual Production	EPA	Megawatt-Hour (MWh)
Wind Efficiency Variables		
Full Time Man Years	IWEA \Iglesias et al. (2010)	Numerical Number
Unit Rate Export Capacity	Eirgrid\ESB	Megawatt (MW)
Number of Wind Farms	Eirgrid\ESB \IWEA	Numerical Number
Annual Production	Wind Power\Eirgrid	Megawatt-Hour (MWh)
Hydro Efficiency Variables		
Storage Capacity	UL	Gigawatt-Hour (MWh)
Operation & Maintenance Costs	UCC	O&M \MW \YR
Unit Rate Export Capacity	ESB	Megawatt (MW)
Number of Employees	ESB	Numerical Number
Annual Production	ESB	Megawatt-Hour (MWh)
Electricity Distribution Variables		
Labour	Ofgem\NIE	Numerical Number
Distribution Length	ESB Networks	Kilometres (km)
Transformer Capacity	ESB Networks	Megavolt Ampere (MVA)
Distribution Losses	ESB Networks	Megawatt-Hour (MWh)
Categorical Variable	CSO	(0,1)
Energy Consumed	SEAI	Megawatt-Hour (MWh)
Number of Customers	ESB Networks	Numerical Number
Service Area	CSO	Kilometre Squared (km^2)
Industrial Output	CSO	Thousands Euro (000s)
Customer Line Density	ESB Networks	No of Customers\ Distribution Length (km)
Wind Electricity Generation Variables		
Fuel Consumption	SEAI Wind Atlas\Met Eireann	Megawatt-Hour (MWh)
Unit Rate Export Capacity	Eirgrid\ESB	Megawatt (MW)
Full-Time Man Hours O & M	EWEA\IWEA	Numerical Number
Annual Production	SEMO\Wind power	Megawatt-Hour (MWh)

Note: Environmental Protection Agency (EPA); KEMA - Energy Consultancy Firm; Irish Wind Energy Association (IWEA); UL - University of Limerick; UCC - University College Cork; Office of Gas and Electricity Markets (OFGEM); Central Statistics Office (CSO); Sustainable Energy Authority of Ireland (SEAI); European Wind Energy Association (EWEA)

5.4 Model Specification

In the literature there is no universal encompassing definition of efficiency performance across industries. Tong and Ding (2008) state *"efficiency means getting any given result with the smallest possible inputs, or getting the maximum possible output from given resources"* whilst Abbott (2006) define efficiency as *"resources are being used in an optimal fashion to produce outputs of a given quantity"*. As such, numerous efficiency performance techniques, approaches and performance indicators dependent on industry characteristics and research objectives have been adduced in the literature (Mahmoudi et al., 2011; Zhou and Ang, 2008; Ang, 2006). Energy industries such as electricity, gas, and coal often operate in markets, which lack prices and costs determined under competitive conditions. Under such market environments the usual indicators of performance, profitability and rates of return, cannot accurately establish industry's economic performance (Abbott, 2006).

Kulshrestha and Parikh (2002) state these "quasi"-public sector environments do not operate on the pre-tense of profit maximisation that normally drives private sector behaviour. In these situations, Abbott (2006) affirm the levels and changes of productivity efficiency are more appropriate barometers of energy industry efficiency performance. As such, the present research thesis adduces a three tier comprehensive systematic framework to establish the technical efficiency performance of the Irish EPS focusing on the electricity generation and distribution processes. The three tier framework is specifically employed as efficiency gains can be attained in the generation and distribution of electricity and because the RES wind will form a significant share of the all-island SEM generation portfolio in the coming decades. This added RES is necessary to meet stated energy and emission reduction targets. The three tier efficiency study incorporates:

1. **National Level - All Island Generation Efficiency Study (AIGES)**
2. **County Level - Republic of Ireland Distribution Efficiency Study (ROIDES)**
3. **Individual Level - Republic of Ireland Wind Efficiency Study (ROIES)**

The three tier efficiency framework employed in this thesis, whilst applied to the Irish EPS can be extended and applied to other countries and sectors. Data relating to the County and Individual level analysis in NI was not available for research so the ROIDES and ROIWES incorporates the twenty-six counties in ROI. The presented research thesis analyses the technical efficiency of the electricity generation and distribution processes associated with the SEM. The year under observation is 2008, the first full operational year of the All-Island SEM existing between the ROI and NI. Another reason the research focuses on the year 2008 is the fluctuating electricity demand profile experienced in recent years. The demand is mapped to half hours based on the historic half hourly load shape in ROI and NI from 2008.

The load shape for 2009 was available but the shape was heavily skewed compared to typical demand profiles, due to the impact of the global economic crisis which reduced demand during the year. A similar effect has been observed for the 2010, 2011 profiles. SEM demand levels are not expected to return to normal levels until the latter part of 2012 (Redpoint, 2010). Discussions with the Market Operator indicated that the 2008 shape would be a better assumption of a typical demand shape and as such forms the base year (SONI, 2011). At the time of research a full and accurate dataset for the year 2008 was only available enabling a snapshot measurement of technical efficiency of the All Island SEM.

5.5 Efficiency Model Orientation

As outlined previously in Section 4.4 DEA efficiency analysis can be conducted by adopting input-minimising or output-maximising models. *Input oriented models* - whose objective is to minimise inputs while producing at least the given output levels. *Output oriented models* - that attempts to maximise outputs while using no more than the observed amount of any input (Cooper et al., 2007). It is pertinent to stipulate the model orientation adopted at each efficiency level and the motivating factors. Output-oriented efficiency measurements are appropriate if one assumes the electricity industry to be a competitive market (Liu et al., 2010). This is the case for electricity generation in the SEM. The DEA literature related to electricity generation efficiency measurement supports this viewpoint (see Section 3.7).

Focusing on the national level efficiency research context, output-oriented models are adopted to reflect thermal and wind generating unit behaviour during the period under analysis, as the objective of operators was to produce maximum energy without any kind of restrictions. Productive behaviour is not motivated by exogenous factors. In this sense, the electricity supply is not conditioned by demand or decisions of systems managers, or by competition with other operators in the generation market or firms that use alternative technologies (Iglesias et al., 2010). For hydro generating units, input-oriented models are employed to estimate technical efficiency as generation output levels are fixed. Energy generation for hydro generating units is not decided by individual generators but rather it is dictated by consumer demand.

At the county level efficiency study, traditionally, efficiency analysis of the electricity distribution sector assumes output is fixed in the market with a legal duty to serve all customers in a predefined service territory (Von Hirschhausen et al., 2006). Electricity distribution utilities are obliged to meet their customers requirements for electricity with a goal of minimising the amount of resources they use in doing so whilst maintaining an appropriate level of service quality (Doraisamy, 2004). Hattori et al. (2005) states that demand for distribution services is a derived demand that is beyond the control of distribution utilities but has to be met, hence input-oriented specification is generally regarded as the appropriate form. In this case, technical efficiency measures the ability of electricity distribution utilities to minimise inputs to produce a given level of outputs. For the individual level efficiency analysis the focus of researchers

was to assess the technical efficiency of wind farms under the objective of maximising outputs whilst keeping input resources constant, hence output-oriented models are the appropriate model orientation direction.

Table. 5.9: Efficiency Model Orientation

Efficiency Study Level	**Model Orientation**
National Level - (AIGES)	
Thermal Efficiency Study	Output Orientation
Hydro Efficiency Study	Input Orientation
Wind Efficiency Study	Output Orientation
County Level - (ROIDES)	
Distribution Efficiency Study	Input Orientation
Individual Level - (ROIWES)	
Wind Efficiency Study	Output Orientation

5.6 National Level - All Island Generator Efficiency Study (AIGES)

The National level research study incorporates a multi input-output efficiency performance evaluation and a comparison of a large set of energy indicators of Irish power plants. A key issue in any such multi-indicator study is the determination of objectives, performance indicators and the setting of input-output weights in a market reflective realistic manner (Sozen et al., 2010). The fundamental function of the electricity power generation system, is to convert energy from the numerous sources into consistent reliable electricity and to provide this electric energy at an acceptable cost. There is no universal applicable rational template available for selection of variables for performance analysis of power plants and the justification behind the selected input-output indicators is that they are measurable, based on valid available data, and are under control of the electric power plant. The general consensus stipulates the underlying efficiency evaluation model is optimised when the adopted input indicators reflect the resources consumed and the outputs reflect the service levels of the power plant and the degree to which the objective of supplying electricity to consumers is achieved.

A review of standard literature reveals significant judgement into the appropriate choice of variables. Barzel (1964) conveniently model the production function of generating units within an engineering framework. In this framework, the pertinent inputs are the fuel quantity consumed (F) and capital (K), installed power, which is the maximum nominal power for which power plants were designed for, while labour (L) inputs contribute to production through operation and maintenance services under the assumption that a single output energy production exists (Park and Lesourd, 2000). However, Pollitt (1995) state this model formulation inadequately captures the multi-dimensional nature of electricity generation; but acknowledges, it

is the standard characterisation extensively adopted in the literature. There are three primary sources of electricity generation connected to the SEM, thermal power plants, wind power plants (wind farms) and hydro power plants. The National level AIGES proposes to model the operational characteristics of these power plants by adopting the previously explained engineering framework to establish the technical efficiency of these units. The national level dataset consists of eighteen thermal power plants, eighty-two wind farms in nine wind regions and five hydro power plants represented in Figure 5.2. After meticulously reviewing the relevant literature the following indicators were chosen as fitting factors of efficiency of electric power generation in the National context. Electricity generated from thermal power plants consume the following inputs:

- *Fuel Consumption:* It is expressed in TJs. The different fuels (such as coal, oil, gas) utilised in thermal power generation are converted to TJ equivalents, and then aggregated to obtain annual fuel input. As such, figures have already adjusted for the quality of fuel used in different power plants.
- *Unit Rate Export Capacity:* Capital is measured in terms of installed generating capacity MW.
- *Heat Value Fuel Used:* The sum of the heat value of fossil fuels consumed by power plant operation, expressed as (kCal/kg). The final input parameter, heat value of fossil fuels was incorporated as a full dataset concerning labour employed at thermal power plants was not available and in some cases thought to be commercially sensitive.

In terms of wind modelling, the focus is onshore wind and the approach adopted by Redpoint (2010) is employed where wind is modelled in aggregated form and the countries wind resource is separated into wind regions for performance efficiency analysis as shown in Figure 5.2. The inputs for the wind region context include:

- *Labour:* Number of full-time man hours employed in the operation & maintenance, and control of the wind farms in each region.
- *Unit Rate Export Capacity:* Capital is measured in terms of installed/export generating capacity MW.
- *Wind Availability:* Each region has an associated half hourly profile which represents the wind availability in that region in each half hour, as a percentage of total installed capacity in that region (%).

The hydro model inputs are:

- *Storage Capacity:* This is the maximum quantity of water that can be utilised by the hydro plant.

- *Number of Employees:* It is the number of employees employed at each of the hydro power plants. All employees are given equal weights for efficiency analysis and status is ignored. *Unit Rate Export Capacity:* Capital is measured in terms of installed/export generating capacity MW and

- *Operational and Maintenance costs:* Administration and general, labour, station power, transmission, capital additions but not major maintenance and ongoing repair. It is expressed in (1000/MW/yr). It reflects the total amount of electricity produced by a single plant/unit within a year, it is expressed in MWh.

There is a single homogeneous output indicator for the thermal, hydro and wind efficiency study - *Annual Electricity Production.* It is a measure of the volume of electricity generation activity and therefore reflects the costs incurred. An ability to measure each of these indicators in relative units allows extensibility of the suggested approach for interregional and international comparisons (Vaninsky, 2006). The models adopted for the AIGES are presented in Table 5.10.

Table. 5.10: Electricity Generation Efficiency Models

National Level - All Island Generator Efficiency Study (AIGES)				
Thermal Efficiency Model	(I) Fuel Consumption Terajoules (TJ)	(I) Unit Rate Export Capacity (MW)	(I) Heat Value Fuel Used (kCal/kg)	(O) Annual Production (MWh)
Wind Efficiency Model	(I) Full Time Man Hours	(I) Unit Rate Export Capacity (MW)	(I) Wind Availability (%)	(O) Annual Production (MWh)
Hydro Efficiency Model	(I) Operation and Maintenance (O&M/MW/YR)	(I) Unit Rate Export Capacity (MW)	(I) Number of Employees	(O) Annual Production (MWh)

Note: (I) Inputs (O) Output

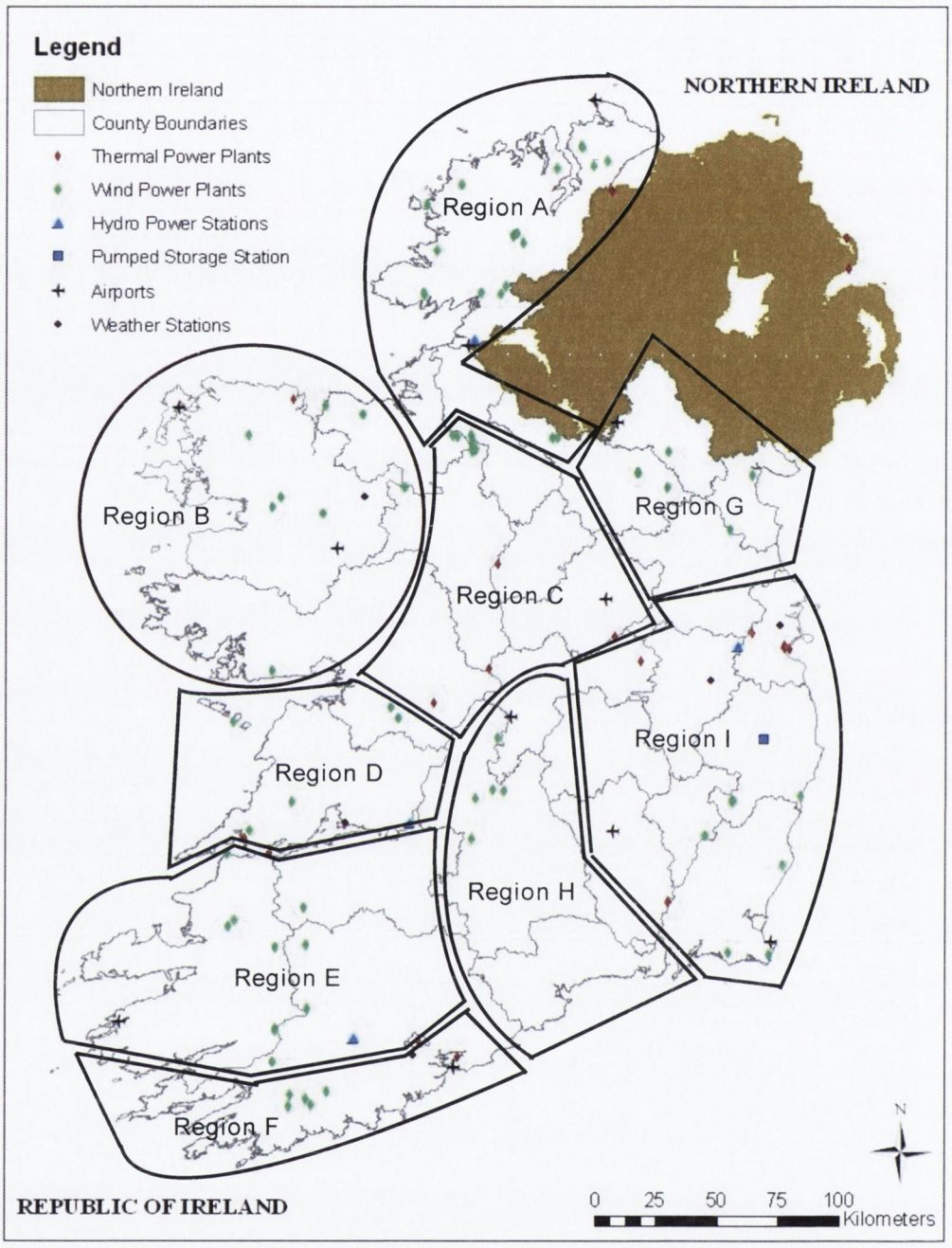


Fig. 5.2: Power Stations in Ireland

5.7 County Level - Republic of Ireland Distribution Efficiency Study (ROIDES)

The previous Section 5.6 established technical efficiency in the National context and the forthcoming section will focus on another function of the Irish EPS - County level distribution. The deregulation of the European electricity sector and numerous other countries has separated the previously vertically integrated sector into different businesses (Jamasb and Pollitt, 2005).

Table. 5.11: Frequency of Variables Employed from Selected Studies

Inputs	Citations	Outputs	Citations
network length:		***units sold:***	
LV lines (km)	(3)	LV electricity sales (MWh)	(2)
MV lines (km)	(1)	HV electricity sales (MWh)	(2)
HV lines (km)	(3)	residential electricity sales (MWh)	(4)
total network length	(9)	non-residential electricity sales (MWh)	(2)
labour:		industrial sales (MWh)	(3)
employees	(6)	non-industrial sales (MWh)	(1)
labour/manpower (hours)	(6)	commercial sales (MWh)	(1)
transformer capacity:		total electricity sales (MWh)	(6)
substation transformer capacity		***number of customers***	
HV/MV and MV/MV (MVA)	(1)	LV customers (#)	(3)
substation transformer capacity MV/LV		HV customers (#)	(2)
(MVA)	(1)	M/HV customers (#)	(1)
(distribution) transformer capacity		residential customers (#)	(1)
(MVA)	(9)	industrial customers (#)	(1)
		total customers (#)	(9)
service area (km^2)	(1)		
customer density (# customers/km^2)	(1)	service area (km^2)	(3)
losses	(5)	service reliability (sales/losses (%))	(1)
maximum demand	(1)	total network length (km)	(1)
transformers	(1)	line length 1-24 kv (km)	(1)
total electricity sales (MWh)	(2)	distance index	(1)
residential sale to total sales ratio	(1)	maximum demand (MW)	(2)
OPEX	(1)		
TOTEX	(1)		
goods and services	(2)		
materials	(1)		
capital	(3)		
general expenses	(1)		
Environmental variables			
network length (km)	(1)		
losses (MWh)	(1)		
load factor (average demand/peak demand)	(1)		
customer density (customers/ transformers)	(1)		
consumption density (sales/customer)	(1)		
distance index	(1)		

Note: (Ramos-Real et al., 2009; Weyman-Jones, 1995; Korhonen and Syrjanen, 2003; Estache et al., 2004; Hattori et al., 2005; Agrell et al., 2005; Pombo and Taborda, 2006; Pardina and Rossi, 2000; Burns and Weyman-Jones, 1996; Bagdadioglu et al., 1996; Weyman-Jones, 1991; Pollitt, 1995; Bagdadioglu et al., 1996; Hjalmarsson and Veiderplass, 1992; Hjalmarsson and Veiderpass, 1992; Forsund and Kittlesen, 1998; Meibodi, 1998; Jamasb and Pollitt, 2001; Grifell-Tatje and Lovell, 2003*b*; Kittelsen, 1993, 1999; Resende, 2002; Hattori, 2001) are studies that specifically classify the variables employed into input, output and exogenous variables.

Electricity sector reforms are transforming the market structure by introducing market-oriented competition into electricity generation and supply, to enhance the efficiency of the natural monopoly activities of distribution and transmission through structural and regulatory reforms (Ramos-Real et al., 2009; Hattori et al., 2003). Performance measurement, optimisation and policy-making of electricity distribution utilities are of critical importance to industry regulators (Azadeh et al., 2009; Sadjadi and Omrani, 2008).

A fundamental concept is establish benchmarks for efficient operation and potentials for efficiency improvement (Edvardsen and Forsund, 2003). The modelling of the production activity of transportation of electricity has links with engineering economics (Forsund, 1999). Edvardsen and Forsund (2003) define the output of electricity distribution utilities as the energy delivered through a network of lines and transformers to the consumption nodes of the network and losses in lines and transformers. Therefore it is important to ensure that only significant, relevant and acceptable variables are incorporated into the model (Rossi and Ruzzier, 2000). Jamasb and Pollitt (2001) postulate DEA frontier efficiency analysis models for electricity distribution adopt the following inputs most frequently: operating costs, number of employees, transformer capacity and network length. The most frequently adopted outputs are: electricity delivered, number of customers and the size of the service area. Table 5.11 adopted from Mota (2004) survey the frequency of the use of indicator variables.

The objective of this research level is to model the electricity distribution production process. The county level ROIDES employs a dataset of twenty-six Electricity Distribution Counties (EDC)s associated with the ESB networks distribution company in the ROI. The County level empirical study evaluates the technical efficiency of ESB networks interconnected distribution system, with each EDC responsible for medium and low voltage electricity distribution in a particular geographical region. Each EDC, region, or municipality is considered as a DMU under DEA analysis. Similar to the National level AIGES the year under observation is 2008, the first full operational year of the All-Island SEM. The Irish Transmission System, referred to as "The National Grid", is a meshed network of approximately 6,500kV of high voltage, 110,000 volts (110kV), 220,000 volts (220kV) and 400,000 volts (400kV), overhead lines and underground cables and over 100 transmission stations. At these transmission stations power is transmitted from the grid, transformed into medium voltage (MV) and low voltages (LV), 38,000 volts (38kV), 20,000 volts (20kV) and 10,000 volts (10kV), and diverted into the lower voltage distribution system or directly to large industrial operations (Eirgrid, 2012).

The Medium Voltage (MV) and Low Voltage (LV) networks are not represented graphically in Figure 5.3 as such a feat would result in Ireland being blacked out due to the extensiveness of the network at these voltage levels. Appendices B.1 and B.2 provide a comprehensive numerical breakdown of the network statistics associated with the transmission and distribution systems which includes the MV and LV network. The models adopted in the County level analysis are

drawn from the extensive electricity distribution benchmarking literature Section 3.8 and earlier research on the characteristics of ESB networks.

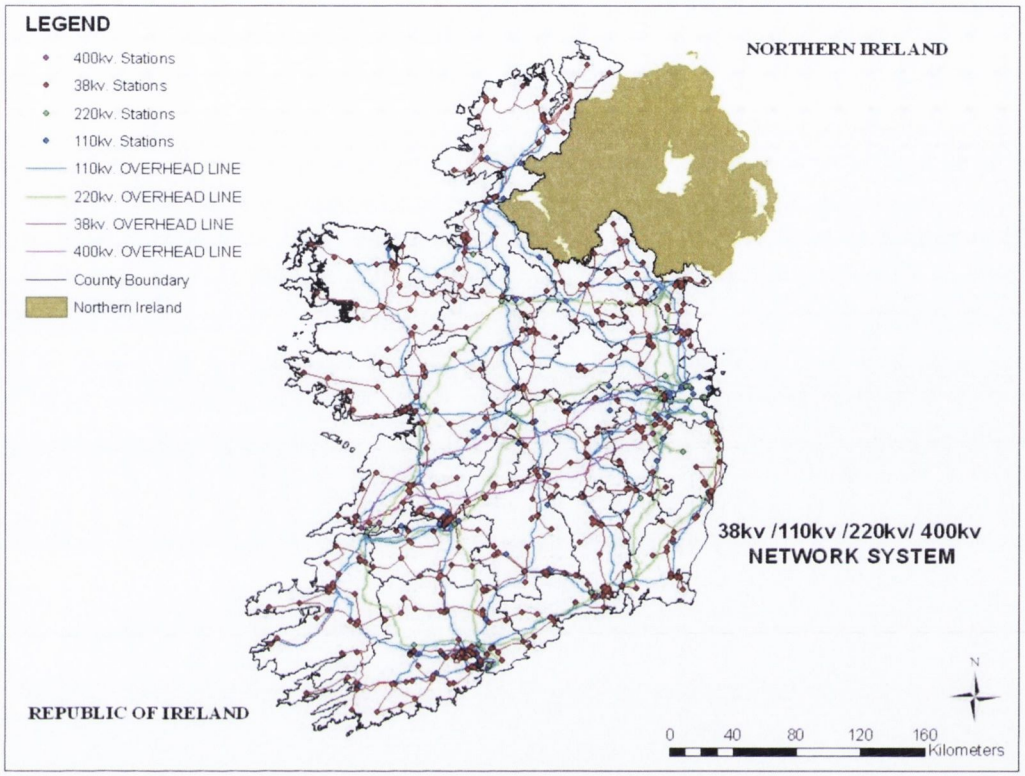


Fig. 5.3: Electricity Transmission Distribution Network

The input and output variables adopted in this study are all expressed in physical units and assess technical efficiency. The adopted six model analysis incorporates internationally recognized variables judiciously to capture the essence of the electricity distribution process associated with ESB networks. The database developed for DEA analysis in this study has been sourced predominately through collaborating and consultation with ESB networks, other sources of variable information include public sector databases. To model the electricity distribution process the following inputs were employed:

- *Labour:* This incorporates the number of ESB network employees within each EDC irrespective of their status. It includes operation & maintenance, technical, non-technical as well as administrative employees.
- *Distribution Network Length:* This represents the 38kV, MV and LV distribution network measured in km per EDC.
- *Transformer Capacity:* It is the total capacity of transformers connected to the distribution system for the distribution purpose. This is measured in Megavolt Amperes (MVA).

- *Distribution Losses:* It is the total losses incurred within the area served by the EDC and is expressed in MWhs. Losses are included as a proxy for the technical quality of the grid or the service quality of the grid.
- *Categorical Variable:* Use of categorical variable (0, 1) to represent if EDC is composed of a city or urban centre.

The distribution outputs include:

- *Energy Consumed:* This represents the energy utilised or consumed within the EDC area. It is expressed in MWhs.
- *Number of Customers:* It is the total number of connection points to supply the customers. Customers are not differentiated based upon their categories. The number of customers captures the number of nodes the utility must supply.
- *Service Area km^2:* The service area encapsulates the geographical differences among EDCs. Both the number of customers and the km^2 of service area represent customer density. The service area is employed an output variable to reflect the difficulty of meeting customer services over a less densely populated area.
- *Diagnostic Parameter:* The industrial output per EDC represents the selling value of goods actually produced in the year, as reported by the businesses themselves, irrespective of whether sold or put into stock (CSO, 2008).
- *Exogenous Variable:* The customer density defined as the number of customers per km length of distribution network.

Table 5.12 provides a complete and inclusive presentation of the models and input-output combinations employed in the County level - ROIDES. Six models were employed to analyse the PTE performance of EDCs in the ROI. Each model focusing on a different aspect of electricity distribution.

Model One (Comprehensive): This is the base model and all other models are a variation of the inputs and outputs employed. This model is designed to encapsulate the overall variables impacting on the PTE of electricity distribution in ROI. This model includes four inputs and three outputs. This model is an amalgamation of models two and three to represent the overall operational characteristic of EDCs under analysis.

Model Two (Basic Traditional): From the extensive DEA literature, the choice of input-output variables for electricity distribution benchmarking needs to account for international experience and data availability. Jamasb and Pollitt (2003) review 20 benchmarking studies in terms of electricity distribution efficiency establishing the number of employees (labour), network length (capital) and transformer capacity (peak load) the most frequently used input variables while output measures being energy delivered and the number of customers. There are

no pre-defined set of variables to assess the performance of electricity distribution utilities and each study is case specific (Giannakis et al., 2005). The basic model incorporates the above mentioned variables. Similar input-output combinations have been employed by (Azadeh et al., 2009; Sadjadi and Omrani, 2008).

Model Three (Quality Service): The inclusion of distribution losses[1] as a proxy for the technical quality of the grid or the service quality of the grid establishes the quality of electricity distribution. This approach has never been done before. Distribution losses are a source of inefficiency and is the difference between electricity required and electricity distributed to end-users. These losses can be of technical and non-technical nature. A reduction in costs to the consumer requires a reduction in both losses and a reduction in CO_2 emissions (Ramos-Real et al., 2009). The input-output combinations in this model have been adopted by (Ramos-Real et al., 2009; Von Hirschhausen et al., 2006; Pacudan and de Guzman, 2002).

[1]Electric power distribution losses constitute losses between sources of supply and points of distribution and in the distribution to consumers, including pilferage.

Table. 5.12: Electricity Distribution Efficiency Models

County level - Republic of Ireland Distribution Efficiency Study (ROIDES)								
Model One	(I) Labour	(I) Distribution Length (km)	(I) Transformer Capacity (MVA)	(I) Distribution Losses (MWh)	(O) Energy Consumed (MWh)	(O) Number of Customers	(O) Service Area (km^2)	
Model Two	(I) Labour	(I) Distribution Length (km)	(I) Transformer Capacity (MVA)	(O) Energy Consumed (MWh)	(O) Number of Customers			
Model Three	(I) Labour	(I) Distribution Length (km)	(I) Distribution Losses (MWh)	(O) Energy Consumed (MWh)	(O) Number of Customers	(O) Service Area (km^2)		
Model Four	(I) Labour	(I) Distribution Length (km)	(I) Transformer Capacity (MVA)	(I) Distribution Losses (MWh)	(I) Categorical Variable (MWh)	(O) Energy Consumed Customers	(O) Number of (km^2)	(O) Service Area
Model Five	(I) Labour	(I) Distribution Length (km)	(I) Transformer Capacity (MVA)	(I) Distribution Losses (MWh)	(O) Energy Consumed (MWh)	(O) Number of Customers	(O) Service Area (km^2)	(ON)Diagnostic Parameter
Model Six	(I) Labour	(I) Distribution Length (km)	(I) Transformer Capacity (MVA)	(I) Distribution Losses (MWh)	(O) Energy Consumed (MWh)	(O) Number of Customers	(O) Service Area (km^2)	(ON)Traditional Environmental Variable

Discretionary models of DEA assume that all inputs and outputs are discretionary, i.e., controlled by the management of each DMU and varied at its discretion. In any realistic situation, however, there exist external exogenously fixed factors or non-discretionary inputs-outputs that are beyond the control of a DMUs management that influence the performance of EDCs. The final three models attempt to acknowledge and account for these influential factors. EDCs may not be operating under equivalent environmental conditions; that is certain EDCs may operate in a more favourable position in terms of population density, topography, geography, industrialised area.

Model Four (Urban): Adapted from Miliotis (1992), a categorical variable is introduced to account for EDCs that contain an city-urban centre. Two groups are formed Urban Distribution Counties (UDC) that contain Irish cities and Rural Distribution Counties (RDC)s that do not. Two DMU groups are formed one containing all 26 EDCs and from this group the DEA efficiency scores of UDCs containing a city are calculated; the second group excludes the UDCs containing a city leaving 21 RDCs. The DEA efficiency scores of the remaining RDCs without a city are calculated. This is equivalent to introducing a categorical variable (Cooper et al., 2007).

Model Five (Diagnostic): Given the nature of the Irish electricity market and the variance in usage across the country, a diagnostic parameter was chosen to highlight county differences. Non-discretionary models with traditional exogenous variables such as inverse density index, customer and network density, and customer dispersion were employed with conflicting results. The industrial output variable was incorporated into the non-discretionary model to account for differences amongst EDCs in terms of electricity characteristics. To the authors knowledge this variable has not been employed in DEA literature in a similar context to this research. This model incorporates all the variables in the comprehensive model whilst adding a non-discretionary variable. This additional variable is in thousands of Euro and represents the selling value of goods produced within EDCs, as reported by the businesses themselves, this variable will represent the different geographical energy configuration across EDC of ESB networks.

Model Six (Exogenous): This model includes the non-discretionary model by employing the traditional exogenous variable customer density, to account for differences across EDCs. This model is similar to model five in terms of inputs-outputs employed differing only in the variable included to account for different electricity distribution characteristics across EDCs. A comparison with model four is therefore sought.

5.8 Individual Level - Republic of Ireland Wind Efficiency Study (ROIWES)

The Individual level efficiency analysis of wind farms was adopted given Ireland's key energy strategy commitment to increasing the use of RES to meet electricity, in order to reduce greenhouse gas emissions and meeting Kyoto commitments. The promotion of electricity generation from renewable energy sources will play a pivotal role in the development of future energy strategies for countries globally. Ireland is no exception, and is currently transforming itself into a society based on sustainable energy structures, technologies and practices with wind energy facilitating this change. Ireland has an abundance of renewable energy resource opportunities, and in particular has one of the most favourable wind regimes for wind energy generation in Europe. As O'Rourke et al. (2009) indicates the wind energy resource in Ireland is four times the European average.

The objective of the Individual level ROIWES research tier is to model the operational technical efficiency of wind generating units located throughout the twenty-six counties of the ROI. The analysis focuses on the evaluation of the *ex-post* operating phase of wind generating units. Each wind generating unit represents a DMU that encompasses a cluster of wind turbines connected to the SEM grid entitled a wind farm. The present research implements an ROIWES, that incorporates eighty-two fully operational Irish wind generating units for the year 2008. The use of annual data greatly reducing the influence multi annual effects. Accepting Iglesias et al. (2010) as a point of departure, the wind farm production process entails three phases:

1. Evaluating the production possibilities of a specific wind farm site, acknowledging wind speeds, weather conditions, topography, grid capacity and financial risks;

2. Project design incorporating technical characteristics, turbine models, turbine layout and installed capacity; and

3. Operating function is based on the first two phases and occurs when the wind farm commences energy production. Wind farm operational performance can be assessed in terms of the availability factor, payback period and productive results.

Krokoszinski (2003) affirm the first two phases relate to wind farm investment occurring prior to energy production (*ex ante*) and are the responsibility of engineers and wind farm developers whilst the third operating phase (*ex post*) depends solely on the wind farm operator. Iglesias et al. (2010) define the technical operating phase in terms of an economic production function defined as:

$$E = F(K, L, F) \tag{5.8.1}$$

where E is annual energy production, K is capital, L labour and F is the wind fuel source. Application of production technology terms to wind farms lead to a concise and comprehensive description of the transformation process associated with wind energy. The output of each

wind generating unit is represented by the annual energy production (E) dispensed to the electricity distribution and transmission grid measured in MWh. Concerning inputs, capital (K) is expressed as the unit rate export capacity MW of each wind farm connected to the SEM. This figure is enumerated by multiplying the nominal power of each wind turbine by the number of wind turbines present. The labour (L) indicator relates to the annual full-time man hours engaged in the operation, maintenance and control function of wind farms. Carroll (2010) states wind is given exogenously by nature, dynamic and a random phenomenon in both time and space. The final and most critical input component of the wind energy production function is wind fuel (F) generated by the wind turbines. The aspects of this intricate production process input are discussed in detail in the subsequent Section 5.9.

5.9 Fuel - Wind Power Output

Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque (Tong, 2010). Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity. Following the principles of wind power generation, the wind power output equation for a wind turbine is given by (Burton et al., 2001; Manwell et al., 2009; Tong, 2010) as:

$$P_w = \frac{1}{2}.p.A.\overline{U^3} \tag{5.9.1}$$

where:
P_w = Power Output Wind (MWh)
p = Air Density (Approximately 1.225 kg/m^3 for standard conditions sea level
37° C according to International Standard Atmosphere-(ISA)
A = Blade Surface Area Swept m^2
U^3 = Wind Speed m/s

5.9.1 Air Density

The density of the air is dependent on the variables such as atmospheric pressure, height, humidity and temperature of the air and can be calculated using an expanded form of the Ideal Gas Law:

$$p = \frac{P_d}{R_d.T} + \frac{P_v}{R_v.T} \tag{5.9.2}$$

where is the density of air (Kg/m^3), P_d is the absolute pressure of dry air (Pa), R_d is the specific gas constant for dry air = 287.05 $J/Kg°K$, T is the temperature (K), P_v is the pressure of water vapour (Pa) and R_v is the specific gas constant for water vapour = 461.495 $J/Kg°K$. Numerous synoptic and climatological Irish weather stations record meteorological elements on an hourly and daily basis such as rainfall, temperatures, air temperature, rainfall, humidity, vapour pressure, wind speed, wind direction and atmospheric pressure, mean sea level pressure.

This data is available on the Irish Meteorological Service. Carroll (2010) compute air density to be 1.24 (Kg/m^3).

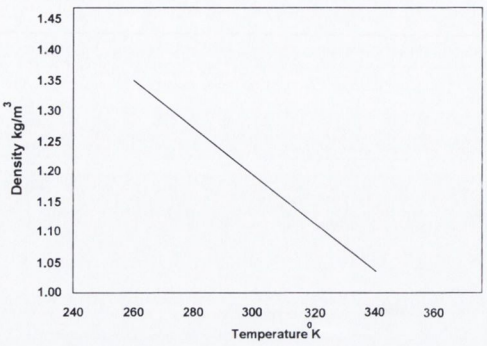


Fig. 5.4: Effect of Temperature on Air Density

5.9.2 Blade Surface Area

The power output of a wind turbine is directly related to the swept area of its blades. The larger the diameter of its blades, the more power it is capable of extracting from the wind. The blade swept area m^2 can be calculated from the formulae:

$$A = [(L + R2)R2] = L(L + 2r) \tag{5.9.3}$$

where A is swept area, L is the length of the blades and r is the radius of the hub Tong (2010). Data on the number of installed wind turbine models and swept area at each wind farm connected to the SEM in 2008 was compiled. The number of wind turbines multiplied by their swept area m^2 gives the total blade surface area at each wind farm.

5.9.3 Wind Speed

Electrical power production by wind power is dependent on both time and positional wind speed variability. Positional wind speed variability is defined by landscape articulation. Whereas, time wind speed variability is defined by altering weather conditions. Wind speed variability is also influenced by various random fluctuations that represent the chaotic nature of wind behaviour. The most prominent factor dictating the power available in the wind spectra is its velocity, when wind velocity doubles, the available power increases eight fold (Mathew, 2006). Wind shear is the variation of wind speed with elevation. It is a crucial issue as it directly impacts the power available at different wind turbine hub heights (Ray et al., 2006).

Furthermore, the growing height of modern wind turbines has increased the need for knowledge of wind shear (Rehman and Al-Abbadi, 2008). Employing wind shear models to analyse in detail wind speed profile characteristics are paramount for accurately predicting the power

output of wind farms. The power law and the log law are the two most frequently used analytical wind shear models for extrapolating wind speeds to higher hub heights at a site (Firtin et al., 2011; Manwell et al., 2003). The two models perform equivalently in shear extrapolation predictions on average, although at any particular site one model may be better than another (Elkinton et al., 2006). The Wind Power Law or Normal Wind Profile (NWP) model is given as:

$$U(Z)/U(Zr) = [Z/Zr]^{\alpha} \tag{5.9.4}$$

where:
U(Z) is the wind speed (metres/second) at height Z (metres)
U(Zr) is the reference wind speed (m/s) at height Zr (m)
α is the power law (Hellmann) exponent, or Wind Shear Coefficient (WSC)

where the Hellmann exponent α is an empirically derived coefficient that varies due to the roughness of the earth's surface. Empirical results indicate Hellmann's exponent often follows the "1/7 power law", where α = 1/7, or 0.143 (Schlichting, 1968). However, the exponent oscillates, depending on specific site parameters such as the roughness of surrounding landscape, elevation, time of day, season, nature of terrain, wind speed and temperature (Manwell et al., 2009). In general, higher exponents are found in urban areas with tall buildings (0.40), small towns (0.30), or areas with many trees (0.24), whereas lowest values (0.10) occur over smooth, hard ground, lake or ocean (Gipe, 2004; Patel, 1999). For calculations the Hellmann exponent of 0.2 is utilised (BSI, 2005).

Sustainable Energy Authority of Ireland (SEAI) utilises Geographic Information Systems (GIS) in the form of a Wind Atlas, which provides data on wind speeds measured at 50m, 75m and 100m above ground level. Reference wind speeds at certain heights, at wind farm coordinates in the ROI enables the employment of the Normal Wind Profile (NWP) model to extrapolate wind speeds to the desired hub heights of the wind farms connected to the SEM in 2008. In the case of the standard wind turbine classes, the normal wind speed profile shall be given by the power law equation:

$$U(Z) = U(Zr)[Z/Zr]^{\alpha} \tag{5.9.5}$$

To achieve higher wind power extraction requires (i) greater wind speed velocity (ii) longer length blades larger swept area and (iii) increased air density. Table 5.13 illustrates the wind electricity generation efficiency models adopted for the third tier Individual level - ROIWES.

Table. 5.13: Wind Electricity Generation Efficiency Model

Individual Level - Republic of Ireland Wind Efficiency Study (ROIWES)					
Efficiency Model One	(I) Fuel Consumption (MWh)	(I) Unit Rate Export Capacity (MW)	(I) Fulltime Man Hours (O & M)		(O) Annual Production (MWh)
Efficiency Model Two	(I) Fuel Consumption (MWh)	(I) Unit Rate Export Capacity (MW)	(I) Fulltime Man Hours (O & M)	(I) Mean Site Elevation (Metres)	(O) Annual Production (MWh)

Note: (I) Inputs (O) Output

5.10 Prevailing Wind Direction in Ireland

The dominant influence on Ireland's wind regime is the Atlantic Ocean. Weather systems travel along the direction of the Gulf Stream across the expanse of the Atlantic heading east which brings temperate conditions, in the form of low-pressure depressions, to what would otherwise be a much colder latitude - ° colder, in fact. As a result, Ireland does not suffer from the extremes of temperature experienced by many other countries at similar latitude. The unique geographical features of Ireland include low-lying central plains in the midlands surrounded by a ring of coastal mountains with constant wind speeds, resulting in Ireland harbouring one of the wind regimes most favourable to wind energy generation in Europe (Troen and Petersen, 1989). Ireland has an exceptional wind energy resource particularly along its Atlantic coastline (Frank and Landberg, 1997; SEI, 2003), with an estimated technical resource of 613 TWh per year (SEI, 2004*b*) of which Ireland currently utilises 2.8 TWh, equivalent to less than half a percent of the estimated technical resource (SEI, 2006).

The dominant prevailing winds are from the south westerly direction. Strong winds tend to be more frequent in winter than in summer. In January the southerly and south-easterly winds are more prominent than in July, which has a high frequency of westerly winds. The diurnal variation is much more pronounced in summer than in winter, with little variation in wind speeds during the night. Wind from the north occasionally, brings very cold weather from the Arctic, characterised by icy winds, snow and frost. When easterly winds sweep Ireland, they originate over central Russia where there is little moisture resulting in hot, dry weather (summer) or cold, dry weather (winter). There are ten Irish meteorological recording stations operational in Ireland. Refer to Figure 5.2. See Appendix B.3 for wind directions in Ireland from 1946-2010. Carroll (2010) provide the wind rose for weather stations in Ireland for 2008 Figure 5.5.

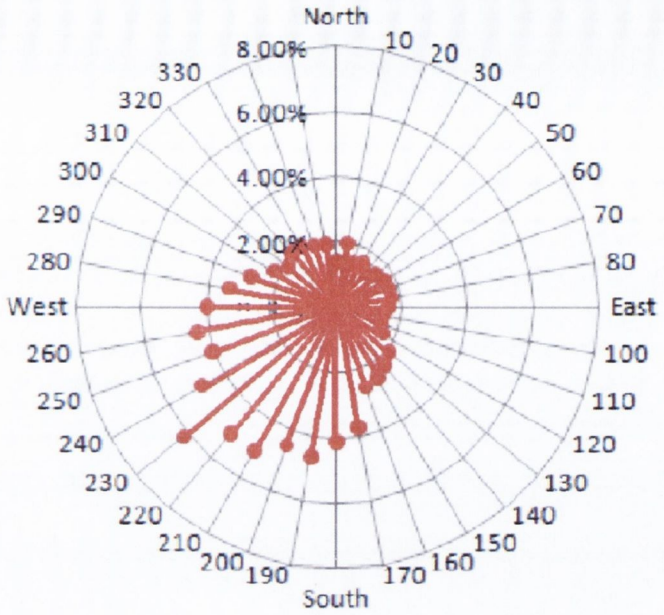


Fig. 5.5: Wind Rose Ireland 2008 (Carroll, 2010)

5.11 Sensitivity Analysis and Validation

Sensitivity analysis is an extremely important attribute of DEA to evaluate the robustness of the results obtained. Cubbin (1993) highlight the important issue of robustness and coherence in the adopted models for research. Sensitivity analysis relates to how efficiency results might alter, change or fluctuate with perturbation to the dataset and is widely employed in economic, engineering, operations research and other disciplines. The topic of sensitivity (stability or robustness) analysis in the DEA literature has incorporated a variety of forms . These studies observe the efficiency responses when DMUs are added or deleted to the set being considered or when inputs or outputs are added or withdrawn from consideration (Cooper et al., 2007). Numerous approaches to sensitivity analysis of DEA are available in the literature (Wilson, 1995; Simar and Wilson, 1998; Jha and Shrestha, 2006*a*; Zhu, 1996).

The most prominent form of stability and sensitivity analysis in DEA literature analysis is the altering, removing and adding of inputs or outputs (Liu et al., 2010). Sensitivity is defined as the effect on DEA efficiency upon inclusion or exclusion of one or more variables from the model and not with respect to parametric variation of input or output variables (Pahwa et al., 2003). The present approach assumes that the data set is correct and precise and removes individual variables one by one to observe differences in the DEA efficiencies (if any), thereby checking the robustness of the base model DEA results obtained. Note: upon removal of a variable, the efficiency score will either remain unchanged or decrease but never will it increase. On the basis of sensitivity analysis, divisions have been classified into different categories (Pahwa

et al., 2003; Jha and Shrestha, 2006*a*; Yadav et al., 2010).

1. *Robustly efficient:* The DEA efficiency level at 1 or slightly below 1, when the variables are removed one at a time.

2. *Marginally efficient:* The efficiency is 1 for the base model and remains at one in some situations, but drops significantly in other situations.

3. *Marginally inefficient:* The DEA efficiency is below 1 but above 0.9 for the base model and stays within that range for sensitivity analysis.

4. *Significantly inefficiently:* The DEA efficiency is between 1 and 0.9 and drops to a much lower value during sensitivity analysis.

5. *Distinctly inefficient:* The DEA efficiency is below 0.9 in all the conditions.

Validation criteria for the adopted models is proposed by Gass and Harris (2001), adopted by Manzoni (2007) and relates to descriptive, analytical and experimental verification of the research models. As adduced by Manzoni (2007), descriptive validation relates to the achievement of sound model structure, model objectives and plausibility of results. This is discussed in Chapter 7. Analytical validation investigates the robustness and characteristics of adopted models. This criteria is highlighted in Chapter 6. Experimental validation appraises the accuracy and efficiency of implementation, data, and methodological tests of model documentation. This is discussed in Chapters 5 and 6. The assumption of an "isotonicity" relationship between input and output factors must be satisfied (**?**). That is, a requirement that the relationship between inputs and outputs not be erratic. Increasing the value of any input while keeping other factors constant should not decrease any output but should instead lead to an increase in the value of at least one output.

Dyson et al. (2001) state this is achieved when increased inputs reduces efficiency whilst increased output increases efficiency. The relationship between inputs-outputs should be positively correlated (Luo and Donthu, 2001). The correlation relationship between input-output variables is statistically verified using Pearson's correlation. The greater the value of the correlation coefficient, the stronger the relationship between two variables is. For an extensive review of data preparation for DEA application, pitfalls, protocols and procedures the reader is referred to (Golany and Roll, 1989; Dyson et al., 2001). All the models adopted in the three tier efficiency evaluation research study adhere to the above mentioned criteria, therefore representing DEA efficiency models of high construct validity.

5.12 DEA-Solver Professional

The software employed in this research thesis is SAITECH DEA-Solver Professional 7 version which accompanied the textbook "Data Envelopment Analysis - A Comprehensive Text with Models, Applications, References and DEA-Solver Software", by Cooper, W.W. Seiford, L.M.

and Tone, K. 2nd edition Springer 2007 (Cooper et al., 2007). The DEA Solver program software is spreadsheet based and employs the platform Microsoft Excel 97/2000 or later to solve DEA models. Installation is menu driven and requires only minimal instructions. The DEA-Solver Pro7 version consists of 167 models incorporated into thirty-nine cluster. The reader is referred to (Cooper et al., 2007; SAITECH, 2012) for an extensive review of all DEA models. However, the DEA-Solver Pro7 version limits the number of DMUs in a research study to a maximum of fifty. Therefore a upgraded extended version entitled DEA-Solver Pro8 accommodation DMU analysis greater than fifty was purchased from www.saitech-inc.com in order to complete the Individual Level - ROIWES. DEA-Solver applies the following notation for characterizing DEA models:

Model Name - I or O - C, V or GRS (5.12.1)

where I and O correspond to "Input" or "Output" orientation, and C or V to "Constant" or "Variable" or "General" returns to scale (which is omitted if necessary). For example, CCR-I-C refers to the Input oriented Charnes Cooper Rhodes (CCR) model under Constant Returns to Scale (CRS). Table 5.14 illustrates the sample Excel sheet for the thermal efficiency study adopted in this thesis. The data file should be prepared in an Excel Workbook spreadsheet in a pre-set format prior to execution of DEA Solver program. The first row (Row 1) contains the problem name (e.g Generating Unit) and Input/Output descriptives for each DMU that are employed. Row 2 has headings for DMUs and must stipulate either (I) or (O) before each item name.

Table. 5.14: Sample Data Sheet of Inputs/Outputs for Thermal Generating Units

Generating Unit	(I) Fuel Consumption Terajoules (TJ)	(I) Unit Rate Export Capacity (MW)	(I) Heat Value Fuel Used (kCal/kg)	(O) Annual Production (MWh)
Aghada	9133.16	995	82438	770360
Ballylumford	20939.13	1213	104886	9212000
Dublin Bay	22956.29	403	11998	6376748.77
Coolkeeragh	18321.91	455	22448	2800000
Edenderry	15738.29	117.5	3583	812539.5
Great Island	1189.72	646	40996	78870
Huntstown	35797.87	744	23996	5179459
Kilroot	18718.19	500	36564	3640000
Loughree	8303.11	91	3583	685229
Marina	4595.48	197	23996	492772
Moneypoint	15137.60	915	23496	4204890
Northwall	2671.17	240	23996	890000
Poolbeg	21758.74	1005	58814	1990000
Rhode Island	63.74	104	20900	5927
Tarbert	11892.55	590	38664	1222338
Tawaghmore	102.95	104	20900	7035
Tynagh	20180.19	384	11998	605610
West Offaly	11905.22	137	3583	951962

Those without (I) and (O) headings will not be considered in the efficiency evaluation and the ordering of (I) and (O) is arbitrary. Boundaries to the dataset are identified by a blank column

and a blank row at the right and bottom respectively. This is necessary for knowing the scope of the data domain. The models adopted in this research thesis and explanatory notations are outlined below. A more detailed and comprehensive framework for employing DEA is presented in Appendix B.4.

Table. 5.15: Adopted DEA and Notations

Model Abbreviation	**Data Envelopment Analysis Efficiency Model**
CCR-I-C	Charnes-Cooper-Rhodes Input Oriented Constant Returns to Scale
CCR-I-V	Charnes-Cooper-Rhodes Input Oriented Variable Returns to Scale
CCR-O-C	Charnes-Cooper-Rhodes Output Oriented Constant Returns to Scale
CCR-O-V	Charnes-Cooper-Rhodes Output Oriented Variable Returns to Scale
BCC-I-C	Banker-Charnes-Cooper Input Oriented Constant Returns to Scale
BCC-I-V	Banker-Charnes-Cooper Input Oriented Variable Returns to Scale
BCC-O-C	Banker-Charnes-Cooper Output Oriented Constant Returns to Scale
BCC-O-V	Banker-Charnes-Cooper Output Oriented Variable Returns to Scale
DRS-I-V	Decreasing Returns to Scale Input Oriented Variable Returns to Scale
DRS-O-V	Decreasing Returns to Scale Output Oriented Variable Returns to Scale
NDSC-O-C	Non-Discretionary Output Oriented Constant Returns to Scale
NDSC-O-V	Non-Discretionary Output Oriented Variable Returns to Scale

5.13 Summary

This chapter discusses extensively the procedure for DEA, the dataset employed and the description of the variables considered in the DEA analysis. The conceptual framework for the successful application of DEA in efficiency analysis is presented in a systematic and concise manner. Issues, guidelines and protocols related to the construction, development and selection of input-output parameters employed in DEA efficiency analysis are defined and pursued. The parsimonious three tier DEA efficiency evaluation of the Irish electricity system is presented. The three level efficiency framework is represented by the AIGES, ROIDES and ROIWES. The procedural steps for a comprehensive sensitivity analysis examining the DEA results to perturbation of the data is demonstrated.

CHAPTER 6

Results and Evaluation of Efficiency Analysis

6.1 Introduction

The findings presented in this Chapter contain the efficiency analysis results of the three tier efficiency study of the SEM discussed in Chapter 5. This Chapter is divided into three sections - the National level Section 6.2, County level Section 6.3 and Individual level Section 6.4 reflecting the efficiency results obtained by the three tier study. Numerous research topics and focuses are defined, pursued and discussed. A sensitivity analysis and model validation of all three efficiency tiers and adopted DEA models is also conducted and presented in this Chapter. The primary focus of this thesis is the measurement of efficiency and inefficiency related to the electricity generation and distribution functions of the All Island SEM. The flexibility in DEA is praised frequently in the literature, its structure may cause troubles if assigned weights to the input/output sets show unrealistic properties. Numerous researchers construct more realistic models to "improve the discrimination of models" through weight restrictions (WR) on output and/or input bundles. Lower and upper bounds are specified for weights of input and output sets and then incorporated to the linear programming system: The main problem in WR models is the possibility of ending up with an inappropriate boundary which is solely contingent upon researchers own value judgments. For this thesis, weights restrictions are not included so the theoretical maximum as opposed to the actual maximum is calculated in terms of efficiency and inefficiency.

6.2 National Level - Application Results and Discussion

DEA is implemented to derive the benchmarks based on the National level comparison of 18 thermal power plants, 9 wind generating regions and 5 hydro power plants connected to the SEM utilising data from the year 2008. Three differing DEA models are constructed to capture the underlying operational characteristics of each form of electricity generation. The construc-

tion of the models enables the investigation of relative efficiency scores and the presence of slacks for each form of power generation. Table 6.1 displays the key characteristics of the input-output data employed to construct the National level DEA models, in the form of average, standard deviation, maximum and minimum values. It is clearly evident significant differences exist amongst power plants when one observes the variation in maximum and minimum values across all variables applied. Observing the thermal maximum and minimum values for annual production (MWWh), 9,212,000 and 5,927 respectively, it is clear the values display extensive divergence. A similar wide divergence in terms of annual production (MWh) is experienced for the wind and hydro data. This trait of divergence is evident for all the input resources consumed across all three forms of electricity generation.

Table. 6.1: Summary of Descriptive Statistics for National Level Data

Thermal Data Parameter	**Input 1** Fuel Consumption Terajoules (TJ)	**Input 2** Unit Rate Export Capacity (MW)	**Input 3** Heat Value Fuel Used (kCal/kg)	**Output 1** Annual Production (MWh)
Average	13300.300	491	30935.5	2606986
Maximum	35797.876	1213	104886	9212000
Minimum	63.748	91	3583	5927
S.D.	9343.917	350.513	26379.74	2550538
N	18	18	18	18
Wind Data Parameter	**Input 1** (I) Full Time Man Hours (O&M)	**Input 2** (I) Unit Rate Export Capacity (MW)	**Input 3** (I) Wind Availability (%)	**Output 1** (O) Annual Production (MWh)
Average	520	104.692	30.714	296928.6
Maximum	1140	243.4	32.78	690524.2
Minimum	300	14.45	28.01	34499.3
S.D.	268.328	69.326	1.560	215656.9
N	9	9	9	9
Hydro Data Parameter	**Input 1** (I) Employees/Unit Rate Export Capacity (MW)	**Input 2** (I) Storage Capacity (GWh)	**Input 3** (I) O & M (OM/MW/YR)	**Output 1** (O) Annual Production (MWh)
Average	0.482	7.198	43200	250000
Maximum	0.7	14.273	70000	441000
Minimum	0.07	1.431	21000	46000
S.D.	0.226	4.855	18626.86	154255.6
N	5	5	5	5

Note: S.D. - Standard Deviation

The efficiency performance of the 32 DMUs studied can be divided into three groups or categories - CCRϕ, BCCϕ and SE scores. The CCR ϕ model is employed to establish TTE under the assumption of CRS characteristics and does not discriminate between DMUs based on their size when computation their efficiencies. The BCCϕ model measures PTE of power plants under the assumption of VRS whilst SE is a ratio of the two CCRϕ/BCCϕ. The efficiency performance scores obtained for the thermal, wind and hydro national level efficiency research are presented in Tables 6.2, 6.3 and 6.4.

Interpreting the results employing the thermal power plant Aghada as a example, it can be stated Aghada has a TTE score of 11%, PTE of 17%, inefficient status, scale efficiency of 69%, presents DRS characteristics, and observes Northwall as the reference peer benchmark performer. Observing the thermal efficiency scores, only DMU 3 Dublin Bay and DMU 12 Northwall obtain an efficiency score of 1 for all three groups CCRϕ, BCCϕ and SE, implying they are at the optimal production frontier and have consistent operational efficiency performance. Both are located in the east of the country (regarded as the developed region). This could be due to them being new thermal pants, due to an advantageous location, or having new novel technological equipment. For thermal power plants, there is considerable variation amongst the CCRϕ scores obtained. Interpreting the results it is evident sixteen power plants are inefficient to varying degrees with DMU 6 Great Island displaying the poorest TTE efficiency score of just 9%. This could be attributed to an ageing power plant or its size. DMU 12 Northwall and DMU 3 Dublin Bay are the benchmark best performers amongst the thermal group of plants. The peer count for DMU 12 Northwall is the highest. It is observed that DMU 12 in the year 2008 is viewed as a peer by 15 other DMUs. DMU 3 Dublin Bay appears slightly less frequently with just 13 DMUs citing it as a peer benchmark performer. Both DMU 12 and DMU 3 appear jointly as peers for 9 DMUs.

Table. 6.2: Thermal Efficiency Results

No.	Generating Unit	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ/BCC ϕ	(RTS)	Reference DMU Peers
1	Aghada	0.119	0.171	Inefficient	0.695	Decreasing	12
2	Ballylumford	0.870	1	Inefficient	0.870	Decreasing	3,12
3	Dublin Bay	1	1	Efficient	1	Constant	3
4	Coolkeeragh	0.488	0.497	Inefficient	0.981	Decreasing	3,12
5	Edenderry	0.437	0.968	Inefficient	0.451	Increasing	3
6	Great Island	0.093	0.096	Inefficient	0.968	Increasing	12
7	Huntstown	0.507	0.768	Inefficient	0.660	Decreasing	3,12
8	Kilroot	0.585	0.610	Inefficient	0.959	Decreasing	3,12
9	Loughree	0.476	1	Inefficient	0.476	Increasing	3
10	Marina	0.250	0.298	Inefficient	0.838	Increasing	3,12
11	Moneypoint	0.841	0.859	Inefficient	0.979	Decreasing	3,12
12	Northwall	1	1	Efficient	1	Constant	12
13	Poolbeg	0.353	0.385	Inefficient	0.916	Decreasing	3,12
14	Rhode Island	0.131	1	Inefficient	0.131	Increasing	12
15	Tarbert	0.246	0.262	Inefficient	0.938	Decreasing	3,12
16	Tawaghmore	0.096	0.703	Inefficient	0.136	Increasing	12
17	Tynagh	0.987	1	Inefficient	0.987	Increasing	3,12
18	West Offaly	0.499	1	Inefficient	0.499	Increasing	3
	Average	**0.499**	**0.701**		**0.749**		

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

The average TTE of thermal plants was just 49%. Ten out of the eighteen thermal plants attain an efficiency score below this average value, thus clearly indicating the total technical operational inefficiency of the thermal plants under investigation. This average theoretical value suggests that the sample thermal power plants could reduce operational costs by up to 51% whilst still maintaining current output levels. Focusing on the renewable efficiency results of the research Tables 6.3 and 6.4, the wind efficiency results show all the wind regions are inefficient bar DMU 6 which is deemed 100% efficient across all efficiency categories exhibiting CRS.

For a graphical representation of the wind regions see Figure 5.2. The average efficiency value is 46% with five of the nine wind regions scoring below this figure. IRS characteristics are prominent amongst the regions. DMU 6 Region F in the south west of the country is the benchmark peer for all 9 DMUs. Region H is the least TTE, this could be due to the region being dominated by low lying central plains where strong winds are least prevalent. Similar efficiency results to the wind analysis, the hydro efficiency model returns only one efficient DMU, namely Turlough Hill DMU 5 which is the benchmark for all other DMUs. The average efficiency score is greater than both thermal and wind at 55%. All but two plants are below this figure. Note Turlough hill is a Pumped Hydroelectric Energy Storage (PHES) whilst the other hydro plants under investigation are Run of River Hydro Plants (RRHP). This fact will require further discussion and analysis in Section 6.2.2.

Table. 6.3: Wind Efficiency Results

No.	Generating Unit	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ/BCC ϕ	(RTS)	Reference DMU Peers
1	Region A	0.982	1	Inefficient	0.982	Increasing	6
2	Region B	0.294	0.430	Inefficient	0.684	Increasing	6
3	Region C	0.206	0.999	Inefficient	0.206	Increasing	6
4	Region D	0.453	1	Inefficient	0.453	Increasing	6
5	Region E	0.377	0.377	Inefficient	1	Constant	6
6	Region F	1	1	Efficient	1	Constant	6
7	Region G	0.193	0.223	Inefficient	0.865	Increasing	6
8	Region H	0.175	1	Inefficient	0.175	Increasing	6
9	Region I	0.541	0.624	Inefficient	0.867	Increasing	6
	Average	**0.469**	**0.739**		**0.692**		

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

Table. 6.4: Hydro Efficiency Results

No.	Generating Unit	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ/BCC ϕ	(RTS)	Reference DMU Peers
1	Ardnacrusha	0.631	1	Inefficient	0.631	Deceasing	5
2	Erne	0.541	0.560	inefficient	0.966	Increasing	5
3	Lee	0.429	1	Inefficient	0.429	Increasing	5
4	Liffey	0.153	0.865	Inefficient	0.176	Increasing	5
5	Turlough Hill	1	1	Efficient	1	Constant	5
	Average	**0.551**	**0.885**		**0.640**		

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

The preceding analysis primarily focused on the TTE of the DMUs being evaluated. To establish the cause of TTE, the BCC model with VRS is employed measuring the PTE of each DMU. The BCC model determines critical sources of inefficiency among the differing forms of electricity generation and establishes improvement directions to promote TTE of inefficient electricity generating DMUs. The TTE is dichotomised into PTE and SE and the nature of RTS is also presented in Tables 6.3 and 6.4. In the thermals context, initially comparing the CCR and BCC efficiency results, the most prevalent change is the number of efficient plants rises from 2 to 7, and inefficient plants falling from 16 to 11. The is due to the convexity constraint being imposed as explained in section 4.5 ensuring that similar sized DMUs are benchmarked and compare with each other. The average BCC efficiency score rises to 70% indicating that the consumption of all inputs theoretically could be reduced by 30% whilst producing the same quantity of outputs. The SE indicates the DMU is on the optimum production scale when the score equals 1. This can also be referred to as the MPSS and is the optimal operational performance of DMUs. The average scale efficiency was 74% for all power plants highlighting scope for improvement of efficiency by altering the operational scales of power plants. DMU 3 Dublin

Bay and DMU 12 Northwall are scale efficient, as they are fully efficient 100% in both CCR and BCC efficiency scores compared to other plants. All other generating plants are scale inefficient as they yield a score of less than 1 for scale efficiency. A scale inefficient plant that exceeds the MPSS will present DRS. Alternatively, a scale inefficient plant that is lower than MPSS will display IRS (Yadav et al., 2010). The NIRS model explained in Section 4.8 establishes the nature of RTS.

Adopted from Shrivastava et al. (2012) thermal power plants with VRS score equal to 1 are considered as *best performer* with VRS score ranging from 0.99 to 0.80 as *moderate performer* and with VRS score 0.79 to 0.69 are considered as *laggards*[1]. Finally, power plants with VRS score less than 0.69 are considered as *poor performer* among the group. Results indicate 7 DMU power plants are best performers and 7 DMUs are in the poor performance category below 0.69. Thermal power plants can be divided up into three groups based on unit rate export capacity - small (below 300MW), medium (300MW to 700MW) and large power plants above 700MW . The distribution of BCC efficiency scores is given in Table 6.5. 89% (8 out of 9)of small power plants show IRS characteristic indicating further expansion unit rate export capacity related to these power plants will improve efficiency performance. Conversely, all large thermal power plants DMUs 1, 2, 7, 11 and 13 present DRS. The two DMUs 3 and 12 exhibiting constant characteristics are from the medium and small categories respectively.

Table. 6.5: Distribution of VRS efficiency scores

No.	Status	PTE BCC ϕ	Total No. Plants	Capacity < 300MW	Distribution 300 to 700MW	> 700MW
1	Best Performer	Equal to 1	7	4	2	1
2	Moderate Performer	From 0.89 to 0.99	2	1	0	1
3	Laggards	From 0.69 to 0.79	2	1	0	1
4	Poor Performers	Below 0.69	7	1	4	2
		Total	**18**	**7**	**6**	**5**

DMU 2 Ballylumford, DMU 9 Loughree, DMU Rhode Island, DMU Tynagh and DMU West Offaly exhibit optimal 100% BCC efficiency with a lower SE and CCR efficiency score, hence are operating at PTE level but not TTE under limited or inappropriate scales. DMU 2 Ballylumford, DMU 5 Edenderry, DMU 6 Great Island, DMU 7 Huntstown, DMU 9 Loughree, DMU 14 Rhode Island, DMU Tawnaghmore, DMU Tynagh and DMU West Offaly all achieve a PTE score higher than their SE score. DMU 2 Ballylumford and DMU 7 Huntstown, demonstrate low values for SE and exhibit DRS as indicated Table 6.2, these plants have considerable scope for improvements in their TTE by resizing (decreasing) there scales of operation to the optimal scale MPSS.

DMU 5 Edenderry, DMU 6 Great Island, DMU 9 Loughree, DMU 14 Rhode Island, DMU Tawnaghmore, DMU Tynagh and DMU West Offaly similarly have PTE score higher than SE but in

[1]Laggards in this context relates to under-performing thermal power plants.

order to improve TTE they should increase their operation scales as they exhibit IRS. Finally, DMU 1 Agahda, DMU 4 Coolkeeragh, DMU 8 Kilroot, DMU 10 Marina, DMU 11 Moneypoint, DMU 13 Poolbeg, DMU 15 Tarbert obtain lower BCC efficiency scores while their SE scores are close to or equal to 1, indicating they are technically inefficient even though they are operating at the optimal production scale MPSS. The corrective efficiency measure for these thermal power plants to improve their technical efficiency is to altering their resource allocation and utilization which would increase their TTE score. The thermal efficiency CCRϕ, BCCϕ and SE efficiency scores are visually compared in 6.1. Considerable variation exists amongst the efficiency performance scores for the 18 thermal power plants.

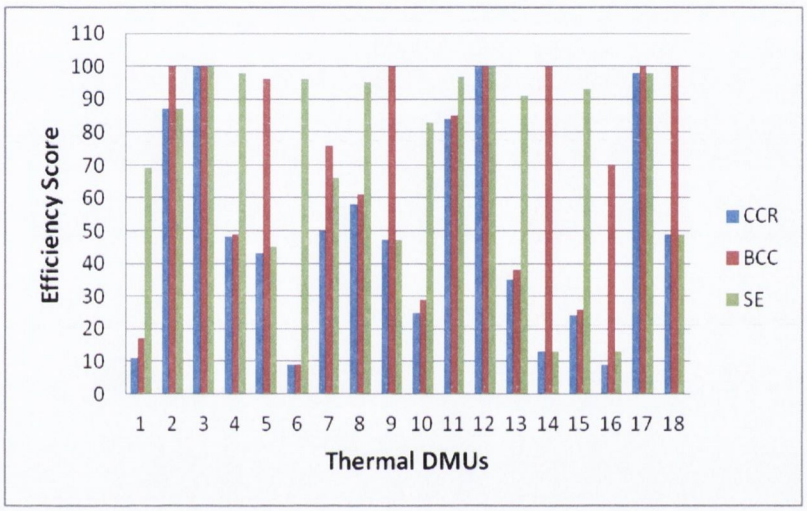


Fig. 6.1: Thermal Efficiency Results

For ease of discussion and analysis the PTE and SE analysis of wind and hydro power plants will be conducted simultaneously. Observing Tables 6.3 and 6.4, the number of wind region DMUs for the BCC model that appear as efficient entities increases to 4, while 5 DMUs show inefficiencies to varying degrees. In the hydro context, the number of efficient DMUs rises to 3. DMU 6 Wind region F and hydro DMU 5 Turlough Hill acquire PTE and SE scores of 1 and hence are operating at the optimal production scale, MPSS. The average technical efficiency scores for wind and hydro are 73% and 88% respectively. It is clearly evident DMU 8 Wind region H displays significant changes from the CCR to BCC formulation: adjusting from 17% to 100% resulting in DMU 8 demonstrating the lowest scale efficiency of 17% (See Tables 6.3 and 6.4), indicating the potential for efficiency improvements by possible restructuring. Wind DMU 1 region A, DMU 3 region C, DMU 4 region D, DMU 8 region H and hydro DMU 1 Ardnacrusha and DMU 3 Lee, all accrue PTE scores superior to their SE scores. All the above DMUs with the exception of hydro DMU 1 Ardnacrusha, present IRS and as such should increase their operational scale to achieve MPSS status via enlarging their input consumption, Ardnacrusha on the other hand should decrease operations.

DMU 2 regions B, DMU 5 region E, DMU 7 region G, DMU 9 region I and hydro DMU Erne all demonstrate higher SE scores than their PTE, resulting in them being deemed technically inefficient. These DMUs should focus on altering their input resources to increase efficiency whilst also increasing and decreasing scales of operation to become efficient. For example, hydro DMU Erne attains a PTE score of 56% and a SE score of 96% depicting room for efficiency improvement in both contexts through restructuring and input utilization. The renewable (wind and hydro) efficiency CCRϕ, BCCϕ and SE efficiency scores are visually compared in Figure 6.2. Note: the first 9 DMU represented in the graph pertain to the wind generating region efficiency scores (A-B) inclusive whilst the last five DMUs relate to the hydro efficiency performance.

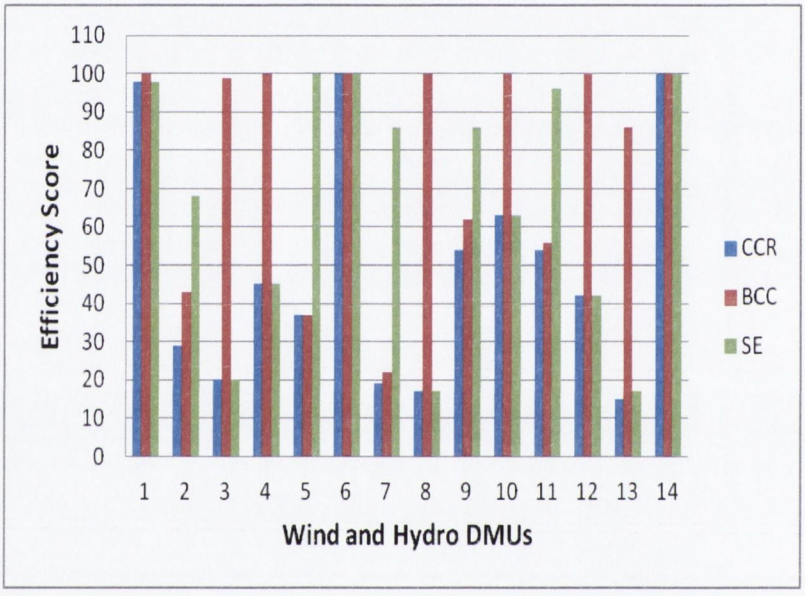


Fig. 6.2: Renewable Efficiency Results

6.2.1 Projection Analysis and Benchmarking

This section investigates the possible corrective measures and directions of improvement for inefficient DMUs to become efficient. The piece-wise linear form of the non-parametric frontier in DEA can cause a few difficulties in efficiency measurement. The problem arises because of the sections of the piece-wise linear frontier that run parallel to the axes that do not occur in most parametric functions (Coelli, 1995). As acknowledged in the methodology literature review Section 4.6, the DEA technique has the capability to identify sources of inefficiency for individual DMUs by employing projection analysis and directions of improvement. The corrective measures to improve the resource utilisation of those inefficient DMUs may be realised by a slack variable analysis. Slacks relate to input excesses and output shortfalls existing in the model. Both the CCR and BCC models generate slack evaluation results for the input-output variables to determine the level of inefficiencies.

However, for electricity generation a VRS BCC model for the three forms of electricity generation is a more appropriate model and for that purpose only the BCC model results have been adopted for discussion. The results of the previous Section 6.2 indicate the majority of the 32 DMUs investigated at the National level are technically inefficient, which suggests excess input resources are being employed to produce a certain level of output. Barros (2008) recommend that a benchmark management procedure has to be adopted for the improvement of efficiency of inefficient DMUs. In accordance with the VRS BCC results, original and targeted values of the selected inputs and outputs for the thermal, wind and hydro efficiency models are given in Tables 6.6, 6.7 and 6.8.

It is clearly evident from the results that DMUs that have been prescribed a DEA efficiency score of 1 for CCRϕ, BCCϕ and SE attain PK efficiency status with slacks zero and no target values for efficiency improvement given. For example, observing the target values for DMU 7 Huntstown thermal power plant, a reduction in fuel consumption -36.60%, unit rate export capacity -31.77%, heat value fuel used remaining unaltered will result in an annual production increase of 30.19% and Huntstown will be PK efficient.

From the data set, those DMUs with the greatest and smallest gap between their original and targeted values are marked ^{A} and ^{B} respectively. DMUs with the greatest input value gap should expend efforts to reduce this gap whilst DMUs with the smallest input value gap should expend less effort in order to perform effectively and achieve PK efficiency status. Results from Table 6.6 indicate that reduction in unit rate export capacity is the most effective improvement method for the main inefficient DMUs. Wind availability is not a significant technical parameter. Wind region E shows the greatest change required in full time man hours -57.14%, unit rate export capacity -79.10% and annual production will increase by 164.65%.

Table. 6.6: Original and Targeted Values for Thermal Parameters

No.	Thermal Power Plants	Fuel Consumption			Unit Rate	Export Capacity		Heat Value	Fuel Used		Annual Production		
		Original Value	Projected Value	%	Original Value	Projected Value	%	Original Value	Projected Value	%	Original Value	Projected Value	%
1	Aghada	9133.16	9133.16	0	995	584,182	-41.29	82438	52609.5	-36.18	770360	4480036	481.55
2	Ballylumford	20939.137	20939.137	0	1213	1213	0	104886	104886	0	9212000	9212000	
3	DublinBay	22956.294	22956.294	0	403	403	0	11998	11998	0	6376748.8	6376748.8	0
4	Coolkeeragh	18321.91	18321.91	0	455	435.221	-4.35[B]	22448	22448	0	2800000	5627569	100.98
5	Edenderry	15738.298	10378.19	-34.06[B]	117.5	117.5	0	3583	3583	0	838905.4	26365.86	3.24[B]
6	GreatIsland	1189.721	1189.721	0	646	162.728	-74.81[A]	40996	22236.75	-45.76[A]	78870	819533.8	939.09[A]
7	Huntstown	35797.876	22695.74	-36.60[A]	744	507.624	-31.77	23996	23996	0	5179459	6742968	30.19
8	Kilroot	18718.199	18718.199	0	500	500	0	36564	29049.54	-20.55	3640000	5959854	63.73
9	Loughree	8303.119	8303.119	0	91	91	0	3583	3583	0	685229	685229	0
10	Marina	4595.486	4595.486	0	197	197	0	23996	20500.72	-14.57	492772	1651298	235.10
11	Moneypoint	15137.604	15137.604	0	915	402.1064	-56.05	23496	23496	0	4204890	4893355	16.37
12	Northwall	2671.171	2671.171	0	240	240	0	23996	23996	0	1890000	1890000	0
13	Poolbeg	21758.749	21758.749	0	1005	808.826	-19.52	58814	58814	0	2990000	7761891	159.60
14	RhodeIsland	63.748	63.748	0	104	104	0	20900	20900	0	5927	5927	0
15	Tarbert	11892.552	11892.552	0	590	495.406	-16.03	38664	38664	0	1222338	4649720	280.40
16	Tawaghmore	102.952	102.952	0	104	104	0	20900	20824.75	-0.36[B]	7035	100000.6	42.15
17	Tynagh	20180.196	20180	0	384	384	0	11998	11998	0	5605610	5605610	
18	West Offaly	11905.225	11905.225	0	137	137	0	3583	3583	0	951962	951962	0

Note: [A] - Those with the greatest difference [B] - Those with the smallest difference

Table. 6.7: Original and Targeted Values for Wind and Hydro Parameters

No.	Wind Farms Plants	Full Time Original Value	Man Hours Projected Value	%	Unit Rate Original Value	Export Capacity Projected Value	%	Wind Availability Original Value	Projected Value	%	Annual Production Original Value	Projected Value	%
1	Region A	1140	1139.868	-0.01[B]	190.5	190.476	-0.01[B]	30.79	30.79	0	637269.8	648604	1.78
2	Region B	420	346.151	-17.58	72.1	72.1	0	30.17	30.17	0	187199.6	435038	132.39
3	Region C	480	279.986	-0.01	41.6	41.6	0	28.49	26.49	0	116818.2	116852.7	0.03[B]
4	Region D	300	300	0	100.42	100.42	0	28.01	28.01	0	260915.2	260915.2	0
5	Region E	840	360	-57.14[A]	243.4	50.86	-79.10[A]	32.78	32.78	0	260915.2	690524.2	164.65
6	Region F	360	360	0	50.86	50.86	0	32.78	32.78	0	690524.2	690524.2	0
7	Region G	360	360	0	101.05	66.901	-33.79	31.47	31.47	0	128381.3	575140.4	347.99[A]
8	Region H	300	300	0	14.45	14.45	0	30.74	30.74	0	34499.3	34499.3	0
9	Region I	480	480	0	127.85	87.942	-31.21	31.2	31.2	0	355834.7	570132.5	60.22

Note: [A] - Those with the greatest difference [B] - Those with the smallest difference

Table. 6.8: Original and Targeted Values for Hydro Parameters

No.	Hydro Power Plants	Employee/ Original Value	Capacity Projected Value	%	Storage Original Value	Capacity Projected Value	%	O&M Original Value	Projected Value	%	Annual Original Value	Production Projected Value	%
1	Ardnacrusha	0.66	0.66	0	3.844	3.844	0	70000	70000	0	441000	441000	0
2	Erne	0.43	0.130	-69.58[A]	14.273	1.772	-87.58[A]	60000	33548.49	-43.92[A]	324000	324000	0
3	Lee	0.7	0.7	0	4.966	4.966	0	21000	21000	0	90000	90000	0
4	Liffey	0.55	0.476	-13.42[B]	11.479	3.710	-67.68[B]	30000	25973.42	-13.42[B]	46000	182011.3	295.68
5	Turlough Hill	0.07	0.07	0	1.431	1.431	0	35000	35000	0	349000	349000	0

Note: [A] - Those with the greatest difference [B] - Those with the smallest difference

The summary statistics of the slack parameter analysis for the BCC case are presented in Table 6.9 for the thermal, wind and hydro national level efficiency evaluation. The presence of slacks reveals the scope for further non-radial reduction in inputs or expansion in the case of outputs once an inefficient DMU is projected on to the production frontier. Observing the mean (amount of slack per DMU) values, it can be stated that the fuel consumption input for each DMU with slack could have been reduced by an average of 18462.236 TJ without altering current levels of output production. The same can be said for unit rate export capacity with an average of 279.128 MW and heat value fuel used 11934.448 (kCal/kg).

The excessive use of inputs in the thermal case accounts for 15.42% of total fuel consumption, 22.1% of unit rate export capacity and 10.71% of heat value fuel used for those DMUs that present with slacks. A similar trend is evident for wind and hydro when observing the capacity parameter. The results indicate excess capacity across all three national level DEA models is significant. Wind availability and hydro O&M are insignificant presenting zero slack, which infers excess in both parameters is not a problem in the Irish electricity sector. In all three DEA models the annual production could be increased through corrective measures.

Table. 6.9: National Level Summary Statistics of Slack Variables

Parameter	**Number of DMU's with Slacks**	**Mean (Amount of Slack per DMU)**	**% of Slack of Total Input**
Thermal Data			
Fuel Consumption	2	18462.236	15.42
Unit Rate Export Capacity	7	279.128	22.1
Heat Value Fuel Used	5	11934.448	10.71
Annual Production	11	1930678.796	45.25
Wind Data			
Full Time Man Hours	4	138.498	11.83
Unit Rate Export Capacity	5	53.330	28.30
Wind Availability	0	0	0
Annual Production	5	267707.685	50.08
Hydro Data			
Employee/Export Capacity	1	0.110	4.56
Storage Capacity	2	6.230	34.61
O & M Costs	0	0	0
Annual Production	1	136011.3	10.88

6.2.2 Further Analysis and Discussion

The thermal power plant DEA efficiency evaluation model can be further scrutinised in terms of power plants geographical regional location, generator and the fuel type employed at each power plant. The study conducted encompasses two countries the ROI and NI, and thirty-two counties Figure 6.3. EirGrid is the independent electricity Transmission System Operator (TSO) in the ROI and the Market Operator (MO) of the wholesale electricity trading system and is solely responsible for development and enhancement of the transmission network in Ireland. Eirgrid (2008) published a report "Grid25" whereby the electricity transmission network is segregated into regions. Eirgrid stipulates segregation is necessary for the purpose of investment, grid infrastructural development, generation capacity, retiring and maintaining existing power plants to ensure that the transmission network has the capacity to meet geographical population and electricity demand growth between now and 2025. This regional plan is represented in Figure 6.3, and forms the basis of the geographical efficiency study of thermal power plants.

The "All-Island" 220/275/400kVkV high-voltage transmission system network consists of an assimilation of base load and mid merit fossil-fuel (coal and peat) steam turbine generation, combined-heat-and-power gas plants (CHP), CCGTs, higher-efficiency aero-derivative gas turbines (ADGTs), lower-efficiency Open Cycle Gas Turbine (OCGT)s, as well as a numerous gas/oil-distillate "peaking" units, amounting to 10.4 (GW) of conventional thermal power plant capacity (Burke, 2010). These power plant characteristics are represented in Table 6.10. Adopting Eirgrid's regional segregation, each region is considered a DMU, eight in total. Table 6.10 illustrates the breakdown of efficiency scores based on thermal plants geographical location on the AIG system. The results indicate considerable discrepancies across regions when observing the CCRϕ, BCCϕ and arithmetic average efficiency scores. A number of points emerge from the analysis, the east region is the best performing region in terms TTE with a score of 78.3%, and the midlands region is the technically best performing with a PTE score of 90%.

Great Island power plant in the south East region, consuming Heavy Fuel Oil (HFO) as its fuel source in Oil Fired Steam Turbines (OFST) generators is extremely inefficient with a TTE and PTE of 9% and 10% respectively. Observing the arithmetic average efficiency scores, the east region outperforms all other regions to be the most efficient. A clear distinct pattern emerges with the east and midland regions being the most efficient whilst all other regions, being more sparsely populated and rural regions are less efficient to varying degrees. This is most likely due to demand profiles and the operation of power plants. The east region contains three power plants Dublin Bay, Northwall and Poolbeg, all three primarily consume gas as their fuel source and operate CCGTs. The east region is composed of counties Meath, Kildare, Wicklow and Dublin which is the capital of the ROI, with a population of 1.2 million (CSO, 2006). Electricity demand is consistent and at its highest in this region. The region itself exhibits the most developed and extensive network infrastructure in the ROI.

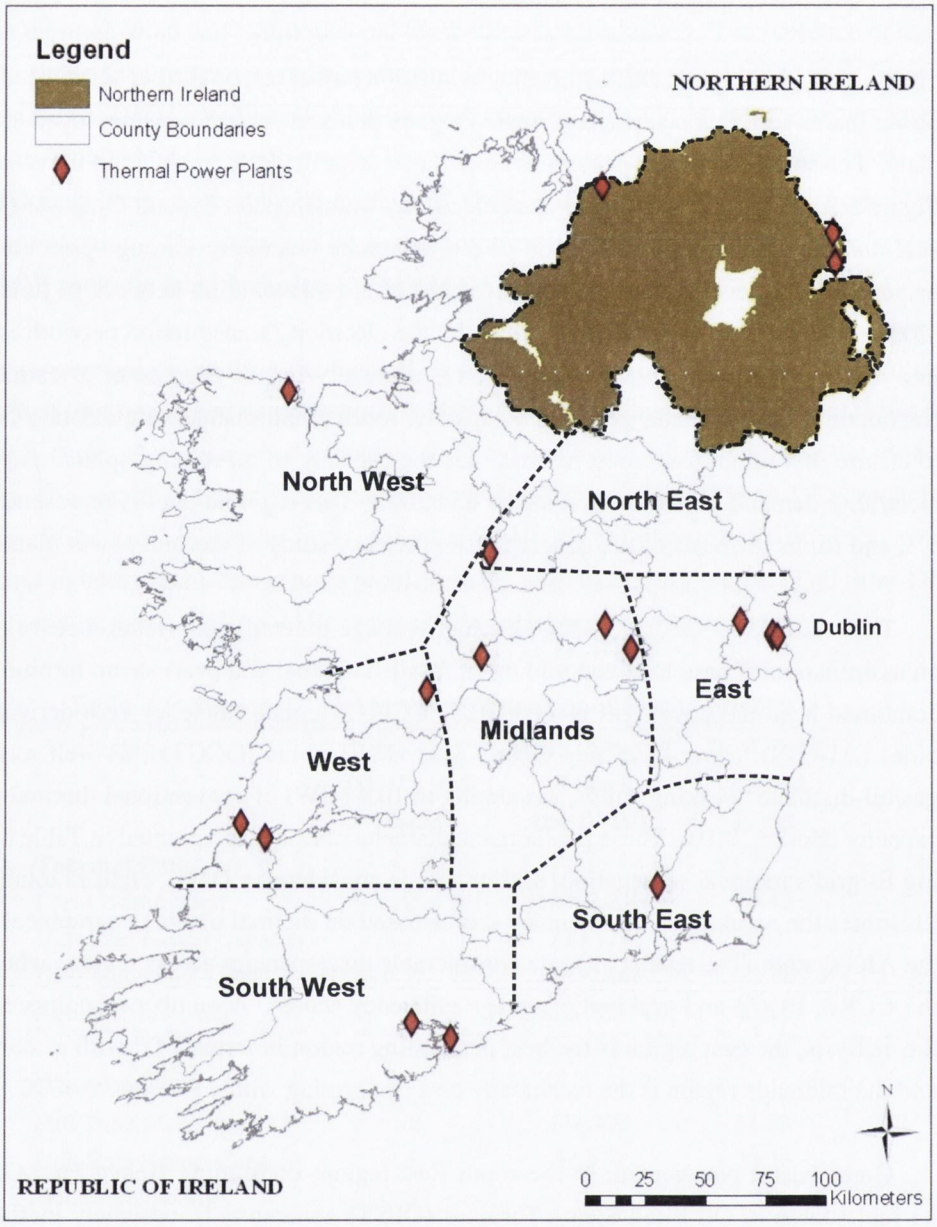


Fig. 6.3: Thermal Power Plants, Geographic Regions and Counties

It has the greatest installed transmission station capacity, and a developed gas pipeline supply network from the UK that is necessary to meet electricity demand (Eirgrid, 2011*b*). As previously outlined both the Dublin Bay and Northwall power plants score 100% efficiency in the CCR and BCC models and are the peer benchmarks for all other power plants. Both are located in the capital of the ROI, Dublin consume the fuel source gas and operate CCGT generators. The south east region was the worst performing region in terms of both the CCR and BCC models.

Table. 6.10: Efficiency Results by Region

Generating Unit & Region	Fuel Type	Generator Type	Total Technical Efficiency CCR ϕ	Pure Technical Efficiency BCC ϕ	Arithmetic Average
Northern Ireland					
Ballylumford	Gas	CCGT	0.870	1	0.935
Coolkeeragh	Gas/DO	CCGT	0.488	0.497	0.492
Kilroot	Coal	Coal/Oil Fired	0.585	0.610	0.597
			0.647	**0.680**	**0.674**
East					
Dublin Bay	Gas	CCGT	1	1	1
Northwall	Gas/DO	CCGT	1	1	1
Poolbeg	Gas/HFO	CCGT	0.353	0.385	0.369
			0.784	**0.795**	**0.789**
South West					
Aghada	Gas/DO	OCGT	0.119	0.171	0.145
Marina	Gas/DO	OCGT	0.250	0.298	0.274
			0.184	**0.234**	**0.209**
Mid West					
Moneypoint	Coal	Coal/Oil Fired	0.841	0.859	0.85
Tarbert	HFO	Oil Fired Steam Turbine	0.246	0.262	0.254
Tynagh	Gas	CCGT	0.987	1	0.993
			0.691	**0.707**	**0.699**
South East					
Great Island	HFO	Oil Fired Steam Turbine	0.093	0.096	0.0945
			0.093	**0.096**	**0.0945**
Midlands					
Edenderry	Peat	Peat Fired Steam Turbine	0.437	0.968	0.702
Rhode Island	DO	OCGT	0.131	1	0.565
West Offaly	Peat	Peat Fired Steam Turbine	0.499	1	0.749
			0.355	**0.989**	**0.672**
North West					
Tawnaghmore	DO	OCGT	0.096	0.703	0.399
			0.096	**0.703**	**0.399**
North East					
Loughree	Peat	Peat Fired Steam Turbine	0.476	1	0.738
Huntstown	Gas	CCGT	0.507	0.768	0.637
			0.491	**0.884**	**0.687**

Note: DO - Distillate Oil HFO - Heavy Fuel Oil OCGT - Open Cycle Gas Turbines CCGT - Combined Cycle Gas Turbine

CCGT manufacturers have achieved (1) technical efficiencies close to 60% and higher, (2) short power plant construction periods (less than 2 years), and (3) low investment costs (IEA, 2010).

These technical developments coupled with low natural gas prices and new natural gas transportation networks have made this technology the dominant choice for new investment in competitive generation markets (Rothwell and Gomez, 2003). This has certainly been evident in Ireland in recent years, with electricity generation sources having altered and changed significantly with the key source, gas and the CCGT generator type playing an ever-increasing role in Ireland's power generation along with the dramatic increase in installed wind power capacity (SONI, 2011). The role of oil and coal has diminished significantly (CSO, 2011*b*). From Table 6.11, CCGT are the most efficient generator type compared with the others, obtaining an average TTE of 74%, PTE score of 80%, with seven plants employing this generator type. Open Cycle Gas Turbine (OCGT) and Oil Fired Steam Turbines (OFST) are the worst performing generators with arithmetic average scores of 35% and 18% respectively.

Table. 6.11: Efficiency Comparison by Generator Type

Generator Type	**Number of Plants**	**Total Technical Efficiency CCR ϕ**	**Pure Technical Efficiency BCC ϕ**	**Arithmetic Average**
CCGT	7	74.4	80	77.2
Coal/Oil Fired	2	71.5	74	73
OCGT	4	14.8	54.3	35
Oil Fired Steam Turbines	2	17	18	17.5
Peat Fired Steam Turbines	3	47.3	99	73
Average		**45**	**65.06**	**55.14**

Note: CCGT - Combined Cycle Gas Turbine OCGT - Open Cycle Gas Turbine

Ireland currently consumes the following fuel sources for electricity generation; Coal, Oil, Heavy Fuel Oil (HFO) & Diesel Oil, Gas and Peat as displayed in Table 6.12. In terms of fuel source, consuming gas is the most efficient with four plants out of eighteen using this fuel source and obtaining a TTE score 84.3%, PTE score 92.8% and an arithmetic average of 89%, well above all other forms of fuel. HFO is the most inefficient fuel source. At present, ROI imports 95% of gas needed to meet Irish demand highlighting the vulnerability of the Irish economy to gas price shocks (Limited, 2010). Gas is a clean fuel with a low carbon content in comparison the other fossil fuels. For example, coal-fired power plants usually takes four to five years to construct, have higher operation and maintenance costs and are the largest polluter of toxic mercury and the largest contributor of hazardous air toxics (Sueyoshi and Goto, 2010). Similarly, Peat is not extensively used in electricity production as it contains a high carbon content, higher than coal, and the technology is not as cost efficient. Consequently, the generator obtains less electricity per tonne of peat, than it would with a more efficient technology or fuel.

Table. 6.12: Efficiency Comparison by Fuel Type

Fuel Type	**Plants Fuel Source**	**TTE CCRϕ**	**PTE BCCϕ**	**Arithmetic Average**
Gas/DO	4	46.3	49.3	47.8
Gas	4	84.3	92.8	89
HFO	2	34	36	35
Coal	2	72	74	73
Peat	3	47.3	99	73.2
DO	2	23	85	54
Gas/HFO	1	35	39	37
Average		**48.84**	**67.87**	**58.42**

Note: DO - Distillate Oil HFO - Heavy Fuel Oil

As stated previously, Turlough Hill is a Pumped Hydroelectric Energy Storage (PHES) resource which consists of an upper and lower reservoir incorporating four 73 MW generators to give a total capacity of 292 MW. Considerable flexibility and operational efficiency is achieved as generation capacity from other sources can be employed to pump water from the lower to the upper reservoir, enabling generators in a pumped storage scheme to be synchronised within seconds, providing instant power to meet peak demand or fluctuating electricity demand. In the last few decades, numerous pumped-hydro facilities have been constructed worldwide, resulting in a storage component of roughly 5% the capacity of all the European countries, 3% in the USA, and 10% in Japan. The purpose of pumped-hydro plants have been used for load levelling, frequency response, and voltage control (Gonzalez, 2004). Dennehy et al. (2010) states much research has been conducted in Ireland, considering a combination of pumped-hydro with wind energy and indicates there are five pumped-hydro generators in the planning process with a total capacity of 415 MW.

The primary objective of Turlough Hill is to provide some balancing capabilities between day and night time supply and demand. The facility achieves this by delivering 292 MW of electricity which is about one tenth of the average national demand continuously for about five hours. In 2008, Turlough Hill produced 349,000 MWh of electricity but in doing so consumed 546,000 MWh. Ardnacrusha, Erne, Lee, Liffey are Run of River Hydro Plants (RRHP) which prioritise energy generation whilst Turlough Hill focuses on load balancing hence the DEA stipulation that DMUs under analysis must display homogeneous underlying technologies is violated.

This may explain why Turlough Hill is deemed PK efficient in the initial hydro DEA model. An adjusted hydro efficiency model omitting Turlough Hill is presented in Table 6.13. The results are altered significantly with DMU 1 Ardnacrusha and DMU 2 Erne attaining an efficiency score of 1 across all CCRϕ, BCCϕ and SE groups. Both these hydro power plants are viewed as

peers with DMU 1 Ardnacrusha cited three times. The average PTE score rises to 73% and the PTE attains 100% efficiency however caution must be extended as the adjusted model is losing discriminatory power due to the fact that number of DMUs is close to the product of inputs and outputs. This relates to the rule of thumb mentioned in the Chapter 5. DMU 3 Lee and DMU Liffey have PTE of 1 with a low SE, hence are technically efficient but scale inefficient and should increase the scale of their operation as they exhibit IRS to become efficient.

Table. 6.13: Adjusted Hydro Efficiency Results

No.	Generating Unit	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ	(RTS)	Peers
1	Ardnacrusha	1	1	Efficient	1	Constant	1
2	Erne	1	1	Efficient	1	Constant	2
3	Lee	0.680	1	Inefficient	0.680	Increasing	1
4	Liffey	0.243	1	Inefficient	0.243	Increasing	1
	Average	**0.73**	**1**		**0.73**		

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

6.2.3 Sensitivity Analysis and Model Validation

A separate linear program is run for each DMU to determine the relative efficiency and in real world data applications the number of DMU's is usually large, and therefore it is pertinent to establish how sensitive the efficiency scores obtained are to the employed inputs and outputs. Sensitivity analysis is conducted by each of the inputs ceteris paribus being excluded from a base case input-output framework and the resulting efficiency scores observed.

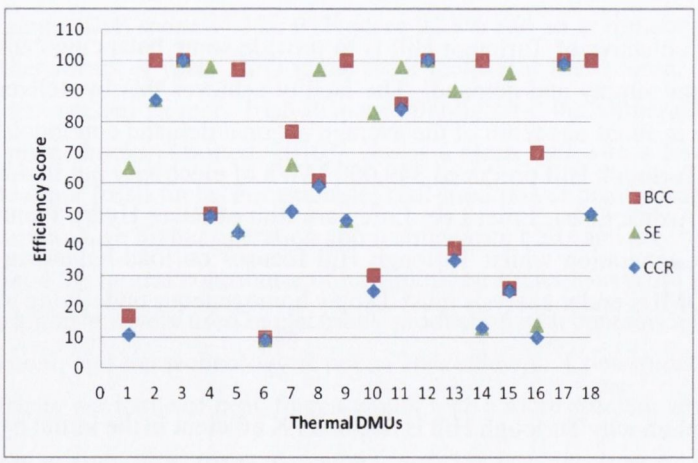


Fig. 6.4: Base Case for Thermals

Note: that calculated efficiency score can never increase upon removal of variables, if it alters, it will only decrease upon removal of variables. A base case must be established for use as a barometer and comparator in terms of efficiency. The base case or comparison case is when all the parameters are included in the model. The CCR CRS, BCC VRS and SE are visually represented in Figure 6.4. From inspection, DMUs 1, 6, 10, 13 and 15 have low CCR and BCC efficiency scores whilst DMUs 3, 12 and 17 achieve high levels of CCR and BCC efficiency. Only the DEA BCC efficiency scores are retained for sensitivity comparison as the BCC technique is a more parsimonious model enveloping the sample data points resulting in efficiency scores equal to or higher than the DEA CCR scores, coupled with most thermal power plants displaying VRS characteristics. Figures 6.5, 6.6 and 6.7 illustrate how the omission of input parameters fuel consumption, unit rate export capacity and heat value fuel used respectively contributes to fluctuations in the obtained efficiency scores.

Figure 6.5 depicts the variance in efficiency scores when fuel consumption is excluded from the inputs. The main visible effect of this modification is the reduction in efficiency of numerous DMUs albeit by varying amounts. This indicates that fuel consumption is an important factor for all thermal plants. This is intuitively what one would expect as fuel consumption plays a significant role in the operation of thermal plants with a strong relationship between this value and annual electricity production. The most significant reduction was observed for DMU 14 indicating this plants efficiency is strongly influenced by the fact it can produce its outputs with less fuel consumed than that of its peers. The DMUs with base case low efficiency scores are reduced further but to a lesser extent.

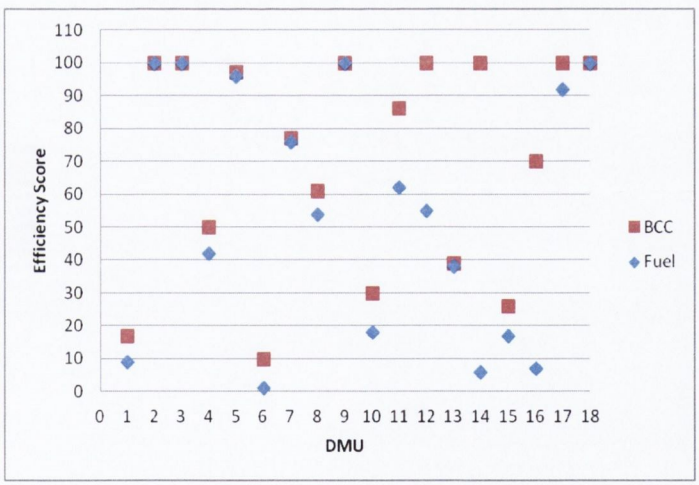


Fig. 6.5: Fuel Consumption Omitted

Figure 6.6 illustrates that the efficiency scores of DMUs 5, 10 and 16 are altered slightly with DMU 16 witnessing the greatest change in efficiency score. The remaining DMUs are not altered significantly.

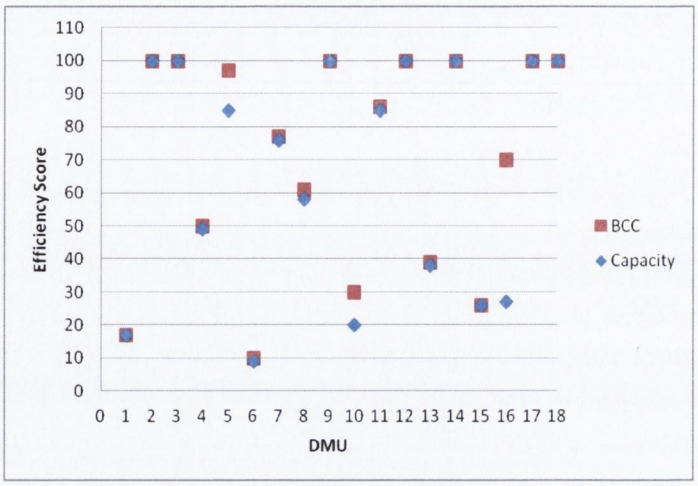


Fig. 6.6: Unit Rate Export Capacity Omitted

Figure 6.7 shows that DMUs 5, 7, 11 and 18 reveal unit rate export capacity contributes to the high efficiency score attained in the base case. It can also be noted that none of the low efficiency scores, DMUs 1, 2, 10, 13 and 15 are not affected greatly by the removal of this parameter. Observing Table 6.14, it is evident a significant portion of the thermal plants are distinctly inefficient with only three power plants DMU 2 Ballylumford, DMU 3 Dublin Bay and DMU 9 Loughree robustly efficient. Table 6.14 also show the relationship between the efficiency of DMUs and the inputs with ** depicting strong influence when the input in question alters the efficiency score by at least 0.5; whilst * refers to weak influence where the input in question alters the efficiency value by less than 0.5.

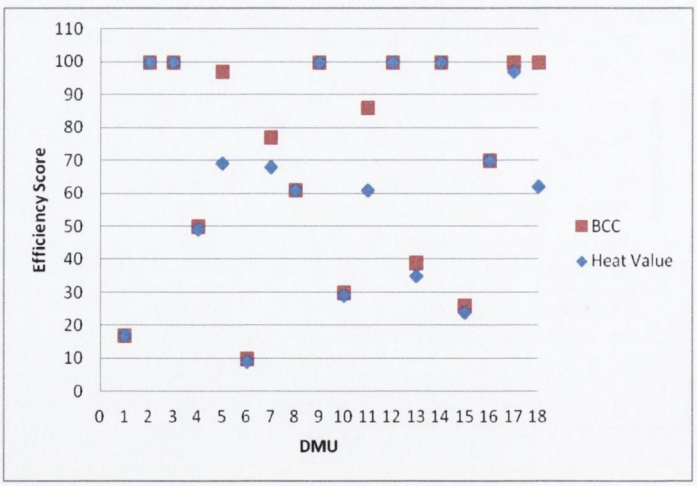


Fig. 6.7: Heat Value Fuel Used Omitted

Unit rate export capacity influences the least number of DMUs and therefore this could be the first parameter to be omitted from the DEA model. As outlined in Section 5.11, for validation

of the adopted thermal DEA model the assumption of the isotonicity relationship between input and output factors, (i.e. an increase in an input must not correspond with a decrease in an output) was investigated (?). If the correlation of selected input and output factors is positive, these factors are isotonically related and can be included in the model.

Table. 6.14: Sensitivity Analysis of Thermal Parameters

No.	Generating Unit	(PTE) BCC ϕ	Fuel Consumption Omitted	Unit Rate Export Capacity Omitted	Heat Value Fuel Used Omitted	Efficiency Status
1	Aghada	0.171	0.091*	0.171	0.171	Distinctly Ineff.
2	Ballylumford	1	1	1	1	Robustly Eff.
3	Dublin Bay	1	1	1	1	Robustly Eff.
4	Coolkeeragh	0.497	0.426*	0.497	0.490*	Distinctly Ineff.
5	Edenderry	0.968	0.968	0.853*	0.695*	Significantly Ineff.
6	Great Island	0.096	0.019*	0.096	0.096	Distinctly Ineff.
7	Huntstown	0.768	0.768	0.768	0.684*	Distinctly Ineff.
8	Kilroot	0.610	0.541*	0.584*	0.610	Distinctly Ineff.
9	Loughree	1	1	1	1	Robustly Eff.
10	Marina	0.298	0.188*	0.209*	0.298	Distinctly Ineff.
11	Moneypoint	0.859	0.625*	0.859	0.610*	Distinctly Ineff.
12	Northwall	1	0.555	1	1	Marginally Eff.
13	Poolbeg	0.385	0.383	0.385	0.352	Distinctly Ineff.
14	Rhode Island	1	0.064*	1	1	Marginally Eff.
15	Tarbert	0.262	0.173*	0.262	0.243*	Distinctly Ineff.
16	Tawaghmore	0.703	0.076**	0.278*	0.703	Distinctly Ineff.
17	Tynagh	1	0.929*	1	0.970*	Marginally Eff.
18	West Offaly	1	1	1	0.624*	Marginally Eff.

Note : ** - Efficiency score altered by at least 0.5; * - Efficiency score altered by lees than 0.5; Ineff. - Inefficient Eff. - Efficient

A Pearson's correlation statistical test was applied to the adopted thermal dataset and the results are given in Table 6.15. Sowlati (2001) state a high degree of correlation between inputs and outputs could imply that the two variables may represent the same thing and hence DEAs discriminatory power will decrease, one of these highly correlated variables could be omitted from the model; although, care must be taken because a mathematical correlation could imply logical or causal correlation. An extremely low correlation between one variable and the other variables could indicate poor explanatory power and does not fit into the model. The results in Table 6.15 indicate that the isotonicity assumption is not violated when utilising the current dataset. The values of correlation coefficients are all positive and the parameters are reasonably correlated, with moderate and high degrees of correlation in all cases: neither too much correlation nor too little correlation would otherwise make it difficult to determine the unique contribution of a variable to the analysis. The sensitivity analysis, model validation and Pearson correlation pertaining to the adopted wind and hydro efficiency models are presented in Appendices C.1 and C.2. As in the case of the thermal efficiency model both models are validated, justified and verified through investigation.

Table. 6.15: Pearson Correlation Matrix for Thermal Data

		Input 1 Fuel Consumption Terajoules (TJ)	**Input 2** Unit Rate Export Capacity (MW)	**Input 3** Heat Value Fuel Used (kCal/kg)	**Output 1** Annual Production (MWh)
Fuel Consumption (TJ)	Pearson Correlation	1	.467	.105	.747**
	Sig. (2-tailed)		.051	.678	
	N	18	18	18	18
Unit Rate Export Capacity (MW)	Pearson Correlation	.467	1	.826**	.561*
	Sig. (2-tailed)	.051		.000	.015
	N	18	18	18	18
Heat Value Fuel Used (KCal/kg)	Pearson Correlation	.105	.826**	1	.358
	Sig. (2-tailed)	.678	.000		.145
	N	18	18	18	18
Annual Production (MWh)	Pearson Correlation	.747**	.561*	.358	1
	Sig. (2-tailed)	.000	.015	.145	
	N	18	18	18	18

Note: ** Denotes Correlation is significant at the 0.01 level * Denotes Correlation is Significant at the 0.05 level

6.2.4 Summary of National Level Analysis

The preceding national level analysis endeavoured to evaluate the SEM generating system by conducting an AIGES for the ROI and NI. A non-parametric approach to frontier analysis, was employed to obtain the efficiency scores for various performance parameters of generating units. The results of the efficiency performance analysis of thirty-two thermal, wind and hydro power plants have been presented. The results of this analysis suggest directions to improve individual electricity generating power plants/regions on the Irish Electricity System. The study finds specific inefficiencies in power plants and the nature of corrective measure required to alleviate them. The key findings include: TTE of the thermal power plants was only 49%, the TTE of the wind regions was 46% and TTE of the hydro power plants was 55%. CCGT generators are the most efficient, gas the most efficient fuel source and the east the most efficient region. Capital (export capacity) is the most prominent input factor implying excess export capacity is a problem on the SEM. The technique employed has provided some interesting results, it has been established that a significant proportion exhibited overall inefficiencies indicating the strong possibility of achieving substantial savings by adopting best practices. The above discussion of the results obtained and evidence from the literature review clearly indicate that all extant studies on power generation plants reveal the presence of inefficiencies.

The approach employed in this study can be utilised in countries with similar small isolated energy markets and power plant structures to assess operational efficiency and determine scope for improvements. Hence, it is for policy makers and government to further scrutinise

the actual scope for feasibility of resizing the scale of operations by taking into account the actual conditions of the market. However, from the perspective of a regulator, such utilities do not exercise control over their sizes of operations. It may therefore, be argued, that the results with BCC VRS formulation should be the ones that should be driving any regulatory incentive scheme as utility managers exercise some control over the production process and input and output decisions made.

6.3 County Level - Application Results and Discussion

The objective of the County level analysis is to establish the technical efficiency performance of EDCs and employ DEA as a benchmarking technique. The adoption of DEA as a form of benchmarking for electricity distribution regulation has become more prominent in recent years. The research presented utilises a dataset of twenty-six EDCs associated with the ESB networks distribution company in the ROI. Please see Figure 6.3 for a graphical representation of the EDCs. Each EDC region, or municipality is considered as a DMU under DEA investigation. The empirical study analyses the technical efficiency of ESB networks interconnected distribution system, each EDC is responsible for medium and low voltage electricity distribution in a particular geographic region in the ROI. Six models are established to encapsulate the underlying characteristics of electricity distribution associated with the SEM for the year 2008. Table 6.16 shows the variables and summary statistics of the data employed in the county level analysis. See Section 5.7 in Chapter 5 for more detail. The input and output variables adopted in this study are expressed in monetary and physical units. To estimate the efficiency scores of EDCs, input oriented focused models are employed taking into account the service obligation of the distribution DMUs to all customers in their predefined area (Erturk and Turut-Asik, 2011).

Table. 6.16: Summary of Descriptive Statistics for County Level Data

County Data Parameter	**Input 1** Labour Employed	**Input 2** Distribution Length (km)	**Input 3** Transformer Capacity (MVA)	**Output 1** Energy Consumption (MWh)	**Output 2** Number of Customers	**Output 3** Service Area (km^2)	**Output 4** Industrial Output ('000)	**Output 5** Customer Density
Average	167.153	6186.846	1077.231	306753.9	84099.12	2703.462	3670943.4	12.692
Maximum	536	19858	6130	2121970	565110	7499.95	31274436	62
Minimum	58	2145	143	65217	17925	826.13	161190	7
S.D.	102.380	3793.214	1280.829	398582.3	106846.7	1727.091	6659936.3	10.264
N	26	26	26	26	26	26	26	26

Note: S.D. - Standard Deviation

Six models employing different combinations of input-outputs sets outlined in Section 5.7 are constructed and the CCRϕ CRS, BCCϕ VRS and SE measures are calculated for each model. If the efficiency value equals 1, the DMU is efficient; if it is less than 1, the evaluated EDC is inefficient (Cooper et al., 2007). The dual linear programming formulations of the CCR and BCC DEA models were run 26 times, i.e one for each DMU or EDC. The efficiency distribution

performance of the selected twenty-six EDCs for the comprehensive model one are presented in Table 6.17.

Table. 6.17: Comprehensive Electricity Distribution County Efficiency Scores

No.	Electricity Distribution County	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ/BCC ϕ	(RTS)	Reference DMU Peers
1	Donegal	0.909	0.987	Inefficient	0.920	Decreasing	4, 16, 19
2	Cavan	0.629	0.671	Inefficient	0.937	Decreasing	4, 16, 24
3	Monaghan	0.714	0.958	Inefficient	0.745	Increasing	4, 16, 24
4	Leitrim	1	1	Efficient	1	Constant	4
5	Sligo	0.950	0.958	Inefficient	0.991	Decreasing	4, 16, 19
6	Roscommon	0.858	0.901	Inefficient	0.952	Decreasing	4, 16
7	Mayo	0.983	1	Inefficient	0.983	Decreasing	19, 24
8	Galway	0.819	1	Inefficient	0.819	Decreasing	4, 16
9	Clare	0.928	0.99	Inefficient	0.937	Decreasing	4, 16
10	Limerick	0.724	0.758	Inefficient	0.955	Decreasing	4, 16
11	Tipperary	0.739	0.836	Inefficient	0.883	Decreasing	4, 16, 19
12	Kerry	0.832	0.902	Inefficient	0.922	Decreasing	4, 16
13	Cork	0.699	1	Inefficient	0.699	Decreasing	4, 16, 19
14	Waterford	0.885	0.898	Inefficient	0.985	Decreasing	4, 16, 19
15	Carlow	0.731	1	Inefficient	0.731	Increasing	4, 16, 19
16	Dublin	1	1	Efficient	1	Constant	16
17	Kildare	0.652	0.652	Inefficient	1	Decreasing	4, 16, 23
18	Kilkenny	0.798	0.865	Inefficient	0.922	Decreasing	19, 24
19	Laois	1	1	Efficient	1	Constant	19
20	Longford	0.740	0.957	Inefficient	0.773	Increasing	16, 19, 24
21	Louth	0.602	0.799	Inefficient	0.753	Increasing	4, 16
22	Meath	0.784	0.809	Inefficient	0.969	Decreasing	4, 16
23	Offaly	1	1	Efficient	1	Constant	23
24	Westmeath	1	1	Efficient	1	Constant	24
25	Wexford	0.703	0.775	Inefficient	0.907	Decreasing	16, 19, 24
26	Wicklow	0.910	0.994	Inefficient	0.915	Decreasing	16, 19
	Average	**0.830**	**0.912**		**0.911**		

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

The efficiency results, show that five DMUs are PK efficient. DMU 4 Leitrim, DMU 16 Dublin, DMU 19 Laois, DMU 23 Offaly and DMU 24 Westmeath attain an efficiency score of unity, one for the CCRϕ, BCCϕ and SE measures, displaying CRS and are their own respective peer benchmarks. This implies they are operating at the optimal production frontier. The efficient EDCs are located predominantly in the east of the country with one exception DMU 4 Leitrim. Focusing initially on the TTE CCRϕ efficiency scores, the results show twenty-one EDCs are inefficient and five are efficient. The average TTE score was 83%, thirteen EDCs score above and below this average value. This implies that the resource utilization of EDCs is suboptimal with room for improvement. DMU 21 Louth is the worst performing EDC attaining a score of 60%. This demonstrates the range of TTE scores lies between 60–100% indicating an acceptable level

of EDC efficiency performance. All five previously stated efficient DMUs are the benchmark best performers amongst the EDC group. The reference peer count for DMU 16 Dublin is the greatest with twenty DMUs deeming it the performance benchmark. DMU 4 Leitrim appears slightly less frequently with seventeen DMUs citing it as a peer benchmark. Both DMU 16 and DMU 4 appear jointly as peers for seven DMUs. The CCR model may underestimate EDCs PTE by benchmarking it against dissimilar and presumably, more scale efficient comparators.

The BCC VRS model was adopted to establish the PTE and SE of the EDCs studied. The results obtained demonstrate the sources of inefficiency amongst the inefficient EDCs and provide possible improvement directions to promote TTE which will be discussed in the subsequent Section 6.3.1. Interpreting the PTE scores, the average efficiency rises to 91% explained by the increase in the number of efficient EDCs to 9. Employing the BCC model enables DMUs to be benchmarked against other DMUs comparable in size resulting in higher efficiency scores. This average efficiency measure indicates consumption of all inputs could be reduced by 9% whilst keep output quantities constant.

The average SE score is quite high 91%, with six EDCs attaining a SE score of unity one. This illustrates SE is not a serious problem across the electricity distribution system. This suggests that resource utilisation is the primary cause of inefficiency and not the scale size of EDCs size of EDCs. EDCs that present a SE score less than one are scale inefficient. A scale inefficient EDC that exceeds the MPSS will present DRS. Alternatively, a scale inefficient EDC that is smaller than the MPSS will present IRS. DMU 7 Mayo, DMU 8 Galway, DMU 13 Cork, and DMU 15 Carlow exhibit 100% BCC efficiency scores but a lower CCR score, hence are operating at optimum PTE but not TTE due to the scale size of their operation. DMUs 7, 8 and 13 are scale inefficient and should decrease the operation scales to improve overall efficiency as they present DRS. DMU 15 Carlow on the other hand should increase operational scales due to IRS characteristics. DMU 1 Donegal, DMU 3 Monaghan, DMU 9 Clare, DMU 20 Longford, DMU 21 Louth, and DMU 26 Wicklow all have PTE scores greater than their corresponding scale efficiency scores. Consequently EDCs Monaghan, Longford and Louth should increase their operation scales as they exhibit IRS to enhance TTE. EDCs Clare and Wicklow display DRS indicating these EDCs have considerable scope for improvements in their TTE by resizing (decreasing) there scales of operation to the optimal MPSS.

The remaining ten EDCs, DMU 2 Cavan, DMU 5 Sligo, DMU 6 Roscommon, DMU 10 Limerick, DMU 11 Tipperary, DMU 12 Kerry, DMU 14 Waterford, DMU 18 Kilkenny, DMU 22 Meath, and DMU 25 Wexford all display a combined inefficiency in their TTE and PTE scores, to varying degrees, with a relatively high SE score. The corrective procedure for these EDCs to improve their technical efficiency is to alter their resource allocation and utilisation in addition to decreasing the operation scales. This would increase their TTE and project the previously inefficient DMUs on to the optimal production frontier. The predominant trait is the

majority of EDCs exhibit DRS characteristics.

Observing individual EDC efficiency results suggests EDCs operating in the relatively more developed eastern part of Ireland, noticeably have higher average relative efficiency scores, with efficiency performance of EDCs deteriorating towards rural, more sparsely populated EDCs of Ireland. This is due to the increased population in Dublin's surrounding EDCs with 40% of Ireland's population residing in the Eastern region of Ireland (CSO, 2011*a*), resulting in a more densely populated distribution network. It is important to note all five EDCs found to be PK efficient are all relatively small sized EDCs in comparison to the others. As a result the possible efficiency gains from reorganizing the electricity distribution system and EDCs is investigated in Section 6.3.2. The average efficiency scores obtained across CCRϕ, BCCϕ and SE measures achieve high levels of efficiency when observing Figure 6.8.

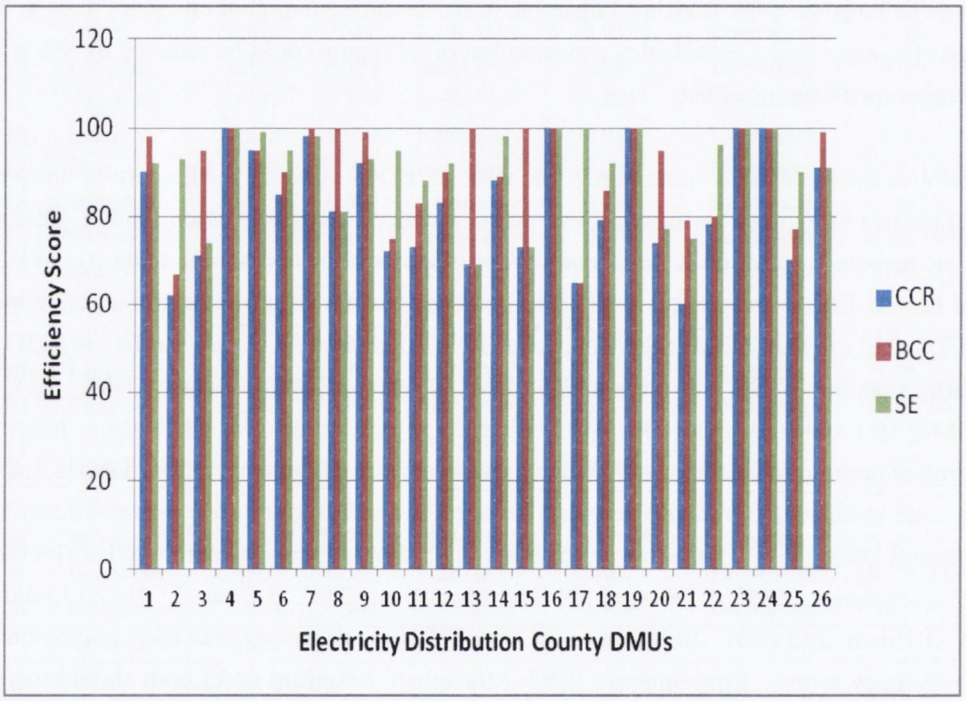


Fig. 6.8: Electricity Distribution County Efficiency Results

6.3.1 Projection Analysis and Benchmarking

A primary objective of the county level distribution efficiency research is the optimisation of EDCs. As DEA models incorporate a mathematical foundation, they are suitable for optimisation purposes (Azadeh et al., 2009). The input-oriented BCC DEA model is preferred for optimization. The original and target values of the EDC inputs-outputs are given in Table 6.18.

Table. 6.18: Original and Targeted Values for County Level Parameters

No.	EDC	X_1			X_2			X_3			Y_1			Y_2			Y_3		
		Original Value	Projected Value	%	Original Value	Projected Value	%	Original Value	Projected Value	%	Original Value	Projected Value	%	Original Value	Projected Value	%	Original Value	Projected Value	%
1	Donegal	235	231.698	-1.40	8691	8586.476	-1.20	1013	798.532	-21.17	288621	336794.439	16.69	94298	94298	0	4860.91	4860.91	0
2	Cavan	144	96.658	-32.88	5334	3579.315	-32.90	372	249.700	32.88	165540	165540	0	40310	42622.927	5.74	1931.77	1931.77	0
3	Monaghan	107	102.534	-4.17	3969	3796	-4.35	153	146.614	-4.17	74201	141921.415	91.27[A]	29248	38824.94	32.74	1295.08	1807.143	39.54
4	Leitrim	65	65	0	2404	2404	0	166	166	0	65217	65217	0 17925	17925	0	1590.03	1590.03	0	
5	Sligo	88	83.992	-4.55	3246	3109.989	-4.19	236	226.111	-4.19	124017	146562.794	18.18	36268	36268	0	1837.52	1837.52	0
6	Roscommon	124	11.582	-10.01	4582	4128.762	-9.89	625	357.433	-42.81	126184	126184	0	32631	35831.707	9.81	2548.19	2548.19	0
7	Mayo	255	255	0	9454	9454	0	505	505	0	259932	259932	0	74396	74396	0	5586.05	5586.05	0
8	Galway	331	331	0	12246	12246	0	1853	1853	0	447743	447743	0	122970	122970	0	6148.77	6148.77	0
9	Clare	160	158.861	-0.71	5926	5879.220	-0.79	1110	634.867	-42.80	217433	217433	0	56344	61705.501	9.52	3450.04	3450.04	0
10	Limerick	188	142.597	-24.15	6962	5272.741	-24.26	1505	1077.272	-28.42	350086	350086	0	93460	96423.801	3.17[B]	2755.91	2755.91	0
11	Tipperary	264	214.344	-18.81	9772	7944.024	-18.71	757	633.222	-16.35	296076	305416.534	3.15[B]	85819	85819	0	4304.72	4304.72	
12	Kerry	253	228.376	-9.73	9386	8463.050	-9.83	1111	778.015	-29.97	281345	327009.041	16.23	91667	91667	0	4806.89	4806.89	0
13	Cork	536	536	0	19858	19858	0	3462	3462	0	911333	911333	0	256391	256391	0	7499.95	7499.95	0
14	Waterford	102	91.434	-10.36	3763	3382	-10.11	662	595.085	-10.11	206805	214760.3	3.85	58178	58178	0	1856.59	1856.59	0
15	Carlow	58	58	0	2145	2145	0	343	343	0	94469	94469	0	24552	24552	0	896.55	896.55	0
16	Dublin	245	245	0	9059	9059	0	6130	6130	0	2121970	2121970	0	565110	565110	0	922.27	922.27	0
17	Kildare	148	96.540	-34.77[A]	5465	3565.937	-34.75[A]	1884	1051.565	-44.18	321900	338418.385	5.13	91680	91680	0	1695.4	1695.4	0
18	Kilkenny	145	125.196	13.66	5355	4636.186	-13.42	223	193.066	-13.42	165978	165978	0	41652	47711.641	14.55	2071.89	2072.89	0
19	Laois	77	77	0	2851	2851	0	153	153	0	126742	126742	0	30345	30345	0	1719.9	1719.9	0
20	Longford	73	69.861	-4.30	2703	2585.257	-4.36	186	178.002	-4.30	68474	96784.235	41.34	24371	24371	0	1091.16	1579.657	44.77[A]
21	Louth	89	71.141	-20.07	3299	2630.892	-20.25	2154	749.705	-65.19[A]	204898	236960.185	15.65	62542	62542	0	826.13	898.348	8.74[B]
22	Meath	147	119.016	-19.04	5451	4396.484	-19.35	1702	970.044	-43.01	293401	293401	0	58906	81115.841	37.70[A]	2342.07	2342.07	0
23	Offaly	88	88	0	3245	3245	0	572	572	0	133359	133359	0	38446	38446	0	2001.17	2001.17	0
24	Westmeath	117	117	0	4332	4332	0	143	143	0	150522	150522	0	43629	43629	0	1856.59	1856.59	0
25	Wexford	182	140.706	-22.69	6723	5211.061	-22.49	599	464.290	-22.49	252985	252985	0	66357	66357	0	2366.85	2366.85	0
26	Wicklow	125	124.306	-0.56[B]	4637	4602.811	-0.74[B]	389	386.840	-0.56[B]	226371	226371	0	49082	62805.654	27.96	2026.62	2026.62	0

Note: [A] - Those with the greatest difference [B] - Those with the smallest difference X_1 - Labour X_2 - Distribution Length X_3 - Transformer Capacity Y_1 - Energy Consumed Y_2 - Number of Customers Y_3 - Service Area

These target efficiency projections denote improvement directions for inefficient EDCs to become efficient. Observing Table 6.18 and using a single example case, for DMU 1 Donegal to be projected on to the production frontier requires a reduction of 1.40% X_1 labour, 1.20% X_2 distribution length and 21.17% X_3 transformer capacity coupled with an increase of 16.69% Y_1 energy consumption and the Y_2 number of customers and Y_3 service area remaining unaltered.

The technical characteristics of the most inefficient 9 DMUs are predominantly rural, medium to large sized EDCs exhibiting DRS attributes. The five PK efficient EDCs are all small sized service areas alluding to the fact these small EDCs are more efficient at integrating their resources. DMUs with the greatest and smallest gap between their original and targeted values are marked ^{A} and ^{B} respectively. For example, DMU 17 Kildare has the greatest gap between the original and projected values for both X_1 labour and X_2 distribution length whilst DMU 26 Wicklow shows the smallest change for all inputs X_1 labour, X_2 distribution length and X_3 transformer capacity. Results from Table 6.18 illustrate X_1, X_2 and X_3 are the most effective improvement method for inefficient DMUs. In order to identify and establish targets for inefficient EDCs a slack analysis is employed to establish if additional specific output amounts or a decrease in specific input amounts leads to improvements in efficiency scores obtained. The presence of slacks reveals the scope for further non radial reduction in inputs or expansion in outputs once an inefficient DMU is projected onto the production frontier. For selected EDCs if the efficiency score is one and slacks $S^+ = S^- = 0$, PK efficiency prevails. This is the case for DMU 4, 16, 19, 23 and 24, however if $S^+ \neq 0$ $S^- \neq 0$ then slacks are present and DMU is weakly efficient. The summary statistics of the slack parameter analysis for the BCC case are presented in Table 6.19.

Table. 6.19: County Level Summary Statistics of Slack Variables

Parameter	**Number of DMU's with Slacks**	**Mean (Amount of Slack per DMU)**	**% of Slack of Total Input**
Labour	8	1.053	0.19
Distribution Length	10	293.076	0.18
Transformer Capacity	8	340.271	9.71
Energy Consumed	9	30921.147	3.48
Number of Customers	9	7730.924	3.182
Service Area	3	357.592	1.526

Upon investigation of the mean (amount of slack per DMU) values it is evident that the distribution length km per EDC presenting with a slack could be reduced by an average 293.076 km without altering current levels of output. The percentage of slack of total the labour and distribution length are insignificant with minimal percentage values of 0.19% and 0.18% respectively. The greatest significant input variable is transformer capacity with a value of 9.71% of slack of total.

6.3.2 Further Analysis and Discussion

The assumption of VRS technologies when considering the underlying characteristics of EDCs is pertinent. As such the BCC VRS numerical efficiency scores attained for the six models are presented in Table 6.20. The primary or base case comprehensive model explained in detail in Section 6.3 is compared to all models. Each model incorporates a combination of variables that have been carefully scrutinised, extensively researched and acknowledged in the literature review (See Section 3.8). The PTE of all twenty-six EDCs across all six adopted models are presented along with some basic statistics including the average, minimum, maximum, standard deviation and the number of efficient EDCs in each model. The efficiency of each EDC is evaluated out of a 100%. The Spearman's rank correlation coefficient is employed to estimate and assess the impact of omitting or including certain variables on the efficiency results obtained in the comprehensive model. A Spearman correlation coefficient of 100% illustrates the omitted or included variable(s) have no significant effect on the efficiency results obtained the base case comprehensive model.

The adoption of model two reflects the basic structural model for efficiency analysis of electricity distribution extensively used in the literature. The low Spearman correlation coefficient of 0.55% in relation to model one suggests omitting service area has a significant effect on the efficiency results. This is represented by the average PTE score declining from 91% to 79% along with the EDC efficiency count falling from 9 to 5. This trend is continued with a low Spearman correlation coefficient 0.56% when comparing model four with model one. This implies that establishing a categorical variable for two EDC groups reflecting RDCs and UDCs has a significant effect on efficiency scores obtained. This ensures EDCs of similar demand and distribution characteristics are compared with each other. Interpreting the VRS PTE scores, it is apparent model four attains the highest average PTE score 95% with seventeen EDCs deemed to be efficient. However, dropping the variable transformer capacity and including distribution losses in model three has considerably less effect on the efficiency results, represented by the Spearman correlation coefficient of 0.76. The number of efficient EDCs and the average PTE falls from 9 to 7 and 91% to 85% respectively. A primary objective of the county level efficiency study was to incorporate an explanatory parameter to account for differences in electricity characteristics across EDCs, not incorporating the traditionally adopted exogenous variables extensively used in the literature.

Models five and six examine this objective, the inclusion of a non-discretionary diagnostic variable in model five increases efficiency for all EDCs with UDCs greatly influenced (DMU 13 Cork, DMU 10 Limerick, DMU 14 Waterford and DMU 8 Galway). Comparing model five with model one in terms of PTE score, an increase from 91% to 94%, with the number of efficient EDCs rising from 9 to 13 is observed. This is intuitively what one would expect with UDCs producing greater industrial output than RDCs. Non-discretionary models employing the traditional exogenous variables inverse density, customer density and customer dispersion

were pursued. The model incorporating the customer density variable was deemed to be most significant and adopted in model six. Comparing model six with model one in terms of PTE score, an increase from 91% to 92%, with the number of efficient EDCs remaining unchanged is observed.

Table. 6.20: Comparison of EDC VRS Efficiency Scores

No.	DMU	Model One (PTE)	Model Two (PTE)	Model Three (PTE)	Model Four (PTE)	Model Five (PTE)	Model Six (PTE)
1	Donegal	0.987	0.715	0.987	1	0.987	0.987
2	Cavan	0.671	0.648	0.614	0.710	0.712	0.671
3	Monaghan	0.958	0.958	0.607	0.958	1	0.958
4	Leitrim	1	1	1	1	1	1
5	Sligo	0.958	0.910	0.922	1	0.958	0.958
6	Roscommon	0.901	0.540	0.901	0.901	0.904	0.901
7	Mayo	1	0.982	1	1	1	1
8	Galway	1	0.568	1	1*	1	1
9	Clare	0.99	0.490	0.992	1	0.992	0.992
10	Limerick	0.758	0.550	0.758	0.758*	1	0.758
11	Tipperary	0.836	0.828	0.775	1	0.887	0.836
12	Kerry	0.902	0.625	0.902	0.914	0.902	0.902
13	Cork	1	0.746	1	1*	1	1
14	Waterford	0.898	0.799	0.882	0.898*	0.960	0.994
15	Carlow	1	1	1	1	1	1
16	Dublin	1	1	1	1*	1	1
17	Kildare	0.652	0.556	0.652	1	0.719	0.666
18	Kilkenny	0.865	0.851	0.651	0.867	0.865	0.865
19	Laois	1	1	0.990	1	1	1
20	Longford	0.957	0.957	0.829	0.957	1	0.957
21	Louth	0.799	0.799	0.799	1	1	0.981
22	Meath	.809	0.525	0.809	1	0.809	0.809
23	Offaly	1	0.759	1	1	1	1
24	Westmeath	1	1	0.722	1	1	1
25	Wexford	0.775	0.758	0.637	0.985	0.775	0.775
26	Wicklow	0.994	0.966	0.788	1	0.994	0.994
	Average	0.912	0.790	0.854	0.959	0.941	0.923
	SCC	–	0.556	0.760	0.560	0.720	0.945
	Min	0.652	0.490	0.607	0.710	0.712	0.666
	Max	1	1	1	1	1	1
	S.D.	0.106	0.175	0.139	0.068	0.09	0.104
	Efficient	9	5	7	17	13	9

Note: * Denotes Urban Distribution Counties (UDC)s, TTE - Total Technical Efficiency, PTE - Pure Technical Efficiency, SE - Scale Efficiency, RTS - Returns to Scale, S.D. - Standard Deviation.

A direct comparison can therefore be made with the constructed diagnostic model employing non-discretionary industrial output in model five and the traditional exogenous variable customer density in model six. Comparing the Spearman correlation coefficient results obtained, it is evident the inclusion of the diagnostic parameter industrial output is statistically more significant at 0.72 when compared the inclusion traditional exogenous parameter customer density 0.94. All EDCs obtain a higher efficiency score in the diagnostic model five when compared with the traditional exogenous model six. The number of efficient EDCs is greater in model five as opposed to model six indicating higher explanatory power in the adopted parameter. As expected the average PTE score is higher in model five at 94% compared to model six 92%. The average efficiency score oscillates over the six adopted models as does the number of efficient EDCs but as expected the number of efficient EDCs is highly correlated with the average PTE of each adopted model. The Pearson correlation matrix is constructed for the six efficiency models in terms of the VRS PTE efficiency score and presented in Table 6.21. Analysing the coefficients it is apparent model one has moderate to high correlation with the first five models and significantly high correlation with model six. The models retaining similar variable structures.

Table. 6.21: Pearson Correlation Matrix for the Six Adopted Models

		Model One	**Model Two**	**Model Three**	**Model Four**	**Model Five**	**Model Six**
Model One	Pearson	1	.600**	.790**	.507**	.732**	.966**
	Sig.		.001	.000	.008	.000	.000
	N	26	26	26	26	26	26
Model Two	Pearson	.600**	1	.236	.341	.355	.603**
	Sig.	.001		.245	.088	.075	.001
	N	26	26	26	26	26	26
Model Three	Pearson	.790**	.236	1	.329	.627**	.790**
	Sig.	.000	.245		.101	.001	.000
	N	26	26	26	26	26	26
Model Four	Pearson	.507**	.341	.329	1	.209	.495*
	Sig.	.008	.088	.101		.305	.010
	N	26	26	26	26	26	26
Model Five	Pearson	.732**	.355	.627**	.209	1	.710**
	Sig.	.000	.075	.001	.305		.000
	N	26	26	26	26	26	26
Model Six	Pearson	.996**	.603**	.790**	.495*	.710**	1
	Sig.	.000	.001	.000	.010	.000	
	N	26	26	26	26	26	26

Note: ** Denotes Correlation is significant at the 0.01 level * Denotes Correlation is Significant at the 0.05 level

Model six shows a moderate to high degree of correlation with the other models. All other correlations amongst models display low correlations with a few exceptions. There is no negative correlation between the models. Overall the correlation among the variables is high concluding that the obtained DEA efficiency measures can be assumed to be robust.

Table. 6.22: Electricity Distribution County Efficiency Scores

No.	DMU	Model One (TTE)	(PTE)	(SE)	Model Two (TTE)	(PTE)	(SE)	Model Three (TTE)	(PTE)	(SE)	Model Four (TTE)	(PTE)	(SE)	Model Five (TTE)	(PTE)	(SE)	Model Six (TTE)	(PTE)	(SE)
1	Donegal	0.909	0.987	0.920	0.643	0.715	0.899	0.908	0.987	0.919	0.947	1	0.947	0.909	0.987	0.920	0.909	0.987	0.920
2	Cavan	0.629	0.671	0.937	0.629	0.648	0.970	0.608	0.614	0.990	0.688	0.710	0.969	0.706	0.712	0.991	0.629	0.671	0.937
3	Monaghan	0.714	0.958	0.745	0.701	0.958	0.731	0.545	0.607	0.897	0.721	0.958	0.752	0.842	1	0.842	0.714	0.958	0.745
4	Leitrim	1	1	1	0.582	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	Sligo	0.950	0.958	0.991	0.840	0.910	0.923	0.922	0.922	1	1	1	1	0.950	0.958	0.991	0.950	0.958	0.991
6	Roscommon	0.858	0.901	0.952	0.40	0.540	0.740	0.858	0.901	0.952	0.861	0.901	0.955	0.881	0.904	0.974	0.858	0.901	0.952
7	Mayo	0.983	1	0.983	0.671	0.982	0.683	0.912	1	0.912	0.983	1	0.983	1	1	1	0.983	1	0.983
8	Galway	0.819	1	0.819	0.511	0.568	0.899	0.819	1	0.819	0.819	1	0.819	0.825	1	0.825	0.819	1	0.819
9	Clare	0.928	0.992	0.935	0.433	0.490	0.883	0.928	0.992	0.935	0.938	1	0.938	0.936	0.992	0.943	0.928	0.992	0.935
10	Limerick	0.724	0.758	0.955	0.544	0.550	0.989	0.724	0.758	0.955	0.724	0.758	0.955	1	1	1	0.724	0.758	0.955
11	Tipperary	0.739	0.836	0.883	0.641	0.828	0.774	0.719	0.775	0.927	0.782	1	0.782	0.820	0.887	0.924	0.739	0.836	0.883
12	Kerry	0.832	0.902	0.922	0.574	0.625	0.918	0.832	0.902	0.922	0.859	0.914	0.939	0.832	0.902	0.922	0.832	0.902	0.922
13	Cork	0.699	1	0.699	0.599	0.746	0.802	0.691	1	0.691	0.699	1	0.699	1	1	1	0.699	1	0.699
14	Waterford	0.885	0.898	0.985	0.712	0.799	0.891	0.882	0.882	1	0.885	0.898	0.985	0.958	0.960	0.997	0.927	0.994	0.932
15	Carlow	0.731	1	0.731	0.579	1	0.579	0.730	1	0.730	0.888	1	0.888	0.731	1	0.731	1	1	1
16	Dublin	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	Kildare	0.652	0.652	1	0.473	0.556	0.850	0.652	0.652	1	1	1	1	0.715	0.719	0.994	0.666	0.666	1
18	Kilkenny	0.798	0.865	0.922	0.798	0.851	0.937	0.640	0.651	0.983	0.798	0.867	0.920	0.798	0.865	0.922	0.798	0.865	0.922
19	Laois	1	1	1	1	1	1	0.985	0.990	0.994	1	1	1	1	1	1	1	1	
20	Longford	0.740	0.957	0.772	0.694	0.957	0.725	0.672	0.829	0.810	0.816	0.957	0.852	0.773	1	0.773	0.827	0.957	0.864
21	Louth	0.602	0.799	0.753	0.313	0.799	0.391	0.602	0.799	0.753	1	1	1	0.703	1	0.703	0.964	0.981	0.82
22	Meath	0.784	0.809	0.969	0.437	0.525	0.832	0.784	0.809	0.969	1	1	1	0.784	0.809	0.969	0.784	0.809	0.969
23	Offaly	1	1	1	0.545	0.759	0.718	1	1	1	1	1	1	1	1	1	1	1	1
24	Westmeath	1	1	1	1	1	1	0.721	0.722	0.998	1	1	1	1	1	1	1	1	1
25	Wexford	0.703	0.775	0.907	0.70	0.758	0.923	0.617	0.637	0.968	0.863	0.985	0.876	0.703	0.775	0.907	0.703	0.775	0.907
26	Wicklow	0.910	0.994	0.915	0.910	0.966	0.942	0.776	0.788	0.984	1	1	1	0.966	0.994	0.971	0.910	0.994	0.915
	Average	**0.830**	**0.912**	**0.911**	**0.651**	**0.790**	**0.846**	**0.790**	**0.854**	**0.925**	**0.895**	**0.959**	**0.933**	**0.878**	**0.941**	**0.934**	**0.860**	**0.923**	**0.93**

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale Model One - Comprehensive Model; Model Two - Traditional Model; Model Three - Quality Model; Model Four - Urban Model; Model Five - Diagnostic Model; Model Six Environmental Model

The TTE CCR, PTE BCC and SE scores for all six adopted models are presented in Table 6.22. The inclusion of a categorical variable to account for differences across EDCs has a significant effect on the efficiency scores. The descriptive statistics for the comprehensive model accounting for Rural Distribution Counties (RDC)s and Urban Distribution Counties (UDC)s containing a city are presented in Table 6.23. The base case comprehensive model was adopted as the full sample of parameters was sought for investigation. The impact of including a categorical variable in model four greatly influences the RDCs efficiency scores in particular. The categorical variable dichotomises the twenty-six EDC dataset into RDCs and UDCs.

Table. 6.23: Descriptive Statistics of RDC and UDC

	Number of EDCs	Average Efficiency Score	Standard Deviation	Minimum Value	Maximum Value	Number of Efficient
All EDCs						
TTE	26	0.830	0.126	0.602	1	4
PTE	26	0.912	0.106	0.652	1	9
SE	26	0.911		0.699	1	6
RDC						
TTE	21	0.911	0.099	0.688	1	9
PTE	21	0.966	0.068	0.710	1	14
SE	21	0.942		0.752	1	9
UDC						
TTE	5	0.825	0.122	0.724	1	1
PTE	5	0.931	0.106	0.758	1	3
SE	5	0.891		0.699	1	1

Note: SE - TTE/PTE, EDC - Electricity Distribution County, RDC - Rural Distribution County, UDC - Urban Distribution County.

The TTE, PTE and SE scores and number of efficient EDCs for the base case comprehensive model and the RDCs and UDCs cases are displayed in Table 6.23. Observing the results the RDCs TTE, PTE and SE are considerably higher than both the comprehensive model and UDCs with more EDCs deemed efficient across all three efficiency categories. For UDCs, TTE and SE are quite low with only one EDC found to be efficient in each case. When the two groups are formed relating to rural and urban EDCs, interestingly it is the former than out performs the latter in terms of TTE, PTE and SE. The possibility of reorganisation of existing EDCs within the ESB networks distribution framework into Electricity Distribution Zones (EDZ)s has been investigated. The main assumptions for reorganization of the EDCs are outlined as follows:

1. Because the twenty-six EDCs belong to a homogeneous group, it is assumed that input and output values of the combined EDC would be the sum of the input and output values of the corresponding EDZ.

2. Because of geographical limitations only adjacent EDCs can be combined into new EDZs.

3. Where possible the intention is to combine an inefficient EDC presenting IRS with an

adjacent efficient EDC to possibly increase the overall efficiency of the new EDZ.

The restructuring of the twenty-six EDCs into eleven EDZs is graphically represented in Figure 6.9. The proposed restructuring is similar to that employed by the Office of Gas Electricity Markets (OFGEM), the electricity distribution regulator for the UK (England, Scotland and Wales). There are fourteen licensed distribution network operators (DNO)s each responsible for a distribution services area in the UK. The primary objectives of the restructuring and amalgamation of the existing EDC network is i) to reduce the number of EDCs therefore reducing the duplication of electricity distribution services ii) to improve resource utilization and iii) promote TTE and PTE.

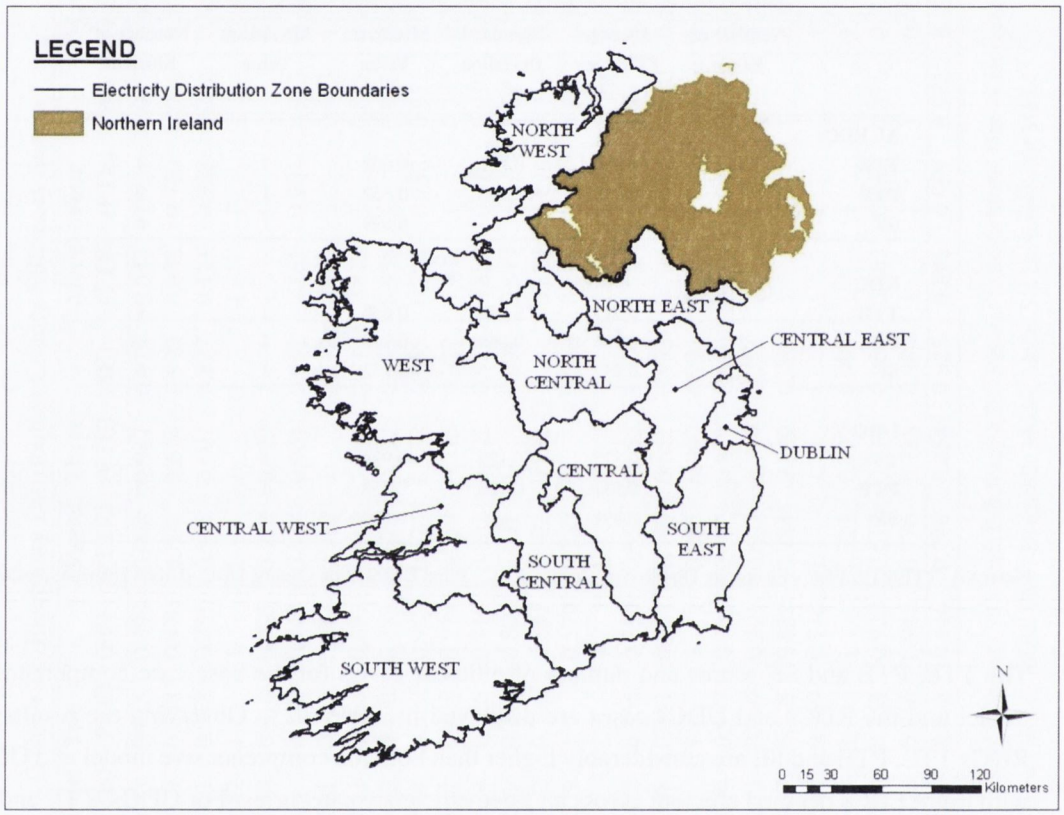


Fig. 6.9: Electricity Distribution Zones (EDZ)

Reorganisation and operational mergers are feasible methods to increase efficiency. Ireland with its relatively small size, sparse population and installed capacity would benefit from the aggregation of twenty-six EDCs to eleven more efficient and manageable EDZs. A restructuring of ESB Networks distribution framework has been hypothesized. To examine the efficiency effect of reorganisation alternatives, the CRS CCR and VRS BCC models are applied, incorporating the input-output combination sets employed in models one, two and three to establish TTE, PTE and SE. The individual EDC results and reorganisation efficiency scores for the base case comprehensive model are displayed in Table 6.24. For example, the EDCs Roscommon, Longford and Westmeath can be amalgamated to form the North Central EDZ.

Table. 6.24: Efficiency Score for Electricity Distribution Zones

Electricity Distribution County	Total Technical Efficiency CCR ϕ	Pure Technical Efficiency BCC ϕ	Scale Efficiency Efficiency CCR ϕ/BCC ϕ
North West Zone			
Donegal	0.909	0.987	0.920
Leitrim	1	1	1
Sligo	0.950	0.958	0.991
	1	**1**	**1**
West Zone			
Mayo	0.983	1	0.983
Galway	0.819	1	0.819
	0.942	**1**	**0.942**
Central West Zone			
Clare	0.928	0.99	0.937
Limerick	0.724	0.758	0.955
	0.893	**0.946**	**0.943**
South West Zone			
Kerry	0.832	0.902	0.922
Cork	0.699	1	0.699
	0.789	**1**	**0.789**
North Central Zone			
Roscommon	0.858	0.901	0.952
Longford	0.740	0.957	0.773
Westmeath	1	1	1
	0.942	**0.993**	**0.948**
Central Zone			
Offaly	1	1	1
Laois	1	1	1
Kilkenny	0.798	0.865	0.922
	1	**1**	**1**
South Central Zone			
Tipperary	0.739	0.836	0.883
Waterford	0.885	0.898	0.985
	0.920	**0.943**	**0.975**
North East Zone			
Cavan	0.629	0.671	0.937
Monaghan	0.714	0.958	0.745
Louth	0.602	0.799	0.753
	0.622	**0.861**	**0.722**
Central East Zone			
Kildare	0.652	0.652	1
Meath	0.784	0.809	0.969
	0.767	**0.971**	**0.789**
South East Zone			
Carlow	0.731	1	0.731
Wexford	0.703	0.775	0.907
Wicklow	0.910	0.994	0.915
	1	**1**	**1**
Dublin East Zone			
Dublin	1	1	1
	1	**1**	**1**

Longford displays IRS and Westmeath is efficient so the necessary criteria are satisfied. The TTE, PTE and SE are found to be 94%, 99% and 94% respectively for North Central. The results

from the efficiency score comparison before and after restructuring are presented in Table 6.25. The prominent aspect of the proposed restructuring of EDCs is the increase in efficiency and resource utilisation for all three comprehensive, basic and quality restructured models across all three efficiency measures. In terms of the number of EDCs deemed efficient the results are varied. For example, observing model two comparison pre and post electricity distribution restructuring, the TTE rises from 65% to 79%, efficient DMUs remaining unchanged, PTE rises form 79% to 92%, efficient DMUs fall form 5 to 3 and finally SE rises from 84% to 86% with the number of efficient DMUs remaining unaltered.

Table. 6.25: Efficiency Score Comparison after Restructuring

	CCR ϕ	Efficient DMUs	BCC ϕ	Efficient DMUs	SE	Efficient DMUs
Comprehensive Model One	0.830	5	0.912	9	0.911	6
Restructured Model One	0.898	4	0.974	6	0.921	4
Basic Model Two	0.651	3	0.790	5	0.846	4
Restructured Model Two	0.799	3	0.925	3	0.863	4
Quality Model Three	0.79	3	0.854	7	0.925	6
Restructured Model Three	0.898	4	0.974	6	0.921	3

6.3.3 Sensitivity Analysis and Model Validation

An important aspect of DEA research is the sensitivity and stability analysis of specific DMUs that are under investigation. Charnes et al. (1985b) conducted the first sensitivity analysis by examining change in a single output case. The sensitivity analysis here will follow the same procedure adopted in Section 5.11. The base case CCR, BCC and SE efficiency scores are presented in Figure 6.10.

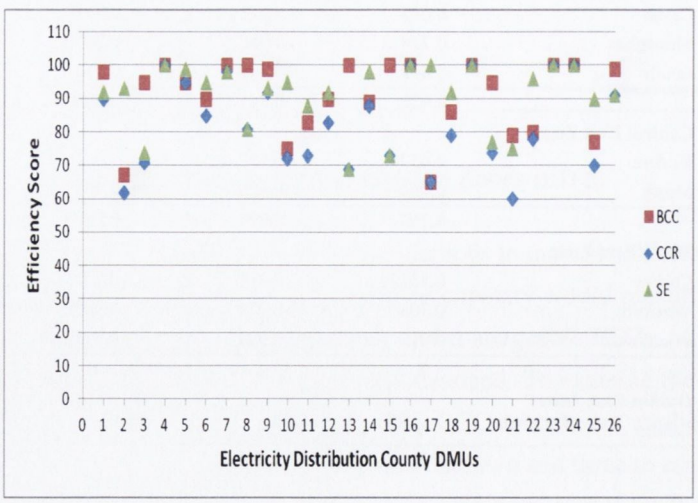


Fig. 6.10: Base Case for Electricity Distribution Counties

Sensitivity analysis is implemented by excluding each input-output parameter ceteris paribus from the base case framework and observing the effect on efficiency scores. Note: that calculated efficiency score can never increase upon removal of variables, if it alters, it will only decrease upon removal of variables. The base case is the comprehensive model that employs three input and three output parameters. Upon inspection, it can be observed that no EDC attains an efficiency score below 60 across all three efficiency measures. This indicates an acceptable level of efficiency performance. Also evident is that DMUs 2, 6, 11, 12, 18, 21 and 25 show considerable variation across all efficiency measures. The base case BCC VRS efficiency scores are retained for sensitivity comparison. The assumption of VRS characteristics in electricity distribution is more pertinent. The forthcoming figures illustrate how the omission of inputs-outputs from the comprehensive model alter the efficiency scores obtained.

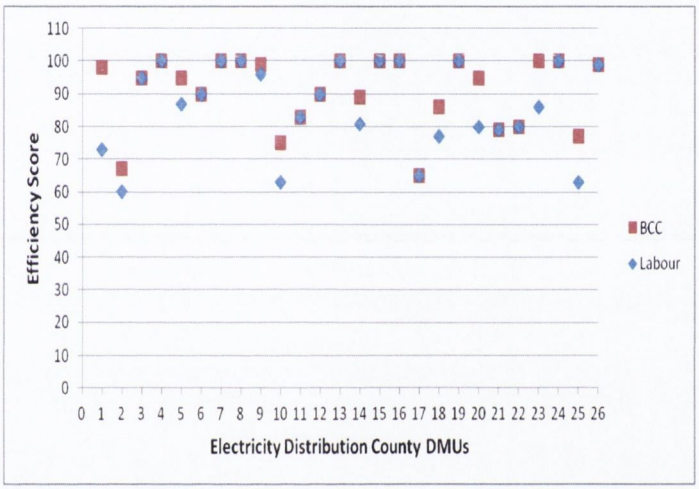


Fig. 6.11: Labour Employed Omitted

Figure 6.11 shows that when labour employed is omitted from the base case model, the efficiency score of ten DMUs are affected. The greatest efficiency difference occurring for DMU 1. Figure 6.12 depicts considerable fluctuation in efficiency scores with fifteen DMUs being affected indicating that distribution length contributes significantly to the higher scores attained in the base case scenario. DMUs 1, 8, and 9 observe significant changes in their efficiency score. It is interesting that the two lowest BCC scoring DMUs are influenced by this modification and their scores are further reduced but not by a great deal.

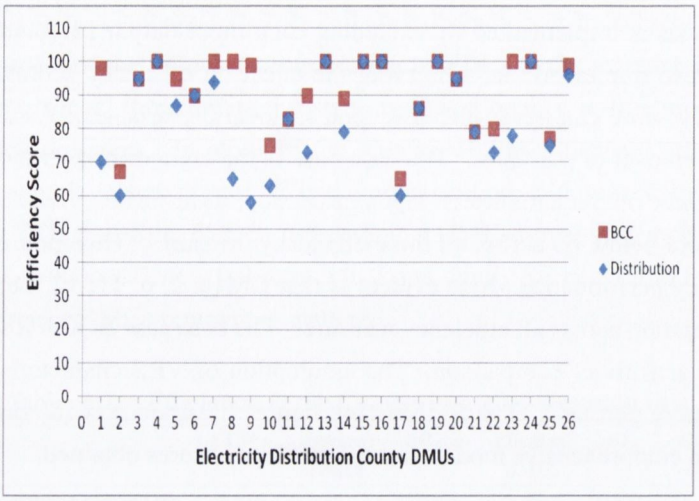


Fig. 6.12: Distribution Length Omitted

Figure 6.13 depicts the change in efficiency score when the parameter transformer capacity is omitted with eleven DMUs being affected. DMU 3 sees the greatest change indicating transformer capacity plays an important role in the efficiency score it attains. DMUs 3, 18 and 25 observe their efficiency scores fall to the 60 mark when transformer capacity is omitted.

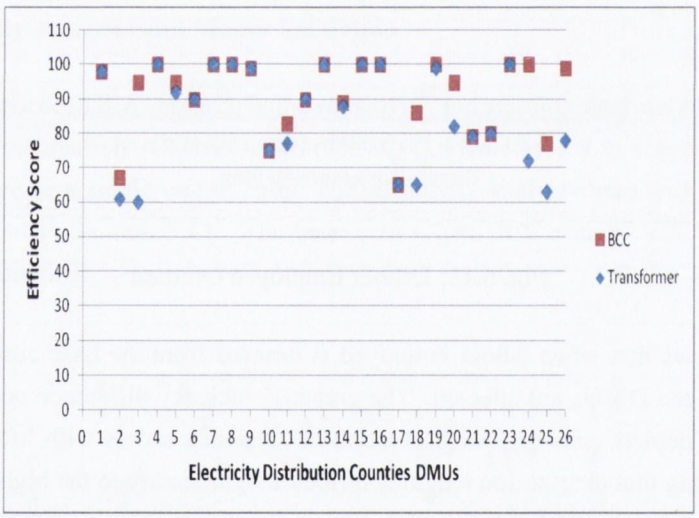


Fig. 6.13: Transformer Capacity Omitted

The efficiency scores in Figures 6.14 and 6.15 when the parameters energy consumption and the number of customers are omitted are not altered significantly. Only a minority few eight DMUs in each case are altered by a small change in efficiency score.

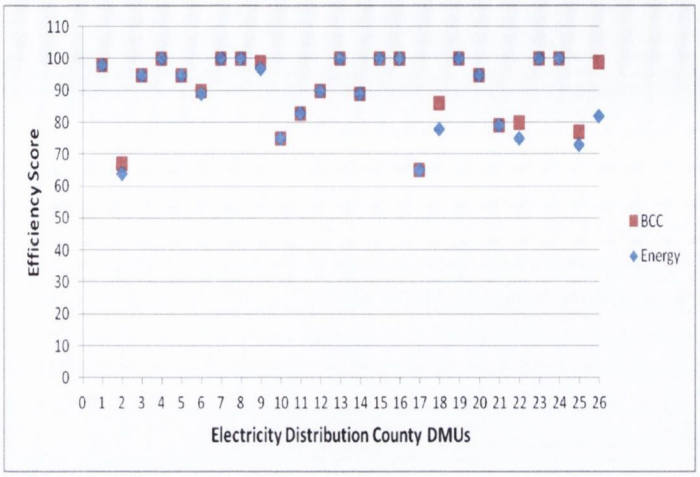


Fig. 6.14: Energy Consumption Omitted

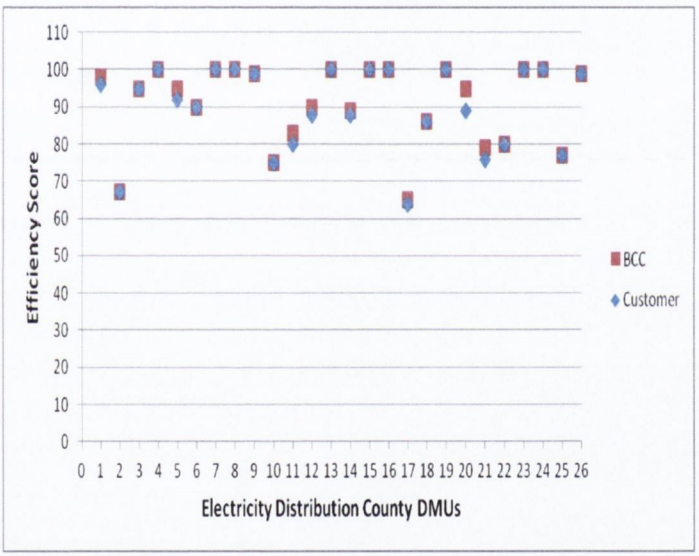


Fig. 6.15: Number of Customers Omitted

Figure 6.16 depicts the extensive vacillating of efficiency scores when the parameter service area is omitted from the base case model. A compelling number of efficiency scores for DMUs are altered, eighteen in total signifying that the modification of omitting service area contributes substantially to the high efficiency scores obtained in the base case. This finding coupled with the results when distribution parameter is omitted is intuitively what would be expected, that distribution length and service area would have an impact on efficiency scores obtained by EDCs.

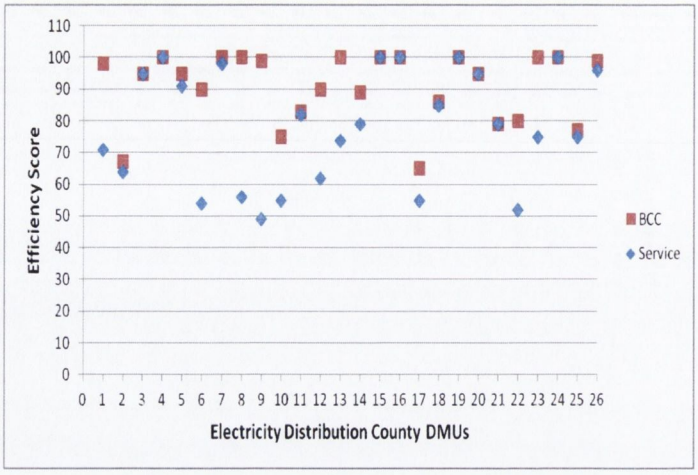


Fig. 6.16: Service Area Omitted

Table 6.26 illustrates the relationship between a DMUs efficiency and the inputs-outputs employed. It is important to note that all efficiency score alterations due to the omission of a parameter display weak influence, that is the efficiency scores are altered by less than 0.5. Nine DMUs are found to be distinctly inefficient whilst another eight DMUs are significantly inefficient. Both parameters energy consumption and number of customers per EDC impact upon the least number of DMUs and hence either could be the first variable to be omitted from the comprehensive model.

The relationship between inputs-outputs should be positively correlated (Luo and Donthu, 2001). The correlation relationship between input/output variables is statistically verified applying Pearson's correlation statistical test. The greater the value of the correlation coefficient, the stronger the relationship between two variables. The Pearson's correlation matrix coefficients for County level data is presented in Table 6.27. It can be concluded strong relationships exist between some variables that attain a coefficient score above 0.9, intuitively in all cases this is acceptable. In all other instances there are acceptable satisfactory levels of correlation present.

The assumption of an "isotonicity" relationship between input and output factors is satisfied Charnes et al. (1985a). That is, a requirement that the relationship between inputs and outputs not be erratic. Increasing the value of any input while keeping other factors constant should not decrease any output but should instead lead to an increase in the value of at least one output. Dyson et al. (2001) state this is achieved when increased inputs reduces efficiency whilst increased output increases efficiency. The preceding sensitivity analysis and model validation approves and acknowledges that the proposed and adopted EDC DEA models are of high construct validity.

Table. 6.26: Sensitivity Analysis of Electricity Distribution Parameters

No.	EDC	(PTE) BCC ϕ	Labour Employed Omitted	Distribution Length Omitted	Transformer Capacity Omitted	Energy Consumption Omitted	Number of Customers Omitted	Service Area Omitted	Status
1	Donegal	0.987	0.731*	0.706*	0.987	0.987	0.966*	0.715*	Significantly Ineff.
2	Cavan	0.671	0.608*	0.608*	0.614*	0.644*	0.671	0.648*	Distinctly Ineff.
3	Monaghan	0.958	0.958	0.958	0.607*	0.958	0.958	0.958	Significantly Ineff.
4	Leitrim	1	1	1	1	1	1	1	Robustly Eff.
5	Sligo	0.958	0.873*	0.873*	0.922*	0.958	0.928*	0.910*	Significantly Ineff.
6	Roscommon	0.901	0.901	0.901	0.901	0.895*	0.901	0.540*	Significantly Ineff.
7	Mayo	1	1	0.941*	1	1	1	0.982*	Robustly Eff.
8	Galway	1	1	0.652*	1	1	1	0.568*	Marginally Eff.
9	Clare	0.992	0.967*	0.584*	0.992	0.979*	0.992	0.490*	Significantly Ineff.
10	Limerick	0.758	0.635*	0.637*	0.758	0.752*	0.758	0.550*	Distinctly Ineff.
11	Tipperary	0.836	0.836	0.836	0.775*	0.836	0.804*	0.828*	Distinctly Ineff.
12	Kerry	0.902	0.902	0.738*	0.902	0.902	0.884*	0.625*	Significantly Ineff.
13	Cork	1	1	1	1	1	1	0.746*	Marginally Eff.
14	Waterford	0.898	0.819*	0.796*	0.882*	0.898	0.884*	0.799*	Distinctly Ineff.
15	Carlow	1	1	1	1	1	1	1	Robustly Eff.
16	Dublin	1	1	1	1	1	1	1	Robustly Eff.
17	Kildare	0.652	0.652	0.601*	0.652	0.652	0.641*	0.556*	Distinctly Ineff.
18	Kilkenny	0.865	0.776*	0.776*	0.651*	0.784*	0.865	0.851*	Distinctly Ineff.
19	Laois	1	1	1	0.990*	1	1	1	Robustly Eff.
20	Longford	0.957	0.805*	0.957	0.829*	0.957	0.897*	0.957	Significantly Ineff.
21	Louth	0.799	0.799	0.799	0.799	0.799	0.766*	0.799	Distinctly Ineff.
22	Meath	0.809	0.809	0.734*	0.809	0.751*	0.809	0.525*	Distinctly Ineff.
23	Offaly	1	0.861*	0.789*	1	1	1	0.759*	Marginally Eff.
24	Westmeath	1	1	1	0.722*	1	1	1	Marginally Eff.
25	Wexford	0.775	0.635*	0.752*	0.637*	0.739*	0.775	0.758*	Distinctly Ineff.
26	Wicklow	0.994	0.994	0.961*	0.788*	0.821*	0.994	0.966*	Significantly Ineff.

Note : EDC - Electricity Distribution County, PTE - Pure Technical Efficiency, ** - Efficiency score altered by at least 0.5, * - Efficiency score altered by lees than 0.5, Ineff. - Inefficient, Eff. - Efficient.

Table. 6.27: Pearson Correlation Matrix for County level Data

		Input 1 Labour Employed	**Input 2** Distribution Length (km)	**Input 3** Transformer Capacity (MVA)	**Output 1** Energy Consumption (MWh)	**Output 2** Number of Customers	**Output 3** Service Area (km^2)	**Output 4** Industrial Output ('000)	**Output 5** Customer Density
Labour Employed	Pearson	1	.957	.548**	.517**	.541**	.874**	.753**	.152
	Sig.			.004	.007	.004	.000	.000	.459
	N	26	26	26	26	26	26	26	26
Distribution Length (km)	Pearson	.957	1	.547**	.516**	.541**	.875**	.753**	.151
	Sig.			.004	.007	.004	.000	.000	.461
	N	26	26	26	26	26	26	26	26
Transformer Capacity (MVA)	Pearson	.548**	.547**	1	.938**	.938**	.171	.751**	.858**
	Sig.	.004	.004		.000	.000	.402	.000	.000
	N	26	26	26	26	26	26	26	26
Energy Consumption (MWh)	Pearson	.517**	.516**	.938**	1	.997**	.132	.713**	.911**
	Sig.	.007	.007	.000		.000	.521	.000	.000
	N	26	26	26	26	26	26	26	26
Number of Customers	Pearson	.541**	.541**	.938**	.997**	1	.161	.726**	.903**
	Sig.	.004	.004	.000	.000		.431	.000	.000
	N	26	26	26	26	26	26	26	26
Service Area (km^2)	Pearson	.874**	.875**	.171	.132	.161	1	.426*	-.288
	Sig.	.000	.000	.402	.521	.431		.030	.262
	N	26	26	26	26	26	26	26	26
Industrial Output ('000)	Pearson	.753**	.753**	.751**	.713**	.726**	.426**	1	.476*
	Sig.	.000	.000	.000	.000	.000	.030		.014
	N	26	26	26	26	26	26	26	26
Customer Density	Pearson	.152	.151	.858**	.911**	.903**	-.228	.476*	1
	Sig.	.459	.461	.000	.000	.000	.262	.014	
	N	26	26	26	26	26	26	26	26

Note: ** Denotes Correlation is significant at the 0.01 level * Denotes Correlation is Significant at the 0.05 level

6.3.4 Summary of County Level Analysis

The county level efficiency study has extended the literature on efficiency analysis to electricity distribution in the ROI. From a DEA research view point adopting the Irish electricity distribution system and EDCs as the main research focus has never been done. The research employs six differing models to capture the underlying characteristics of EDCs. The levels of TTE, PTE and SE are satisfactory with directions for efficiency improvement proposed. Analysis, discussion and presentation of key findings comparing all six models are presented. External factors that are not controllable by EDCs can inhibit efficiency. This was accounted for by adopting a categorical variable to account for urban/rural environments and a diagnostic parameter to account for differing electricity distribution characteristics across EDCs and comparisons were made with employing traditional environmental variables. The diagnostic parameter industrial output has more explanatory power when attempting to account for differing electricity distribution characteristics across EDCs when compared with traditional environmental variables that have been extensively adopted in the DEA literature. The proposed restructuring alternative of employing eleven EDZs as opposed to twenty-six EDCs achieves higher levels of efficiency in

terms of TTE, PTE and SE. The increased efficiency scores are evident in the restructuring of the comprehensive, basic and quality models.

6.4 Individual Level - Application Results and Discussion

Wind power development is the fastest growing energy technology, it is the primary energy mechanism employed by the EU to meet stated targets set in the 2009 EU Renewable Energy Directive (2009/28/EC) to increase the share of renewable energy in the EU to 20% by 2020 (EWEA, 2009). The current individual level research study evaluates the productive efficiency of eighty-one operational wind farms in the ROI connected to the electricity transmission and distribution network of the SEM for the year 2008. The adoption of annual data greatly reduces the influence of seasonal effects. The reader is referred to Figure 5.2 for a graphical representation of the wind farms and their locations throughout the ROI. Each cluster of wind turbines or wind farm is considered one wind electricity generation unit or DMU. Elements of the technique employed by Iglesias et al. (2010) are advocated to encapsulate the underlying characteristics of the wind energy generation units. Table 6.28 presents the characteristics of the variables employed in the wind farm analysis. Considerable variation in values is evident.

Table. 6.28: Summary of Descriptive Statistics for Individual Level Data

Wind Data	**Input 1** Wind	**Input 2** Unit Rate Export Capacity	**Input 3** Full Time Man hours	**Output 1** Annual Production
Average	139135.4	12.244	585.772	33284.28
Maximum	898601.2	72.4	4200	193032.8
Minimum	8665.07	0.66	34	1000
S.D.	163705.6	13.864	617.571	37299.31
N	81	81	81	81

Note: S.D. - Standard Deviation

To appraise the efficiency of wind generating units, specifically output-oriented models are employed to reflect wind farm behaviour during the period under analysis as the objective of operators was to produce maximum energy without any kind of restrictions. Productive behaviour is not motivated by exogenous factors (Iglesias et al., 2010). The CCR CRS, BCC VRS SE measures are displayed in Table 6.29. Observing the results, DMU 29 Kingsmountain and DMU 47 Tournafulla are Pareto Koopmans efficient attaining efficiency scores of unity for the CCR BCC and SE with zero slacks, exhibit CRS attributes and are their own peer benchmark. This denotes both DMUs are operating at the optimal production frontier and are the reference peers. DMU 29 and DMU 47 wind farms are located in counties Sligo and Limerick respectively which are on the west coast of the ROI. The average TTE score for all eighty-one wind farms was 48%, with forty seven obtaining scores below this value. Sixty four wind farms obtain a TTE

score between the range 30-70% indicating poor overall efficiency. The top five performing DMUs range in efficiency score form 85% to 100% whilst the bottom five performing wind farms range in TTE score from 16% to 24%. DMU 29 and DMU 47 are the benchmark best performers amongst the eighty-one wind generating units. DMU 47 is cited as a reference peer 80 times whilst DMU 29 is cited 58 times. Both DMUs appear as reference benchmark peers together for fifty seven wind farm DMUs.

Focusing on the BCC VRS, it incorporates the PTE and SE scores of the wind farm generating units. The results indicate the sources of inefficiencies amongst the wind farms and directions for improvement. As with the previous investigations an efficiency score of one indicates the DMU in question is efficient, if less than this value inefficiency prevails. The average PTE is 61% with the number of efficient wind farm DMUs rising from 2 to 8. This average figure insinuates consumption of all inputs could be reduced by 39% whilst maintaining current output levels. The average SE is acceptable at 81% with room for improvement.

Of the eighty-one wind farms, the 2 PK efficient wind farms exhibit CRS, 48 wind farms display IRS, whilst the remaining 31 demonstrate DRS attributes. The interpretation of this is, 48 inefficient wind farms in terms of size are smaller than the most productive unit whilst 31 wind farms are larger than the most productive unit. Wind farm DMUs 9, 22, 28 and 40 all display BCC score close to or equal to 100% with a poor CCR score alluding to the fact they are operating at optimum PTE but not TTE due to their scale size of operation and should increase their operational scales due to IRS characteristics.

In Table 6.29, there are 43 wind farm DMUs that are exposed to combined inefficiencies in their TTE and PTE to varying degrees, with a relatively high SE score. The corrective procedure for these wind farms in this instance is to alter their resource allocation and utilization in addition to increasing the operation scale to improve TTE and PTE scores. Wind farm DMUs 11, 12, 20, 43, 54, 56, 58, 59, 60, 69, 77, 78 and 80 all express higher BCC efficiency scores compared to their SE, hence are primarily scale inefficient. As such decreasing their scales of operation to the optimal MPSS is the corrective technique to improve TTE, PTE and SE scores. The remaining DMUs 5, 6, 13, 15, 17, 19, 21, 35, 38, 44, 45, 46, 57, 61, 62, 63 and 76 require a combination of decreasing scale size and adjustment of resources to rectify existing inefficiencies in both TTE and PTE scores.

Table. 6.29: Individual Wind Farm Efficiency Scores

No.	Wind Farms	No. Wind Turbines	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE)	(RTS)	Reference DMU Peers
1	Golagh	10	0.930	0.948	inefficient	0.981	Increasing	29, 47
2	Cronaglacht	8	0.503	0.526	inefficient	0.956	Increasing	29, 47
3	Drumlough	8	0.369	0.385	inefficient	0.958	Increasing	47
4	Crockahenny	10	0.324	0.337	inefficient	0.961	Increasing	47
5	Cark	20	0.535	0.686	inefficient	0.779	Decreasing	29, 47
6	Cuillagh	18	0.442	0.587	inefficient	0.752	Decreasing	47
7	Anarget	3	0.494	0.579	inefficient	0.853	Increasing	29, 47
8	Meenadreen	4	0.389	0.424	inefficient	0.917	Increasing	29, 47
9	Burtonport	1	0.228	1	inefficient	0.228	Increasing	47
10	Meenanilta	3	0.636	0.707	inefficient	0.899	Increasing	29, 47
11	Meentycat	38	0.510	1	inefficient	0.510	Decreasing	47
12	Sorne Hill	16	0.579	0.929	inefficient	0.623	Decreasing	29, 47
13	Beam Hill	8	0.492	0.625	inefficient	0.787	Decreasing	47
14	Loughderry	9	0.401	0.403	inefficient	0.995	Increasing	29, 47
15	Lurganboy	6	0.625	0.673	inefficient	0.928	Decreasing	29, 47
16	Killybegs	6	0.354	0.414	inefficient	0.855	Increasing	47
17	Meenachullen	6	0.855	0.902	inefficient	0.947	Decreasing	47
18	Corneen	2	0.392	0.437	inefficient	0.897	Increasing	29, 47
19	Gartnaneane	10	0.390	0.555	inefficient	0.702	Decreasing	29, 47
20	Ratrussan	32	0.413	0.913	inefficient	0.452	Decreasing	29, 47
21	Snugborough	13	0.376	0.535	inefficient	0.702	Decreasing	47
22	Mountain Lodge I	21	0.418	0.818	inefficient	0.511	Increasing	29, 47
23	Mountain Lodge II	3	0.363	0.401	inefficient	0.905	Increasing	29, 47
24	Mullananalt	5	0.435	0.436	inefficient	0.997	Increasing	29, 47
25	Moneenatieve	5	0.490	0.519	inefficient	0.944	Increasing	29, 47
26	Corrie Mountains	8	0.669	0.723	inefficient	0.925	Increasing	29, 47
27	Black Banks	12	0.609	0.614	inefficient	0.991	Increasing	29, 47
28	Spion Kop	2	0.541	0.961	inefficient	0.562	Increasing	29, 47
29	Kingsmountain	10	1	1	Efficient	1	Constant	29
30	Geevagh	6	0.348	0.361	inefficient	0.963	Increasing	29, 47
31	Caranne Hill	4	0.609	0.659	inefficient	0.924	Increasing	29, 47
32	Lacken 1	3	0.628	0.665	inefficient	0.944	Increasing	47
33	Kilronan	9	0.502	0.525	inefficient	0.956	Increasing	29, 47
34	Largan Hill	9	0.434	0.449	inefficient	0.966	Increasing	29, 47
35	Altagowan	9	0.389	0.395	inefficient	0.984	Decreasing	47
36	Bellacorrick	21	0.423	0.432	inefficient	0.979	Increasing	29, 47
37	Burren	2	0.414	0.539	inefficient	0.768	Increasing	29, 47
38	Raheen Barr	22	0.452	0.708	inefficient	0.638	Decreasing	29, 47
39	Cuillalea	4	0.397	0.430	inefficient	0.923	Increasing	29, 47
40	Inis Mean	3	0.231	1	inefficient	0.231	Increasing	29, 47
41	Inverin	5	0.296	0.319	inefficient	0.927	Increasing	29, 47
42	Sonnagh Old	9	0.471	0.476	inefficient	0.989	Decreasing	29, 47
43	Derrybrien	70	0.418	0.926	inefficient	0.451	Decreasing	29, 47
44	Moanmore	7	0.570	0.660	inefficient	0.863	Decreasing	29, 47
45	Boultiagh	13	0.394	0.617	inefficient	0.638	Decreasing	29, 47

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

No.	Wind Farms	No. Wind Turbines	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE)	(RTS)	Reference DMU Peers
46	Knockawarrige	9	0.722	0.854	inefficient	0.845	Decreasing	47
47	Tournafulla	5	1	1	Efficient	1	Constant	47
48	Curraghgraigue	3	0.511	0.589	inefficient	0.867	Increasing	29, 47
49	Carrig	3	0.319	0.377	inefficient	0.846	Increasing	29, 47
50	Skehanagh	5	0.361	0.381	inefficient	0.947	Increasing	29, 47
51	Ballinlough	3	0.435	0.497	inefficient	0.875	Increasing	29, 47
52	Beal Hill	4	0.164	0.173	inefficient	0.947	Increasing	29, 47
53	Beenageeha	6	0.352	0.377	inefficient	0.933	Increasing	47
54	Tursillagh 1	31	0.496	0.883	inefficient	0.561	Decreasing	47
55	Mount Eagle	6	0.380	0.394	inefficient	0.964	Increasing	29, 47
56	Coomagearlahy I	15	0.739	1	inefficient	0.739	Decreasing	47
57	Coomagearlahy II	10	0.374	0.391	inefficient	0.956	Decreasing	29, 47
58	Pallas	20	0.537	0.917	inefficient	0.585	Decreasing	47
59	Glanlee	23	0.495	0.907	inefficient	0.545	Decreasing	29, 47
60	Ballybane	8	0.892	1	inefficient	0.892	Decreasing	47
61	Muingnaminane	18	0.442	0.555	inefficient	0.796	Decreasing	29, 47
62	Gneeves	11	0.373	0.427	inefficient	0.873	Decreasing	29, 47
63	Kealkill	10	0.375	0.404	inefficient	0.928	Decreasing	29, 47
64	Milane Hill	9	0.364	0.371	inefficient	0.981	Increasing	47
65	Curabwee	7	0.412	0.429	inefficient	0.960	Increasing	47
66	Lahanaht	3	0.242	0.275	inefficient	0.88	Increasing	29, 47
67	Coomatalin	4	0.354	0.362	inefficient	0.977	Increasing	47
68	Kilvinane	3	0.635	0.701	inefficient	0.905	Increasing	29, 47
69	Taurbeg	11	0.641	0.843	inefficient	0.760	Decreasing	47
70	Beallough	2	0.414	0.544	inefficient	0.761	Increasing	29, 47
71	Greenoge	4	0.440	0.460	inefficient	0.956	Increasing	29, 47
72	Cronelea I	3	0.501	0.515	inefficient	0.972	Increasing	29, 47
73	Dundalk IT	1	0.434	1	inefficient	0.434	Increasing	29, 47
74	Drybridge	2	0.459	0.608	inefficient	0.754	Increasing	29, 47
75	Dunmore	2	0.353	0.475	inefficient	0.743	Increasing	29, 47
76	Carnsore	12	0.650	0.759	inefficient	0.856	Decreasing	29, 47
77	Ballywater	21	0.465	0.871	inefficient	0.533	Decreasing	29, 47
78	Richfield	18	0.509	0.950	inefficient	0.535	Decreasing	29, 47
79	Cronelea II	3	0.460	0.469	inefficient	0.980	Increasing	29, 47
80	Arklow Banks	7	0.660	0.920	inefficient	0.717	Decreasing	29, 47
81	Cronelea Upper	3	0.220	0.263	inefficient	0.836	Increasing	47
	Average		**0.481**	**0.619**		**0.818**		

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

6.4.1 Projection Analysis and Benchmarking

An advantageous attribute of the non parametric approach DEA is to offer corrective efficiency guidance for inefficient DMUs. The output-oriented BCC VRS is applied for optimisation. For each inefficient wind farm DMU projection target values for input parameters are calculated to make them efficient, on the productive efficiency frontier. Table 6.31 presents the original and target values for the input parameters wind fuel, unit rate export capacity and full time man hours employed in the operation and maintenance of wind farms. Examining the results of Table 6.31 by employing wind farm DMU 32 Lacken 1 as a typical case. To become efficient requires a reduction of -5.28% wind fuel, -31.8% unit rate export capacity, full time man hours remaining unaltered culminating in an increasing in annual production of 50.3%. DMUs with the greatest and smallest gap between their original and targeted values are marked ^{A} and ^{B} respectively. The results from Table 6.31 indicate altering wind fuel and full time man hours are the most effective improvement techniques for inefficient wind farm DMUs.

The summary statistics of the slack parameter analysis for the BCC case are displayed in Table 6.30. The existence of slacks remaining after projection on to the production frontier demonstrates further scope for efficiency improvement. Observing the results, the mean (amount of slack per DMU) implies wind fuel MWh per wind farm exhibiting slacks could be reduced by an average of 22104.560 MWh without altering current levels of output. Inspecting the percentage slack of total input column wind fuel and unit rate export capacity are insignificant with 4.11% and 0.23% respectively. The most significant parameter is full time man hours with 66 wind farm DMUs presenting slacks, mean (amount of slack per DMU) reduction of 244.742 hours with an 34.04% slack of total input.

Table. 6.30: Wind Farm Summary Statistics of Slack Variables

Parameter	**Number of DMU's with Slacks**	**Mean (Amount of Slack per DMU)**	**% of Slack of Total Input**
Wind	21	22104.560	4.118
Unit Rate Export Capacity	2	1.185	0.23
Fulltime Manhours	66	244.724	34.04
Annual Production	0	0	0

Table. 6.31: Original and Targeted Values for Wind Farm Parameters

No.		Wind Original Value	Fuel Projected Value	%	Unit Rate Original Value	Export Projected Value	Capacity %	Full Time Original Value	Man Hours Projected Value	%	Annual Original Value	Production Projected Value	%
1	Golagh	56234.31	56234.31	0	15	15	0	600	379.493	-36.75	41401.2	43638.38	5.40
2	Cronaglacht	55241.5	55241.5	0	4.98	4.98	0	480	182.8	-61.92	14321.6	27191	89.86
3	Drumlough	78052.79	65318.74	-16.31	4.8	4.8	0	480	205.26	-57.24	11758.4	30507.89	159.46
4	Crockahenny	69618.56	68010.69	-2.31	5	5	0	600	212.280	-64.62	10763.2	31933.39	196.69
5	Cark	154914.6	154914.6	0	15	15	0	1200	438.982	-63.42	43588.6	63481.89	45.64
6	Cuillagh	173488.9	155444.5	-10.40	11.88	11.88	0	1080	433.627	-63.42	34899.2	59421.89	70.27
7	Anarget	24913.21	24913.21	0	3.1	3.1	0	180	101.677	-43.51	7000	12076.28	72.52
8	Meenadreen	40674.83	40674.83	0	3.4	3.4	0	240	130	-45.56	8000	18846.85	135.59
9	Burtonport	9595.24	9595.24	0	0.66	0.66	0	60	60	0	1000	1000	0
10	Meenanilta	29511.28	29511.28	0	5	5	0	180	145.443	-19.20	12000	16954.87	41.29
11	Meentycat	898601.2	898601.2	0	72.2	72.2	0	2280	2280	0	193032.8	193032.8	0
12	Sorne Hill	304367.9	304367.9	0	32	32	0	960	882.430	-8.08	89144.7	95926.32	7.61
13	Beam Hill	162724.7	162724.7	0	14	14	0	480	453.936	-5.22	39216	62736.89	59.98
14	Loughderry	94459.8	94459.8	0	7.65	7.65	0	540	292.359	-45.86	19000	47118.97	147.99
15	Lurganboy	40342.4	40242.4	0	5	5	0	360	161.332	-55.19	14321	21277.25	48.57
16	Killybegs	117378	35034.2	-70.1[A]	2.55	2.55	0	360	126.315	-64.91	6000	14471.01	141.18
17	Meenachullen	122238.1	122238.1	0	11.9	11.62	-2.28[B]	360	360	0	51091.7	56628.53	10.84
18	Corneen	35145.37	35145.37	0	3	3	0	120	114.739	-4.38	7000	15999.44	128.56
19	Gartnaneane	188313.3	188313.3	0	15.5	15.5	0	620	517.279	-16.57	37000	66570.47	79.92
20	Ratrussan	621966.5	598980.8	-3.70	48	48	0	1920	1535.593	-20.02	127151.7	139164.6	9.45
21	Snugborough	236626.1	175337.3	-25.90	13.5	13.5	0	540	483.050	-10.55	33731.4	62998.39	86.76
22	Mountain LodgeI	408673.8	402508.5	-1.51	32	32	0	1280	1047.458	-18.17	84958.9	103841.1	22.23
23	Mountain LodgeII	38921.32	38731.18	-0.49	3	3	0	120	120	0	7000	17430.43	149.01
24	Mullananalt	94156.67	94156.67	0	7.5	7.5	0	300	288.992	-3.67	20423.6	46757.71	128.94
25	Moneenatieve	50171.45	50171.45	0	4.25	4.25	0	300	161.139	-46.29	12456.8	23998.3	92.65
26	Corrie Mountains	39431.5	39431.5	0	4.8	4.8	0	480	156.099	-67.48	14897.5	20593.36	38.23
27	Black Banks	82647.39	82647.39	0	10.2	10.2	0	720	324.716	-54.90	28567.3	46489.86	62.74
28	Spion Kop	10424.6	110424.6	0	1.2	1.2	0	480	43.400	-90.9[A]	3124.3	3250.681	4.5[B]
29	Kingsmountain	73725.75	73725.75	0	25	25	0	600	600	0	66637.8	66637.8	0
30	Geevagh	61029.35	61029.35	0	5.1	5.1	0	360	193.629	-46.21	10745.1	29692.99	176.34
31	Caranne Hill	42827.62	42827.62	0	3.4	3.4	0	240	133.803	-44.25	13000	19705.96	51.58
32	Lacken1	63033.61	59707.52	-5.28	6.6	4.5	-31.8[A]	180	180	0	18765.3	28.204.34	50.30
33	Kilronan	54878.46	54878.46	0	5	5	0	200	182.657	-8.67	14238	27078.16	90.18
34	Largan Hill	61282.63	61282.63	0	5.94	5.94	0	237.6	210.368	-11.46	14000.5	31139.67	122.42
35	Altagowan	104652.5	103502.1	-1.10	7.65	7.65	0	306	304.576	-0.47[B]	19789.2	50083.26	153.08
36	Bellacorrick	73725.75	73725.75	0	6.5	6.5	0	1260	239.534	-80.99	16000	37002.42	131.27
37	Burren	18222.36	18222.36	0	2	2	0	120	70.428	-41.31	4125.7	7644.058	85.28
38	Raheen Barr	230901.7	230901.7	0	18.7	18.7	0	1320	622.524	-52.84	52315.7	73874.98	41.21
39	Cuillalea	44668.57	44668.57	0	3.4	3.4	0	240	157.032	-34.57	8765	20340.47	132.05
40	Inis Mean	8718.08	8718.08	0	0.675	0.675	0	180	180	0	1000	1000	0

Note: [A] - Those with the greatest difference [B] - Those with the smallest difference

No.		Wind Original Value	Fuel Projected Value	%	Unit Rate Original Value	Export Projected Value	Capacity %	Full Time Original Value	Man Hours Projected Value	%	Annual Original Value	Production Projected Value	%
41	Inverin	42812.86	42812.86	0	3.96	3.96	0	300	144.693	-51.77	6589.2	20597.15	212.59
42	Sonnagh Old	103230.2	103230.2	0	7.65	7.65	0	540	303.947	-43.71	23865	50063.46	109.78
43	Derrybrien	711642	711642	0	60	60	0	4200	1849.601	-55.96	150798.5	162781.7	7.95
44	Moanmore	136769.2	136769.2	0	12.6	12.6	0	420	391.955	-6.68	38955.6	59007.98	51.47
45	Boultiagh	232220.9	232220.9	0	19.5	19.5	0	780	627.262	-19.58	38955.6	59007.98	51.47
46	Knockawarrige	301749.7	201296.8	-33.29	22.5	22.5	0	540	540	0	64713.1	75716.63	17
47	Tournafulla	101660.2	101660.2	0	7.5	7.5	0	300	300	0	49752.1	49752.1	0
48	Curraghgraigue	29511.28	29511.28	0	2.55	2.55	0	102	97.705	-4.21	7685.7	13030.18	69.54
49	Carrig	25600.15	25600.15	0	2.55	2.55	0	102	91.968	-9.84	4328.1	11469.37	165.00
50	Skehanagh	52938.58	52.938.58	0	4.25	4.25	0	170	165.198	-2.82	9567.9	25102.57	162.36
51	Ballinlough	31012.52	31012.52	0	2.55	2.55	0	102	99.908	-2.05	6783.3	13629.29	100.92
52	Beal Hill	54098.49	54098.49	0	4.29	4.29	0	240	167.679	-30.13	4439.6	25629.54	477.29[A]
53	Beenageeha	54667.07	54012.52	-1.20	3.96	3.96	0	360	175.789	-51.17	9255.3	24520.79	164.94
54	Tursillagh1	307255.2	277257.3	-9.76	21.8	21.8	0	1860	736.271	-60.42	71818.2	81322.42	13.23
55	Mount Eagle	62894.19	62894.19	0	5.1	5.1	0	360	196.365	-45.45	12000.8	30437.19	153.63
56	CoomagearlahyI	488716.1	488716.1	0	45	45	0	900	900	0	110329.6	110329.6	0
57	CoomagearlahyII	108774.3	108774.3	0	8.5	8.5	0	600	318.562	-46.91	20187.1	51583.72	155.53
58	Pallas	436915.2	436915.2	0	40	40	0	1200	1163.87	-3.01	106946	116607.5	9.03
59	Glanlee	358183.8	358183.8	0	31.6	31.6	0	1380	944.103	-31.59	90879.5	100088.4	10.13
60	Ballybane	168089.6	168089.6	0	20	20	0	480	480	0	71009.4	71009.4	0
61	Muingnaminane	148525.7	148525.7	0	15.3	15.3	0	1080	424.839	-60.66	35193.5	63410.81	80.18
62	Gneeves	125446	124377.3	-0.85	9.35	9.35	0	660	356.440	-45.99	23000	53836.37	134.07
63	Kealkill	113795.2	113795.2	0	8.5	8.5	0	600	330.174	-44.97	21000	51949.29	147.38
64	Milane Hill	87809.39	80662.89	-8.14	5.94	5.94	0	540	245.262	-54.58	14345.5	38633.24	169.31
65	Curabwee	67091.41	66933.91	-0.23[B]	4.92	4.92	0	420	209.473	-50.13	13457.3	31363.19	133.06
66	Lahanaht	26399.87	26399.87	0	4.25	4.25	0	180	126.265	-29.85	4000	14511.76	262.79
67	Coomatalin	82877.24	80198.17	-3.23	5.95	5.95	0	240	240	0	14000	38641.54	176.01
68	Kilvinane	33109.04	33109.04	0	4.5	4.5	0	180	140.979	-21.68	12345.6	17589.68	42.48
69	Taurbeg	340796.8	241846.2	-29.04	25.3	25.3	0	660	660	0	70232.9	83262.7	18.55
70	Beallough	18673.36	18673.36	0	1.7	1.7	0	68	65.244	-4.05	4000	7343.46	83.59
71	Greenoge	55756.85	55756.85	0	5.2	5.2	0	208	187.843	-9.69	12765.4	27749.08	117.38
72	CroneleaI	64211.81	64211.81	0	6.9	6.9	0	276	233.3711	-15.45	17459.4	33846.46	93.86
73	DundalkIT	8665.07	8665.07	0	0.85	0.85	0	34	34	0	1987.8	1987.8	0
74	Drybridge	18179.64	18179.64	0	1.7	1.7	0	68	64.52	-5.12	4346	7146.43	64.44
75	Dunmore	22018.23	20551.69	-6.66	1.7	1.7	0	68	68	0	3850	8093.052	110.21
76	Carnsore	129897	129897	0	12	12	0	480	374.796	-21.92	43821.6	57719.43	31.71
77	Ballywater	399998.4	399998.4	0	43	43	0	1720	1242.085	-27.79	101004.4	115907.7	14.76
78	Richfield	350291.9	341110.8	-2.62	27	27	0	1080	894.915	-17.14	88196	92802.54	5.22
79	CroneleaII	72385.56	72385.56	0	6.9	6.9	0	276	245.362	-11.10	17435	37108.36	112.84
80	Arklow Banks	183757	183757	0	25.2	25.2	0	1008	640.700	-36.44	71417.8	77571.7	8.62
81	Cronelea Upper	35042.18	32438.28	-7.43	2.55	2.55	0	102	102	0	3735.5	14198.26	280.09

Note: [A] - Those with the greatest difference [B] - Those with the smallest difference

6.4.2 Further Analysis and Discussion

The eighty-one wind farms adopted in the previous sections are randomly distributed throughout the Irish landscape and hence are operating in contrasting wind farm efficiency environments. There exists exogenous factors that influence the efficiency scores obtained by each wind farm. Iglesias et al. (2010) states the efficiency scores obtained in the previous sections represent ex ante decisions and as such the sources of inefficiencies can be characterised by the following:

1. Poor wind resource assessment: less wind than anticipated, excessive wind with directional changes impacting upon efficiency.
2. Selection of wind turbine: inadequate selection concerning nominal power, diameter, height, generator type or mechanical capacity.
3. Wind Farm Design: positioning the wind turbines in the wrong direction, ignoring topography of altitude, distance to connection points.

Krokoszinski (2003) stipulates external factors beyond the control of management such as unforeseen weather conditions, grid restrictions, sabotages and administrative reasons can hinder wind farm efficiency performance. A second wind farm model to account for different wind farm operating environments is proposed by retaining the base case wind farm model but incorporating an uncontrollable exogenous parameter.

The parameter mean site elevation was incorporated into the base case wind model as an exogenously fixed parameter impacting on efficiency score attained. Referring to Section 5.12, the NDSC-O-C(V) models were run for the eighty-one wind farms and the results are presented in Table 6.32. The results attained are compared with the base case wind farm efficiency scores. Upon inspection comparing models one and two, it can be seen the inclusion of the exogenous variable has a positive affect on the average efficiency scores with TTE rising from 48% to 56%, PTE rising a smaller amount from 61% to 64% with SE rising from 81% to 88%. The number of efficient wind farm DMUs also rises across all three efficiency measures. Comparing the Spearman correlation coefficient results obtained in Table 6.32, it is evident the inclusion of the exogenously defined parameter mean site elevation in model two is statistically significant 0.870 for the NDSC-O-V TTE case but as much for the NDSC-O-C PTE 0.947.

Table. 6.32: Individual Wind Farm Efficiency Scores

No.	Wind Farm	Model (TTE) CCR ϕ	One (PTE) BCC ϕ	SE CCR ϕ/BCC ϕ	Model (TTE) NDSC-O-C ϕ	Two (PTE) NDSC-O-V ϕ	SE
1	Golagh	0.930	0.948	0.981	0.930	0.948	0.981
2	Cronaglacht	0.503	0.526	0.956	0.503	0.526	0.956
3	Drumlough	0.369	0.385	0.958	0.369	0.385	0.958
4	Crockahenny	0.324	0.337	0.961	0.324	0.337	0.961
5	Cark	0.535	0.686	0.779	0.574	0.686	0.977
6	Cuillagh	0.442	0.587	0.752	0.486	0.587	0.827
7	Anarget	0.494	0.579	0.853	0.580	0.784	0.739
8	Meenadreen	0.389	0.424	0.917	0.389	0.424	0.917
9	Burtonport	0.228	1	0.228	0.228	0.999	0.228
10	Meenanilta	0.636	0.707	0.899	0.636	0.707	0.899
11	Meentycat	0.510	1	0.510	0.818	1	0.818
12	Sorne Hill	0.579	0.929	0.623	0.857	0.980	0.874
13	Beam Hill	0.492	0.625	0.787	0.567	0.625	0.907
14	Loughderry	0.401	0.403	0.995	0.663	0.683	0.970
15	Lurganboy	0.625	0.673	0.928	0.625	0.673	0.928
16	Killybegs	0.354	0.414	0.855	0.354	0.415	0.853
17	Meenachullen	0.855	0.902	0.947	0.997	1	0.997
18	Corneen	0.392	0.437	0.897	0.392	0.437	0.897
19	Gartnaneane	0.390	0.555	0.702	0.558	0.573	0.973
20	Ratrussan	0.413	0.913	0.452	0.772	0.922	0.837
21	Snugborough	0.376	0.535	0.702	0.538	0.546	0.985
22	Mountain Lodge I	0.418	0.818	0.511	0.722	0.828	0.871
23	Mountain Lodge II	0.363	0.401	0.905	0.363	0.401	0.905
24	Mullananalt	0.435	0.436	0.997	0.435	0.436	0.997
25	Moneenatieve	0.490	0.519	0.944	0.490	0.519	0.944
26	Corrie Mountains	0.669	0.723	0.925	0.669	0.723	0.925
27	Black Banks	0.609	0.614	0.991	0.609	0.614	0.991
28	Spion Kop	0.541	0.961	0.562	0.541	0.961	0.562
29	Kingsmountain	1	1	1	1	1	1
30	Geevagh	0.348	0.361	0.963	0.348	0.361	0.963
31	Caranne Hill	0.609	0.659	0.924	0.609	0.659	0.924
32	Lacken 1	0.628	0.665	0.944	1	1	1
33	Kilronan	0.502	0.525	0.956	0.502	0.525	0.956
34	Largan Hill	0.434	0.449	0.966	0.434	0.463	0.937
35	Altagowan	0.389	0.395	0.984	0.550	0.559	0.983
36	Bellacorrick	0.423	0.432	0.979	0.575	0.592	0.971
37	Burren	0.414	0.539	0.768	0.414	0.539	0.768
38	Raheen Barr	0.452	0.708	0.638	0.696	0.730	0.953
39	Cuillalea	0.397	0.430	0.923	0.397	0.430	0.923
40	Inis Mean	0.231	1	0.231	0.282	0.999	0.282
41	Inverin	0.296	0.319	0.927	0.3555	0.387	0.917
42	Sonnagh Old	0.471	0.476	0.989	0.471	0.476	0.989
43	Derrybrien	0.418	0.926	0.451	0.718	0.926	0.775
44	Moanmore	0.570	0.660	0.863	1	1	1
45	Boultiagh	0.394	0.617	0.638	0.618	0.643	0.961

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale S.D. - Standard Deviation

No.	Wind Farm	Model (TTE) CCR ϕ	One (PTE) BCC ϕ	SE CCR ϕ/BCC ϕ	Model (TTE) NDSC-O-C ϕ	Two (PTE) NDSC-O-V ϕ	SE
46	Knockawarrige	0.722	0.854	0.845	0.867	0.890	0.974
47	Tournafulla	1	1	1	1	1	1
48	Curraghgraigue	0.511	0.589	0.867	0.511	0.590	0.866
49	Carrig	0.319	0.377	0.846	0.319	0.377	0.846
50	Skehanagh	0.361	0.381	0.947	0.361	0.390	0.925
51	Ballinlough	0.435	0.497	0.875	0.435	0.497	0.875
52	Beal Hill	0.164	0.173	0.947	0.203	0.217	0.935
53	Beenageeha	0.352	0.377	0.933	0.352	0.377	0.933
54	Tursillagh 1	0.496	0.883	0.561	0.705	0.883	0.798
55	Mount Eagle	0.380	0.394	0.964	0.380	0.394	0.964
56	Coomagearlahy I	0.739	1	0.739	0.875	1	0.875
57	Coomagearlahy II	0.374	0.391	0.956	0.374	0.391	0.956
58	Pallas	0.537	0.917	0.585	0.791	0.939	0.842
59	Glanlee	0.495	0.907	0.545	0.678	0.907	0.747
60	Ballybane	0.892	1	0.892	0.999	1	0.999
61	Muingnaminane	0.442	0.555	0.796	0.515	0.559	0.921
62	Gneeves	0.373	0.427	0.873	0.373	0.427	0.873
63	Kealkill	0.375	0.404	0.928	0.375	0.404	0.928
64	Milane Hill	0.364	0.371	0.981	0.364	0.371	0.981
65	Curabwee	0.412	0.429	0.960	0.412	0.429	0.960
66	Lahanaht	0.242	0.275	0.88	0.242	0.275	0.88
67	Coomatalin	0.354	0.362	0.977	0.354	0.362	0.977
68	Kilvinane	0.635	0.701	0.905	0.635	0.701	0.905
69	Taurbeg	0.641	0.843	0.760	0.730	0.843	0.865
70	Beallough	0.414	0.544	0.761	0.414	0.544	0.761
71	Greenoge	0.440	0.460	0.956	0.440	0.460	0.956
72	Cronelea I	0.501	0.515	0.972	0.501	0.515	0.972
73	Dundalk IT	0.434	1	0.434	0.434	0.999	0.434
74	Drybridge	0.459	0.608	0.754	0.459	0.608	0.754
75	Dunmore	0.353	0.475	0.743	0.353	0.475	0.743
76	Carnsore	0.650	0.759	0.856	0.998	0.999	0.998
77	Ballywater	0.465	0.871	0.533	0.812	1	0.812
78	Richfield	0.509	0.950	0.535	0.985	1	0.985
79	Cronelea II	0.460	0.469	0.980	0.460	0.469	0.980
80	Arklow Banks	0.660	0.920	0.717	1	1	1
81	Cronelea Upper	0.220	0.263	0.836	0.220	0.263	0.836
	Average	**0.481**	**0.619**	**0.818**	**0.566**	**0.649**	**0.888**
	SCC	-	-	-	.870	.947	-
	Min	0.164	0.173		0.203	0.217	0.228
	Max	1	1	1	1	1	1
	S.D.	0.163	0.229	-	0.222	0.242	-
	Efficient	2	8	2	5	11	5

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale S.D. - Standard Deviation

The preceding analysis has primarily focused on the individual efficiency of eighty-one wind farms in the ROI, the forthcoming analysis extends the research to evaluate the efficiency of wind power generation on a county efficiency basis. As outlined in Section 5.7 the ROI consists of twenty-six counties. Employing the base case model, the wind farm parameter values are amalgamated to form a county wind DMU and the DEA Solver-Pro is run again to establish wind county efficiency scores. The results are presented in Table 6.33.

Table. 6.33: Wind Farm County Efficiency Scores

No.	Electricity Distribution County	No. Wind Farms	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE)	(RTS)	Reference DMU Peers
1	Donegal	174	0.776	1	inefficient	0.776	Decreasing	7, 10
2	Cavan	80	0.675	0.926	inefficient	0.728	Decreasing	7, 10
3	Monaghan	5	0.732	0.777	inefficient	0.942	Increasing	7, 10
4	Leitrim	27	0.871	0.880	inefficient	0.989	Increasing	7, 10
5	Sligo	23	1	1	Efficient	1	Constant	5
6	Roscommon	27	0.709	0.718	inefficient	0.987	Increasing	7, 10
7	Mayo	52	1	1	Efficient	1	Constant	7
8	Galway	87	0.690	0.810	inefficient	0.851	Decreasing	7, 10
9	Clare	20	0.742	0.750	inefficient	0.989	Decreasing	5, 7
10	Limerick	5	1	1	Efficient	1	Constant	10
11	Tipperary	15	0.685	0.705	inefficient	0.971	Increasing	5, 7
12	Kerry	85	0.763	1	inefficient	0.763	Increasing	7, 10
13	Cork	58	0.670	0.799	inefficient	0.838	Decreasing	7, 10
14	Waterford	2	0.669	1	inefficient	0.669	Increasing	5, 7
15	Carlow	7	0.772	0.799	inefficient	0.966	Increasing	5, 7
16	Louth	3	0.720	0.922	inefficient	0.780	Increasing	5, 7
17	Meath	2	0.602	0.962	inefficient	0.625	Increasing	7, 10
18	Wexford	51	0.817	0.985	inefficient	0.828	Decreasing	5, 7
19	Wicklow	13	0.855	0.857	inefficient	0.997	Decreasing	5, 7
	Average		**0.776**	**0.889**		**0.878**		

Note: TTE - Total Technical Efficiency PTE - Pure Technical Efficiency SE - Scale Efficiency RTS - Returns to Scale

Out of the nineteen counties investigated 16 are inefficient and 3 are efficient. The most efficient counties in terms of wind energy generation are DMU 5 Sligo, DMU 7 Mayo and DMU 10 Limerick. These 3 counties are the benchmark best performers with DMU 7, DMU 10 cited as reference peers ten times by the other wind county DMUs, each of these counties are PK efficient. The efficiency results emphasize Ireland's exceptional wind resource, four times that of the European average SEI (2006) with the west coast of Ireland having the highest wind speeds in Europe, hence most efficient wind energy productive counties. DMU 5, DMU 7 and DMU 10

wind counties are all located along the west of the ROI facing the Atlantic ocean. Observing the average values, the TTE 77%, PTE 88% and SE 87% achieve above average acceptable levels of efficiency with room for improvement.

The subsequent investigation combines the efficiency results obtained from the National level and Individual level efficiency studies to establish the TTE, PTE and SE on a county generation basis in terms of all three forms of electricity generation (thermal, wind and hydro). The database consists of a hundred and one electricity generating units, incorporating fifteen thermal power plants, eighty one wind farms and five hydro power plants connected to the SEM for the year 2008 and the results are presented Table 6.34.

Observing the results it is apparent for PTE, counties Longford and Offaly are the best performing with 100% efficiency and Monaghan the worst performing county with 43%. For TTE, Limerick attained 86% efficiency whilst Offaly poor performance is reflected in the 31% score. SE is generally quite high across counties with Monaghan achieving the highest score of 99%. The county Limerick situated in the south west of the island is the best performing county in terms of overall generation attaining TTE, PTE and SE scores of 86% 92% and 92% respectively. Limerick consists of just wind generation. The worst performing county is Offaly located in the centre of the ROI with low TTE 31%, high PTE 100% and low SE score of 31%.

Table. 6.34: County Electricity Generation Efficiency Scores

No.	Generation Source	DMU	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ/BCC ϕ
Donegal						
1	Wind	Golagh	0.930	0.948	inefficient	0.981
2	Wind	Cronaglacht	0.503	0.526	inefficient	0.956
3	Wind	Drumlough	0.369	0.385	inefficient	0.958
4	Wind	Crockahenny	0.324	0.337	inefficient	0.961
5	Wind	Cark	0.535	0.686	inefficient	0.779
6	Wind	Cuillagh	0.442	0.587	inefficient	0.752
7	Wind	Anarget	0.494	0.579	inefficient	0.853
8	Wind	Meenadreen	0.389	0.424	inefficient	0.917
9	Wind	Burtonport	0.228	1	inefficient	0.228
10	Wind	Meenanilta	0.636	0.707	inefficient	0.899
11	Wind	Meentycat	0.510	1	inefficient	0.510
12	Wind	Sorne Hill	0.579	0.929	inefficient	0.623
13	Wind	Beam Hill	0.492	0.625	inefficient	0.787
14	Wind	Loughderry	0.401	0.403	inefficient	0.995
15	Wind	Lurganboy	0.625	0.673	inefficient	0.928
16	Wind	Killybegs	0.354	0.414	inefficient	0.855
17	Wind	Meenachullen	0.855	0.902	inefficient	0.947
18	Hydro	Erne	0.541	0.560	inefficient	0.966
Average			**0.511**	**0.649**		**0.827**
Cavan						
19	Wind	Corneen	0.392	0.437	inefficient	0.897
20	Wind	Gartnaneane	0.390	0.555	inefficient	0.702
21	Wind	Ratrussan	0.413	0.913	inefficient	0.452
22	Wind	Snugborough	0.376	0.535	inefficient	0.702
23	Wind	Mountain Lodge I	0.418	0.818	inefficient	0.511
24	Wind	Mountain Lodge II	0.363	0.401	inefficient	0.905
Average			**0.392**	**0.609**		**0.694**
Monaghan						
25	Wind	Mullananalt	0.435	0.436	inefficient	0.997
Average			**0.435**	**0.436**		**0.997**
Letrim						
26	Wind	Moneenatieve	0.490	0.519	inefficient	0.944
27	Wind	Corrie Mountains	0.669	0.723	inefficient	0.925
28	Wind	Black Banks	0.609	0.614	inefficient	0.991
29	Wind	Spion Kop	0.541	0.961	inefficient	0.562
Average			**0.577**	**0.704**		**0.855**
Sligo						
30	Wind	Kingsmountain	1	1	Efficient	1
31	Wind	Geevagh	0.348	0.361	inefficient	0.963
32	Wind	Caranne Hill	0.609	0.659	inefficient	0.924
33	Wind	Lacken 1	0.628	0.665	inefficient	0.944
Average			**0.646**	**0.671**		**0.957**
Roscommon						
34	Wind	Kilronan	0.502	0.525	inefficient	0.956
35	Wind	Largan Hill	0.434	0.449	inefficient	0.966
36	Wind	Altagowan	0.389	0.395	inefficient	0.984
Average			**0.441**	**0.456**		**0.968**

No.	Generation Source	DMU	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ/BCC ϕ
Mayo						
37	Wind	Bellacorrick	0.423	0.432	inefficient	0.979
38	Wind	Burren	0.414	0.539	inefficient	0.768
39	Wind	Raheen Barr	0.452	0.708	inefficient	0.638
40	Wind	Cuillalea	0.397	0.430	inefficient	0.923
41	Thermal	Tawaghmore	0.096	0.703	Inefficient	0.136
Average			**0.356**	**0.562**		**0.688**
Galway						
42	Wind	Inis Mean	0.231	1	inefficient	0.231
43	Wind	Inverin	0.296	0.319	inefficient	0.927
44	Wind	Sonnagh Old	0.471	0.476	inefficient	0.989
45	Wind	Derrybrien	0.418	0.926	inefficient	0.451
46	Thermals	Tynagh	0.987	1	Inefficient	0.987
Average			**0.480**	**0.744**		**0.717**
Clare						
47	Wind	Moanmore	0.570	0.660	inefficient	0.863
48	Wind	Boultiagh	0.394	0.617	inefficient	0.638
49	Thermal	Moneypoint	0.841	0.859	Inefficient	0.979
50	Hydro	Ardnacrusha	0.631	1	Inefficient	0.631
Average			**0.609**	**0.784**		**0.777**
Limerick						
51	Wind	Knockawarrige	0.722	0.854	inefficient	0.845
52	Wind	Tournafulla	1	1	Efficient	1
Average			**0.861**	**0.927**		**0.922**
Tipperary						
53	Wind	Curraghgraigue	0.511	0.589	inefficient	0.867
54	Wind	Carrig	0.319	0.377	inefficient	0.846
55	Wind	Skehanagh	0.361	0.381	inefficient	0.947
56	Wind	Ballinlough	0.435	0.497	inefficient	0.875
Average			**0.406**	**0.461**		**0.883**
Kerry						
57	Wind	Beal Hill	0.164	0.173	inefficient	0.947
58	Wind	Beenageeha	0.352	0.377	inefficient	0.933
59	Wind	Tursillagh 1	0.496	0.883	inefficient	0.561
60	Wind	Mount Eagle	0.380	0.394	inefficient	0.964
61	Wind	Coomagearlahy I	0.739	1	inefficient	0.739
62	Wind	Coomagearlahy II	0.374	0.391	inefficient	0.956
63	Wind	Pallas	0.537	0.917	inefficient	0.585
64	Wind	Glanlee	0.495	0.907	inefficient	0.545
65	Wind	Ballybane	0.892	1	inefficient	0.892
66	Wind	Muingnaminane	0.442	0.555	inefficient	0.796
67	Thermal	Tarbert	0.246	0.262	Inefficient	0.938
Average			**0.465**	**0.624**		**0.805**
Cork						
68	Wind	Gneeves	0.373	0.427	inefficient	0.873
69	Wind	Kealkill	0.375	0.404	inefficient	0.928
70	Wind	Milane Hill	0.364	0.371	inefficient	0.981
71	Wind	Curabwee	0.412	0.429	inefficient	0.960
72	Wind	Lahanaht	0.242	0.275	inefficient	0.88
73	Wind	Coomatalin	0.354	0.362	inefficient	0.977
74	Wind	Kilvinane	0.635	0.701	inefficient	0.905
75	Wind	Taurbeg	0.641	0.843	inefficient	0.760

No.	Generation Source	DMU	(TTE) CCR ϕ	(PTE) BCC ϕ	Status	(SE) CCR ϕ/BCC ϕ
76	Thermal	Aghada	0.119	0.171	Inefficient	0.695
77	Thermal	Marina	0.250	0.298	Inefficient	0.838
78	Hydro	Lee	0.429	1	Inefficient	0.429
Average			**0.381**	**0.480**		**0.799**
Waterford						
79	Wind	Beallough	0.414	0.544	inefficient	0.761
Average			**0.414**	**0.544**		**0.761**
Carlow						
80	Wind	Greenoge	0.440	0.460	inefficient	0.956
81	Wind	Cronelea I	0.501	0.515	inefficient	0.972
Average			**0.470**	**0.487**		**0.964**
Dublin						
82	Thermal	Huntstown	0.507	0.768	Inefficient	0.660
83	Thermal	Northwall	1	1	Efficient	1
84	Thermal	Poolbeg	0.353	0.385	Inefficient	0.916
85	Thermal	Dublin Bay	1	1	Efficient	1
Average			**0.715**	**0.788**		**0.894**
Kildare						
86	Thermal	Edenderry	0.437	0.968	Inefficient	0.451
Average			**0.437**	**0.968**		**0.451**
Longford						
87	Thermal	Loughree	0.476	1	Inefficient	0.476
Average			**0.476**	**1**		**0.476**
Louth						
88	Wind	Dundalk IT	0.434	1	inefficient	0.434
89	Wind	Drybridge	0.459	0.608	inefficient	0.754
Average			**0.446**	**0.804**		**0.594**
Meath						
90	Wind	Dunmore	0.353	0.475	inefficient	0.743
Average			**0.353**	**0.475**		**0.743**
Offaly						
91	Thermal	Rhode Island	0.131	1	Inefficient	0.131
92	Thermal	West Offaly	0.499	1	Inefficient	0.499
Average			**0.315**	**1**		**0.315**
Wexford						
93	Wind	Carnsore	0.650	0.759	inefficient	0.856
94	Wind	Ballywater	0.465	0.871	inefficient	0.533
95	Wind	Richfield	0.509	0.950	inefficient	0.535
96	Thermals	Great Island	0.093	0.096	Inefficient	0.968
Average			**0.429**	**0.669**		**0.723**
Wicklow						
97	Wind	Cronelea II	0.460	0.469	inefficient	0.980
98	Wind	Arklow Banks	0.660	0.920	inefficient	0.717
99	Wind	Cronelea Upper	0.220	0.263	inefficient	0.836
100	Hydro	Liffey	0.153	0.865	Inefficient	0.176
101	Hydro	Turlough Hill	1	1	Efficient	1
Average			**0.498**	**0.703**		**0.741**

Table 6.35 bifurcates the twenty-six counties of the ROI into two economic terms producers or consumers relating to whether the county in question is a consumer of electricity or a producer of electricity. Of the twenty-six, ten counties are established as producers whilst the remaining sixteen are deemed consumers of electricity. This indicates the energy generation imbalanced characteristics and the extent to which energy generated MWh must flow through the electricity system to meet demand and energy consumption.

Table. 6.35: County Electricity Producer or Consumer Status

No	County	Status	No	County	Status
1	Donegal	Producer	14	Waterford	Consumer
2	Cavan	Producer	15	Carlow	Consumer
3	Monaghan	Consumer	16	Dublin	Producer
4	Letrim	Consumer	17	Kildare	Producer
5	Sligo	Consumer	18	Kilkenny	Consumer
6	Roscommon	Consumer	19	Laois	Consumer
7	Mayo	Consumer	20	Longford	Producer
8	Galway	Producer	21	Louth	Consumer
9	Clare	Producer	22	Meath	Consumer
10	Limerick	Consumer	23	Offaly	Producer
11	Tipperary	Consumer	24	Westmeath	Consumer
12	Kerry	Producer	25	Wexford	Consumer
13	Cork	Producer	26	Wicklow	Consumer

Interestingly of the five counties that contain a city, only three Galway, Cork and Dublin are deemed producers of electricity whilst Limerick and Waterford are consumers. Twenty-four counties employ some form of electricity generation, be it thermal, hydro or wind or a mixture of all three forms. The counties Kilkenny and Laois are the only two counties that do not employ any form of electricity generation.

6.4.3 Sensitivity Analysis and Model Validation

Sensitivity analysis and model validation are core concepts of successful DEA applications and therefore must be acknowledged and adhered to. The present approach assumes the data set is accurate, precise, credible and omits individual variables one by one cetris paribus to observe the differences in the DEA efficiencies (if any), thereby establishing the robustness of the base case model DEA efficiency results obtained. Note: upon removal of a variable, the efficiency score will either remain unchanged or decrease but will never increase.

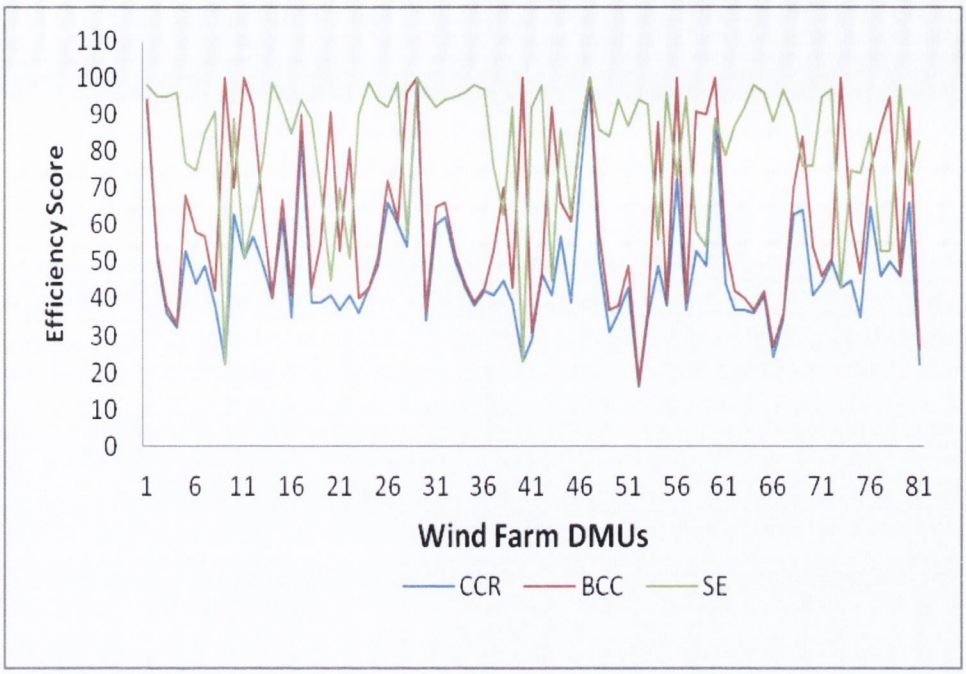


Fig. 6.17: Base Case For Wind Farms

The wind farm base case is the approach employed by (Iglesias et al., 2010), incorporates three input parameters wind fuel, unit rate export capacity and full time man hours with one single output parameter annual production. The CCR CRS BCC VRS and SE scores for the eighty-one wind farms in the ROI connected to the SEM in 2008 are graphically represented in Figure 6.17.

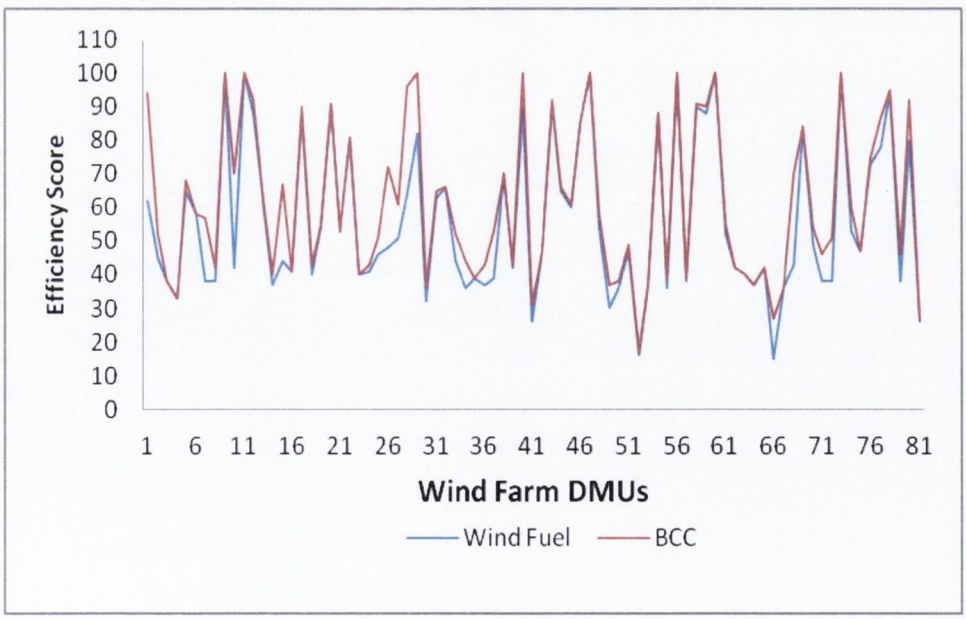


Fig. 6.18: Wind Farm Fuel Omitted

The use of annual wind data greatly reduces the influence of seasonal effects. The base case line graph clearly demonstrates the extensive oscillation of efficiency scores across the efficiency measures with the lowest efficiency score attained for the BCC of 17%. Similar to the national and county level the assumption VRS characteristics is more appropriate for wind energy generation and hence the BCC efficiency scores are retained for comparison with the perturbed data. Figure 6.18 depicts the change in efficiency score when the parameter wind fuel is omitted from the base case scenario. Fifty-one DMUs observe a change in efficiency score indicating wind fuel plays a significant role in determining the higher efficiency score obtained in the base case. Figure 6.19 illustrates the effect on efficiency values when unit rate export capacity is omitted from the inputs in the base case. The predominant visual effect of this modification is the considerable reduction in efficiency scores of seventy-one DMUs. This input parameter is the most important for wind farm generation significantly impacting on the efficiency scores obtained.

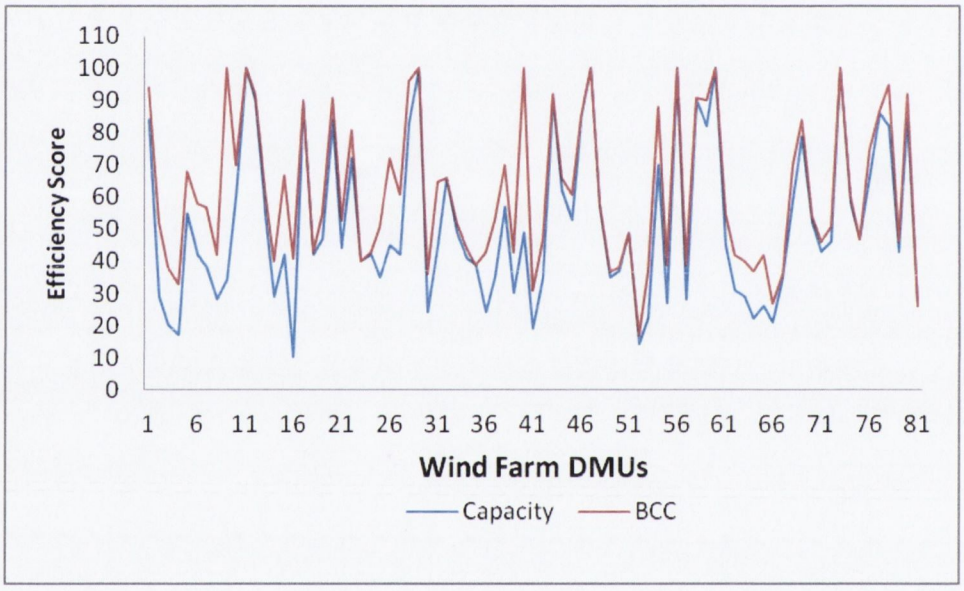


Fig. 6.19: Wind Farm Unit Rate Export Capacity Omitted

Figure 6.20 shows the influence on efficiency of omitting full time man hours from the base case model. It can be observed there is little difference between the BCC base case efficiency scores and that of the perturbed data with only nine DMUs detecting a change in efficiency score. This indicates that full time man hours for the majority of DMUs does not contribute significantly to the high efficiency score obtained in the base case.

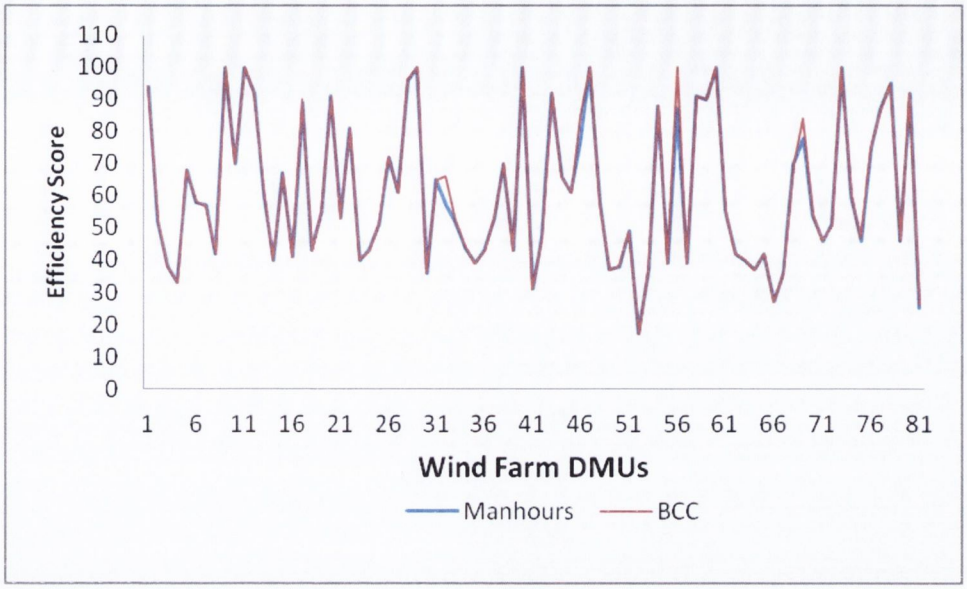


Fig. 6.20: Wind Farm Full Time Man Hours Omitted

Table 6.36 demonstrates the relationship between the wind farm DMUs efficiency score obtained and the input/outputs chosen in the base case scenario. The predominant attribute of the evaluated wind farm DMUs is that sixty-five are deemed distinctly inefficient. Only four wind farms DMU 11 Meentycat, DMU 47 Tournafulla, DMU 60 Ballybane, DMU 73 Dundalk IT are robustly efficient. Observing the results in Table 6.36 ** depicts a strong influence when the input in question alters the efficiency score by at least 0.5; whilst * refers to weak influence when the input in question alters the efficiency value by less than 0.5. The parameter full time man hours impacts upon the least number of wind farm DMUs and could theoretically be the first variable to be omitted from the base case model. It only impacts upon nine DMUs.

To establish the construct validity of the adopted wind farm models, a Pearson correlation analysis is employed to check the isotonicity relationship Golany and Roll (1989) among the inputs and outputs. It is evident from Table 6.37 a significantly positive correlation among the inputs and outputs exists. Thus, the isotonicity assumption of the input-output factors in the adopted wind farm DEA models is validated. The greater the value of the correlation coefficient, the stronger the relationship between the two variables. This is evident between the parameters wind fuel and unit rate export capacity with a Pearson coefficient of .969. This is evidently what one would expect and is acceptable as an increase in unit rate export capacity will increase the wind fuel harnessed at a particular wind farm. Bowlin (1987) state the number of inputs and outputs must be small or equal to one-third of the DMUs. This stipulation is satisfied for the wind farm DEA models. It is paramount the number of DMUs exceeds the number of input-output factors by a significant amount to ensure the measurements of relative efficiencies are meaningful.

Table. 6.36: Sensitivity Analysis of Wind Farm Parameters

No.	EDC	(PTE) BCC ϕ	Wind Fuel Omitted	Unit Rate Export Capacity Omitted	Full Time Man Hours Omitted	Status
1	Golagh	0.948	0.624*	0.840*	0.948	Significantly Ineff.
2	Cronaglacht	0.526	0.450*	0.296*	0.526	Distinctly Ineff.
3	Drumlough	0.385	0.385	0.202*	0.385	Distinctly Ineff.
4	Crockahenny	0.337	0.337	0.172*	0.337	Distinctly Ineff.
5	Cark	0.686	0.657*	0.551*	0.686	Distinctly Ineff.
6	Cuillagh	0.587	0.587	0.425*	0.587	Distinctly Ineff.
7	Anarget	0.579	0.380*	0.386*	0.579	Distinctly Ineff.
8	Meenadreen	0.424	0.389*	0.287*	0.424	Distinctly Ineff.
9	Burtonport	1	1	0.343**	1	Marginally Eff.
10	Meenanilta	0.707	0.425*	0.606*	0.707	Distinctly Ineff.
11	Meentycat	1	1	1	1	Robustly Eff.
12	Sorne Hill	0.929	0.881*	0.905*	0.929	Distinctly Ineff.
13	Beam Hill	0.625	0.617*	0.557*	0.625	Distinctly Ineff.
14	Loughderry	0.403	0.379*	0.291*	0.403	Distinctly Ineff.
15	Lurganboy	0.673	0.448*	0.427*	0.673	Distinctly Ineff.
16	Killybegs	0.414	0.414	0.107*	0.414	Distinctly Ineff.
17	Meenachullen	0.902	0.898*	0.902	0.897*	Significantly Ineff.
18	Corneen	0.437	0.401*	0.426*	0.437	Distinctly Ineff.
19	Gartnaneane	0.555	0.548*	0.478*	0.555	Distinctly Ineff.
20	Ratrussan	0.913	0.913	0.844*	0.913	Significantly Ineff.
21	Snugborough	0.535	0.535	0.440*	0.535	Distinctly Ineff.
22	Mountain Lodge I	0.818	0.818	0.720*	0.818	Distinctly Ineff.
23	Mountain Lodge II	0.401	0.401	0.401	0.401	Distinctly Ineff.
24	Mullananalt	0.436	0.410*	0.428*	0.436	Distinctly Ineff.
25	Moneenatieve	0.519	0.468*	0.351*	0.519	Distinctly Ineff.
26	Corrie Mountains	0.723	0.488*	0.457*	0.723	Distinctly Ineff.
27	Black Banks	0.614	0.512*	0.420*	0.614	Distinctly Ineff.
28	Spion Kop	0.961	0.644*	0.836*	0.961	Significantly Ineff.
29	Kingsmountain	1	0.828*	1	1	Marginally Eff.
30	Geevagh	0.361	0.329*	0.247*	0.361	Distinctly Ineff.
31	Caranne Hill	0.659	0.633*	0.457*	0.659	Distinctly Ineff.
32	Lacken 1	0.665	0.665	0.665	0.570*	Distinctly Ineff.
33	Kilronan	0.525	0.447*	0.499*	0.525	Distinctly Ineff.
34	Largan Hill	0.449	0.363*	0.419*	0.449	Distinctly Ineff.
35	Altagowan	0.395	0.395	0.392*	0.935	Distinctly Ineff.
36	Bellacorrick	0.432	0.375*	0.240*	0.432	Distinctly Ineff.
37	Burren	0.539	0.391*	0.359*	0.539	Distinctly Ineff.
38	Raheen Barr	0.708	0.702*	0.576*	0.708	Distinctly Ineff.
39	Cuillalea	0.430	0.426*	0.302*	0.430	Distinctly Ineff.
40	Inis Mean	1	0.903*	0.490**	1	Marginally Eff.
41	Inverin	0.319	0.268*	0.197*	0.319	Distinctly Ineff.
42	Sonnagh Old	0.476	0.476	0.359*	0.476	Distinctly Ineff.
43	Derrybrien	0.926	0.910*	0.917*	0.926	Marginally Ineff.
44	Moanmore	0.660	0.650*	0.621*	0.660	Distinctly Ineff.
45	Boultiagh	0.617	0.607*	0.536*	0.617	Distinctly Ineff.
46	Knockawarrige	0.854	0.854	0.844*	0.780*	Distinctly Ineff.
47	Tournafulla	1	1	1	1	Robustly Eff.

Note : EDC - Electricity Distribution County PTE - Pure Technical Efficiency ** - Efficiency score altered by at least 0.5 * - Efficiency score altered by lees than 0.5 Ineff. - Inefficient Eff. - Efficient

No.	EDC	(PTE) BCC ϕ	Wind Fuel Omitted	Unit Rate Export Capacity Omitted	Full Time Man Hours Omitted	Status
48	Curraghgraigue	0.589	0.541*	0.574*	0.589*	Distinctly Ineff.
49	Carrig	0.377	0.304*	0.352*	0.377	Distinctly Ineff.
50	Skehanagh	0.381	0.362*	0.375*	0.381	Distinctly Ineff.
51	Ballinlough	0.497	0.477*	0.491*	0.497	Distinctly Ineff.
52	Beal Hill	0.173	0.165*	0.140*	0.173	Distinctly Ineff.
53	Beenageeha	0.377	0.377	0.222*	0.377	Distinctly Ineff.
54	Tursillagh 1	0.883	0.883	0.701*	0.883	Distinctly Ineff.
55	Mount Eagle	0.394	0.367*	0.273*	0.394	Distinctly Ineff.
56	Coomagearlahy I	1	1	1	0.872*	Marginally Eff.
57	Coomagearlahy II	0.391	0.388*	0.289*	0.391	Distinctly Ineff.
58	Pallas	0.917	0.901*	0.908*	0.917	Marginally Ineff.
59	Glanlee	0.907	0.882*	0.824*	0.907	Significantly Ineff.
60	Ballybane	1	1	1	1	Robustly Eff.
61	Muingnaminane	0.555	0.525*	0.450*	0.555	Distinctly Ineff.
62	Gneeves	0.427	0.427	0.314*	0.427	Distinctly Ineff.
63	Kealkill	0.404	0.404	0.299*	0.404	Distinctly Ineff.
64	Milane Hill	0.371	0.371	0.222*	0.371	Distinctly Ineff.
65	Curabwee	0.429	0.429	0.269*	0.429	Distinctly Ineff.
66	Lahanaht	0.275	0.150*	0.211*	0.275	Distinctly Ineff.
67	Coomatalin	0.362	0.362	0.359*	0.361	Distinctly Ineff.
68	Kilvinane	0.701	0.437*	0.593*	0.701	Distinctly Ineff.
69	Taurbeg	0.843	0.843	0.799*	0.788*	Distinctly Ineff.
70	Beallough	0.544	0.494*	0.528*	0.544*	Distinctly Ineff.
71	Greenoge	0.460	0.384*	0.434*	0.460	Distinctly Ineff.
72	Cronelea I	0.515	0.384*	0.467*	0.515	Distinctly Ineff.
73	Dundalk IT	1	1	1	1	Robustly Eff.
74	Drybridge	0.608	0.537*	0.584*	0.608	Distinctly Ineff.
75	Dunmore	0.475	0.475	0.475	0.466*	Distinctly Ineff.
76	Carnsore	0.759	0.734*	0.664*	0.759	Distinctly Ineff.
77	Ballywater	0.871	0.788*	0.866*	0.871	Distinctly Ineff.
78	Richfield	0.950	0.950	0.829*	0.950	Significantly Ineff.
79	Cronelea II	0.469	0.383*	0.439*	0.469	Distinctly Ineff.
80	Arklow Banks	0.920	0.803*	0.855*	0.920	Significantly Ineff.
81	Cronelea Upper	0.263	0.263	0.263	0.258*	Distinctly Ineff.

Note : EDC - Electricity Distribution County PTE - Pure Technical Efficiency ** - Efficiency score altered by at least 0.5 * - Efficiency score altered by lees than 0.5 Ineff. - Inefficient Eff. - Efficient

Table. 6.37: Pearson Correlation Matrix for Individual level Data

		Input 1 Wind Fuel	**Input 2** Unit Rate Export Capacity (MW)	**Input 3** Full Time Man Hours	**Input 4** Mean Site Elevation (Metres)	**Output 1** Annual Production (MWh)
Wind Fuel	Pearson	1	.969**	.844**	.202	.958**
	Sig.		.000	.000	.071	.000
	N	81	81	81	81	81
Unit Rate Export Capacity (MW)	Pearson	.969**	1	.840**	.166	.987**
	Sig.	.000		.000	.138	.000
	N	81	81	81	81	81
Full Time Man Hours	Pearson	.844**	.840**	1	.198	.822**
	Sig.	.000	.000	.077	.000	
	N	81	81	81	81	81
Mean Site Elevation (Metres)	Pearson	.202	.166	.198	1	.170
	Sig.	0.71	.138	.077		.130
	N	81	81	81	81	81
Annual Production (MWh)	Pearson	.958	.987	.822	.170	1
	Sig.	.000	.000	.000	.130	
	N	81	81	81	81	81

Note: ** Denotes Correlation is significant at the 0.01 level * Denotes Correlation is Significant at the 0.05 level

6.4.4 Summary of Individual Level Analysis

The individual level research study applies DEA in an ex post production framework to establish the relative efficiency of eighty-one operational wind farms in the ROI for the year 2008. The analysis of wind energy efficiency generation is relevant and pertinent in light of Ireland's commitment to increase electricity contribution from renewable energy sources. The reasons behind inefficient wind farm DMUs are discussed and corrective measures suggested. The findings of the research state: the average efficiency scores obtained for the eighty-one individual wind farms are TTE 48%, PTE 61% and SE 81%. The results clearly show poor efficiency performance of wind farms. Only two wind farms are deemed efficient. Observing wind energy generation on a county basis, it is found counties Sligo, Mayo and Limerick located in the west of Ireland are the best benchmark efficiency performers.

An exogenous parameter was employed to account for different wind farm operating environments and was found to be statistically significant. Accounting for all three forms of electricity generation county Limerick in the south west is the most efficient in terms of TTE PTE and SE whilst county Offaly performs sub-optimally in relation to the other counties. It is established that only ten counties are electricity producers whilst the remaining sixteen are all consumers of electricity. The analysis of results from several perspectives provides invaluable

information concerning wind farm efficiency generation and the approach employed may be easily extended to other wind farms for estimation of efficiency scores, ranking and optimisation of wind farms. The results of the wind farm generation efficiency performance are of interest to industry professionals involved in the sector. These include engineers, wind farm companies (developers), operators and technology suppliers. The results can assist government and local county councils in terms of best practice policy to development renewable energy plans to exploit wind resources throughout the ROI.

CHAPTER 7

Discussion and Conclusions

7.1 Introduction

The thesis presents the application of Data Envelopment Analysis (DEA) to the electricity generation and distribution functions of the Irish Electricity Power System (EPS) entitled the all island Single Electricity Market (SEM). The purpose of this research is to study the technical, policy and market challenges associated with increasing the levels of energy efficiency in the electricity generation and distribution functions of the SEM system with a particular emphasis on wind power. Section 7.2 reviews the main findings presented throughout the thesis. Section 7.3 discusses and interprets the main contributions, policy implications and salient issues proposed by the results of the research thesis. Section 7.4 provides a critical assessment and outlines some possible future research avenues arising from the work presented in this thesis.

7.2 Key Findings

As set out in the introductory chapter the core focus of this thesis is efficiency performance measurement. The initial research objectives defined and outlined in Chapter 1 sought to determine the efficiency of the Irish EPS. The aim of the research thesis is to evaluate the operational efficiency performance of the Irish EPS in light of Irish commitments to curb climate change, ensure security of supply, foster economic competitiveness, reduce dependency on imported fossil fuels, support the extensive deployment of renewable energy technologies and ultimately attain Irish 2020 energy efficiency objectives. In this thesis, Chapter 2 formed the conceptual framework prior to the research being executed by presenting the global energy challenge and the unique underlying dynamic attributes of the test system. Chapter 3 provides an extensive literature review of economic efficiency and methodologies employed in its estimation. Chapter 4 details the advocated DEA methodology, its underlying mathematical notation and models employed to evaluate economic efficiency in the EPSs context. Chapter 5 describes data sources,

parameters employed in the research and the procedural process required for successful application of DEA. Finally, Chapter 6 displays the results, analysis and discussion relating to the application of DEA to the test system.

This thesis presented a detailed three tier methodological framework determining EPS efficiency performance measurement. The DEA methodology was applied to the test system, the all island SEM and an operational technical efficiency evaluation of the generating and distribution functions of the Irish EPS was conducted. The year under observation is 2008, the first fully operational year of the SEM. The main conclusions stemming from the DEA application are presented:

National level - **All Island Generation Efficiency Study (AIGES)**
The focus of the National level analysis was to establish the operational technical efficiency performance of electricity generation in terms of thermal power plants, wind regions and hydro power plants.

- The findings indicate the Total Technical Efficiency (TTE) scores for thermal power plants, wind regions and hydro power plants were 49%, 46% and 55% respectively. In terms of Pure Technical Efficiency (PTE) the scores obtained were 70%, 73% and 88% respectively. The results exhibit the sub optimal performance of electricity generation with considerable scope for improvement in efficiency.
- Dublin Bay, Northwall thermal power plants, Wind region F and Turlough Hill hydro power plant are deemed Pareto-Koopmans (PK) efficient and are the reference peer benchmark performers within their respective electricity generation technologies.
- Focusing on thermal power plant electricity generation, it is found the East is the most efficient region, Combined Cycle Gas Turbines (CCGT) is the most efficient form of electricity generation and Gas is the most efficient fuel source.
- The results of the slack analysis conducted indicate excess unit rate export capacity over the three forms of electricity generation (thermal, wind and hydro) is significant.
- The findings indicate directions for inefficient electricity generating units to become efficient by either altering the scale size of their operation or alternating their utilization of resources or a combination of these two.

County level - **Republic of Ireland Distribution Efficiency Study (ROIDES)**
The aim of the County level study was to establish the operational technical efficiency of electricity distribution and the merits of employing DEA benchmarking as a form of incentive regulation.

- Six differing models employing various input-output combinations were established to encapsulate the underlying characteristics of electricity distribution associated with the SEM in 2008.

- It was established that the distribution of electricity in the SEM attained acceptable, high levels of efficiency. The average TTE and PTE scores for the twenty-six Electricity Distribution Counties (EDC) dataset were 83% and 91% respectively. The lowest efficiency score for an EDC was 60%, Louth. Counties Leitrim, Dublin, Laois, Offaly and Westmeath are deemed PK efficient and are the peer benchmark performers.

- The inclusion of the industrial output as an exogenous parameter accounting for electricity distribution differences across EDCs was found to be statistically more significant than the inclusion of traditional exogenous parameters employed in the literature such as network density.

- It was shown that significant electricity distribution efficiency gains are attainable through the restructuring and amalgamation of the twenty six EDCs into eleven Electricity Distribution Zones (EDZ)s. The application and merits of employing DEA benchmarking as a form of incentive regulation for the SEM has been verified.

- The projection analysis and benchmarking results offer scope for inefficient EDCs to improve their efficiency by adopting DEA best practice methods outlined.

Individual level - **Republic of Ireland Wind Efficiency Study (ROIWES)**
The individual level research study evaluates the technical efficiency performance of eighty-one operational wind farms.

- The average TTE and PTE of the eighty one wind farms was 48% and 61% respectively illustrating significant improvements in efficiency performance is required. The wind farms Kingsmountain and Tournafulla in the counties Kerry and Limerick respectively located in the south west of Ireland are deemed PK efficient and are the peer benchmark performers for the other eighty wind farms.

- Employing the wind generation technology in terms of county efficiency, it was shown that counties Sligo, Mayo and Limerick located on the west coast of Ireland where the wind resource is best are PK efficient.

- Acknowledging the three forms of electricity generation (thermal, wind and hydro) on a county basis, Limerick located in the south west is the best performing county in terms of overall generation attaining TTE and PTE score of 86% and 92% respectively.

- Ten of the twenty six counties investigated are established as producers of electric power whilst the remaining sixteen are consumers of electricity. Only three of the five counties that contain a city are deemed producers of electric power.

7.3 Contribution to Knowledge and Policy Implications

The purpose of the research thesis was to analyse the technical, policy and market challenges associated with increasing the levels of energy efficiency in the electricity generation and distribution functions of the all island SEM system with a particular emphasis on wind power. Wind power energy will make a significant contribution to the future generation portfolio mix of the all island SEM. The literature on DEA applications to EPSs efficiency performance measurement is wide and extensive. The research presented contributes to this field of research of EPS efficiency performance in a number of ways.

The research conducted in this thesis adds to the field of research in evaluating the technical efficiency of EPSs. Firstly, in its application to the test system - all island SEM, secondly, in its employment of input-output parameters and alternative combinations to develop new models based on the DEA techniques for the efficiency assessment EPSs. The input-output parameters, alternative combinations and constructed DEA models are the salient contributions to knowledge in this thesis. A significant contribution of the current research is the wind generating regional DEA model employed in the National level efficiency context as it provides a new framework for evaluating wind generation on a regional basis.

Thirdly, the three tier DEA efficiency performance evaluation framework presented in the thesis. This type of framework has not been applied as most studies focus on a single form of electricity generation and a single function of the EPS. The concept of the three tier methodological efficiency framework is transferable and applicable to other sectors of a countries economy. Fourthly, numerous DEA studies have been conducted to establish electricity distribution efficiency by employing traditional exogenous variables to account for differing electricity characteristics across regions.

The research contributes to knowledge by advancing DEA applications to electricity distribution by incorporating a new diagnostic parameter industrial output to account differences across regions in terms of electricity distribution characteristics as opposed to incorporating traditional exogenous variables extensively employed in the literature. The observed results discussed in Chapter 6 reflect this significance. The three tier methodological efficiency framework, DEA models, parameters employed and methods developed are generic and internationally applicable to other EPS for efficiency performance measurement.

The results presented in this thesis have a number of practical policy implications. The empirical operational efficiency results can provide useful information to policy makers and government responsible for the electricity generation and distribution functions associated with the evolving and dynamic Irish EPS market regime. In relation to electricity generation, the efficiency results can when formulating forward thinking future generation capacity statements stipulate and guide what power plants to retire, what form of generation is most inefficient, what

fuel source is most inefficient, what region, county or area is most inefficient and consequently what policies and corrective measures are necessary to improve the efficiency of electricity generation. The DEA benchmark approach employed in this thesis offers an alternative form of electricity distribution regulation open to the Commission for Energy Regulation (CER) in Ireland as opposed to the status quo of RPI-X Operating Expenditure (OPEX) and Capital Expenditure (CAPEX) regulation. Ultimately, the more energy efficient use of electric power at the generation and distribution levels, the more it will enhance energy sustainability due to lower fossil fuel consumption resulting in reduced Greenhouse Gas (GHG) emissions and increased Renewable Energy Sources (RES) integration.

The three tier efficiency framework employed in this thesis, whilst applied to the Irish EPS can be extended to other sectors and functions of the Irish economy or indeed that of any economy. Whilst acknowledging the parameters for establishing technical efficiency would change depending on the research being conducted, the framework of investigating technical efficiency in a National, County and Individual context could remain. Examples of other possible avenues for research employing the three tier efficiency framework include transport (rail, road, bus), tourism (hotels), ports, schools, hospitals, County Councils.

With fluctuating energy prices, concerns about global warming and sustainable development, energy efficiency has become a vital part of energy strategies in many countries (Ang, 2006). The implementation of an effective solution to improve energy policy and the operational technical efficiency of the all-island SEM over the longer term requires the support, interaction and commitment from all key industry players. The complexity of a modern EPS is considerable and as such significant liaising and cooperation between the EU, local and national government, Transmission System Operators (TSO), Distribution System Operators (DSO), generators, suppliers and the industry regulator is paramount to ensure the common goal of improved Irish EPS efficiency performance is attained.

In conclusion, the dynamics of EPSs and the processes of electricity generation, transmission, distribution and consumption are consistently adapting and evolving. For the Irish EPS to facilitate the transition to a well functioning, energy efficient, low carbon, high renewable energy based system, it is evident dynamic, proactive forward thinking energy efficiency policy is required. DEA can provide a direct mechanism for the improved energy efficiency of the all island SEM. Policy makers and government need to adapt and facilitate DEA efficiency performance measurement and improvement directions in the electricity generation and distributing functions, it will ensure Ireland can achieve the stated EU 20-20-20 energy efficiency objectives of attaining a low carbon energy system and economy, mitigating CO_2 emissions, ensuring sustainability of energy supply through added RES - Wind power and fostering competitiveness through electricity market reform and interconnection.

7.4 Critical Assessment and Directions for Future Research

Whilst the research presented in this thesis adds to the field of DEA applications to EPSs technical efficiency research, there are some limitations to acknowledge.

The absence of data on NI for the County and Individual level efficiency analysis is a significant limitation. The research is confined to just ROIDES and ROIWES, data from the ROI was only available at the time of this research. The possibility of extending the efficiency analysis to include data from NI was explored but data was not available at the time of research. If this data were made available the County and Individual level efficiency analysis would incorporate a more comprehensive All Island Distribution Efficiency Study (AIDES) and All Island Wind Efficiency Study (AIWES).

The lack of Operating Expenditure (OPEX) and Capital Expenditure (CAPEX) data in the technical efficiency distribution dataset is a limitation of this research. A further research enhancement objective could be to shift the efficiency benchmarking focus from establishing technical efficiency to evaluating cost efficiency. The current research thesis employs physical measures of inputs such as labour and capital stock as proxies for the operating and capital costs. Benchmarking using physical quantities of inputs measures the potential for improvement in efficiency in terms of reductions in physical units. It is argued employing physical quantities of inputs may not capture the real costs or quality of labour and assets (e.g the mix of technical and non-technical staff, asset age and composition). At the time of this research operating and capital expenditure were not available. Doraisamy (2004) states the aim of regulators is to promote cost reductions in the distribution network so that prices to consumers will be lowered.

The thesis offers a platform for extended future research on the efficiency of the Irish EPS. The unique specific contextual setting in which the research was undertaken suggests further interesting avenues and objectives to be pursued by future research. The current research can be extended with respect to one or more of its components. Further research identified as needing scrutiny and consideration as a result of this thesis include the following:

The current thesis employs DEA models under static conditions and could be extended to incorporate DEA models under dynamic (time dependent) conditions. That is, the current research investigates efficiency in terms of a single year in isolation 2008 and could be extended to multi period efficiency analysis. This could facilitate DEA window analysis[1]. by employing DEA Malmquist Productivity Index which represents the Total Factor Productivity (TFP) growth of a DMU, by reflecting i) progress or regress in efficiency along with ii) progress or

[1]Window analysis relates to a tabular method for examining the changes in the efficiencies of a set of DMUs over time. A set of time periods (1 ..t) is chosen and the efficiency of each unit (1..n) is computed separately for each period so that the efficiency of a given unit over each period is treated as a new unit resulting in a total number of tn units (Cooper et al., 2007).

regress of the frontier technology between two periods of time under multiple inputs and multiple outputs framework Cooper et al. (2007).

With regards to Ireland's commitments to mitigating CO_2 emissions, a possible area for further research would be the implementation of DEA emissions modelling to evaluate the environmental efficiency of thermal power plants. This was beyond the scope of the present thesis as the primary focus was on the operational efficiency performance of thermal power plants and not environmental efficiency performance. DEA emissions modelling extends the traditional DEA models of efficiency measurement to acknowledge the presence of desirable and undesirable outputs. DEA emissions modelling would provide strategies and directions on efficiency improvement and emissions reductions. This would benefit Ireland immensely in relation the EU Emission Trading Scheme[2].

Further scope for research includes extending the thermal efficiency analysis to a micro power plant level. That is treat each thermal power generating unit as a DMU and not the entire power plant annual production (MWh). This added knowledge would be beneficial when determining which generating units are to be retired. In the individual wind farm context, if data were a made available the research could be extended, by rather than employing aggregated annual wind farm data, treat each 3 month bracket as DMU to investigate seasonal effects on the technical operational efficiency of wind farms. This knowledge could be beneficial in terms of reducing operation and maintenance costs. These are potential future areas for future research.

[2]The EU Emission Trading Scheme set a centralised cap on carbon CO_2 emissions in the polluting energy and industrial sectors across each member state. This also created an energy market in which participants trade excess permits as required.

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APPENDIX A

Chapter Four - Economic Efficiency and Data Envelopment Analysis

A.1 Empirical DEA Applications to Electricity Generation

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Abbott, 2006)	DEA, TFP (MI)	7 electricity distribution jurisdiction in Australia for the 1969-199 period	Physical capital (distribution Lines, capacity lines of transmission stations and generation capacity line), energy usage TJ	Energy Consumption MWh	Improvement in Industry Performance
(Nakano and Managi, 2008)	DEA, GMM Lunberger Productivity	9 Japanese electricity Companies from 1978-2003	Number of Employees, Quantity of Fuel Used , Real Capital Stock (Yen)	Electricity Production	Regulatory reforms contribute productivity growth to
(Shrivastava et al., 2012)	DEA	60 coal fired power plants in India	Coal Consumption, Fuel Oil Consumption, Auxiliary Power Consumption	Electricity Generated	Results indicate poor performance due to over use of input resources.
(Fare et al., 1990)	Malmquist Index	19 coal-fired steam electric generating plants 19751981	Fuel, Installed Capacity Employees	Electricity Generated	On average, rates of productivity growth are relatively stable.
(Sueyoshi and Goto, 2010)	RAM, Range Adjusted Measure	USA Coal-fired power plants	Number of Employees, Investment Costs, Total non-Fuel O&M, Fuel consumption	SO_2 released each year NO_2 emitted each year CO_2 emitted each year	Plant managers need to balance between their environmental performance and operational efficiency.
(Behera and Dash, 2010)	DEA	74 plants from 2003/04 to 2007/08	Generation Capacity, Auxiliary Power, Planned Maintenance, Forced Outages, Coal Consumption	Power Generated	It is found the average technical efficiency of these plants is 83.2% with as many as 38 plants below the mean level.
(Fang et al., 2009)	DEA	25 Chinese and US Coal Mining Companies	Operating Costs, Total Assets, Number of Employees	Earnings per Share, Operating Revenue, Net Profit	Efficiency of Chinese coal mining companies much lower than US coal firms

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Olatubi, 2000)	DEA	Coal fired steam plants in the US	Fuel Consumption Capital Labor	Net Electricity Produced	Results indicate considerable opportunities for cost reduction in the industry
(Sozen et al., 2010)	DEA	15 Turkish thermal power plants	Capacity Usage Factor, Thermal Efficiency, Average Operational Time, Project Production Capacity	Fuel Cost/Actual Production, CO_2, SO_2, N_2O Tonnes	Two efficiency indexes, operational and environmental performance were defined and pursued.
(Lam and Shiu, 2001)	DEA	30 regions in China	Generating Capacity Total Fuel Used Labor	Electricity Generated	Eastern regions of China achieve the highest levels of technical efficiency.
(Liu et al., 2010)	DEA	12 power pants of Taiwan 2004-2006	Installed Capacity, Electricity Used, Heating Value of Fuel	Net Electricity Produced	All power plants achieved acceptable overall operational efficiencies.
(Chien et al., 2007)	DEA, (MI)	8 thermal power plants in Taiwan	Number of Employees, Installed Capacity , Total Production Costs,	Energy generated	Analysis indicates productivity improvements.
(Jain et al., 2010)	DEA	30 Indian state owned generating utilities	Installed Capacity Coal Consumption Oil Consumption Auxiliary Consumption Energy Losses	Units Generated Energy Sold	11 generating utilities are found to be efficient
(Chitkara, 1999)	DEA, (MI)	Coal based generating Units India	Specific Coal Consumption (SCC), Specific Oil Consumption (SOC)	Auxiliary Power Consumption (APC)	Study indicates specific inefficiencies in units and the corrective measure to alleviate them
(Golany, 1988)	DEA				It presents the decision-maker with a set of alternative efficient points in order to compare different sets of inputs.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Vaninsky, 2006)	DEA	Electric power generation in USA in 1991-2004	Operating Expenses, Energy Loss, Total Expenses	Utilization of Net Capacity	Obtained results point to relative stability in efficiency over the period
(Athanassopoulos et al., 1999)	DEA	UK Utilities	Fuel, Controllable Costs, Capital Expenditure	Electricity Produced, Plant Availability Accidents Incurred Generated Pollution	Target scenario setting.
(Thakur et al., 2006)	DEA	26 Indian State Owned Electric Utilities SOEU	Total Costs, Number of Employees, Adjusted Costs	Energy Sold, Customers, Distribution Line Length	The results indicate that the performance of several SOEUs is sub-optimal.
(Golany et al., 1994)	DEA	Power plants in Israel	Fuel Consumption, Installed Capacity, Internal Power, Capital, Manpower, Misc Expenses, Fuel Stock	Generated Power, Operational Availability, Deviation from Load, Deviation from operational Parameters, SO_2 emissions	Systematic framework for the selection of factors is presented
(Thakur and S., 2009)	DEA	34 State Owned Electric Utilities SOEUs	Installed Capacity Auxiliary Consumption	Energy Generated	Study indicates the existence of large inefficiencies in particular Scale inefficiencies.
(Meenakumari and Kamaraj, 2008)	DEA	29 State Owned Electric Utilities SOEUs in India	Installed Capacity, Distribution Line Length, T&D Losses	Energy Supplied, Number of Customers	From the results of this is a existence of study it is observed that there inefficiency in 22 SOEUs.
(Diewert and Nakamura, 1999)	DEA	77 power plants in 28 different countries	litres per plant-year of diesel fuel & lubrication oil, Labour, Materials	Electricity Produced	The single factor efficiencies for the power plants in our data sample fail to identify best practice in an overall sense

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Goto and Tsutsui, 1998)	DEA	9 vertically integrated Japanese and 14 US utilities from 1983-1993	Generation Capacity Fuel (kCal) Labour Power Purchases	Residential Sales GWh, Non-residential Sales GWh	Cost efficiencies of Japanese electric utilities higher than US utilities over the period with allocative the cause.
(Sueyoshi and Goto, 2001)	DEA	25 electric power companies from 1984 to 1993	Generation Capacity, Fuel Consumption, Number of Employees	Electricity Generated	A new slack-adjusted data envelopment analysis (SA-DEA) model which explicitly incorporates an influence of slacks into its efficiency measurement.
(Arocena and Waddams Price, 2003)	DEA	Spanish Electricity Generators	Fuel, Installed Capacity, Labour, Particulates	Annual Production, Availability, CO_2, SO_2 tonnes	Publicly owned generators were more efficient under cost of service regulation
(Korhonen and Luptacik, 2004)	DEA	24 Power plants	Total Costs	Electricity Generated, DUST, NO_x, SO_2 emissions	Two approaches for the estimation of eco-efficiency are presented.
(Park and Lesourd, 2000)	DEA, SFA	64 conventional power plants in South Korea	Fuel Consumption, Installed Power, Labor	Energy Production	DEA efficiencies incorporated into standard production function model and appear statistically more significant.
(Meibodi, 1998)	DEA, SFA	26 electricity utilities	Labour, Capital, Fuel	Electricity Generated	The empirical evidence suggests that public ownership of electricity production might have an adverse effect on technical efficiency.
(Barros and Peypoch, 2008)	DEA, Regression	Thermoelectric power generating plants in Portugal	Number of Workers, Book Value of Physical Assets, Operational Costs,	Electricity Production, Maximum Capacity to evaluate efficiency, Two-stage Procedure.	Combines DEA with Simar-Wilson method

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Barros, 2008)	Malmquist Index	Portugal Hydroelectric energy generating plants 2001-2004	Number of Workers, Capital, Operational Costs, Investment	Production in MWh	
(Jha and Shrestha, 2006*b*)	DEA, GAMS	Hydro power plants Nepal	Installed Capacity, Total O&M Expenditure, Number of Employees	Energy Generated, Winter Peaking Capacity, Summer Peaking Capacity	Average overall efficiency 50%, technical efficiency 74%, and scale efficiency 71%.
(Jha et al., 2007)	DEA	Hydropower plants in Nepal	Installed Capacity, Annual O&M Costs, Number of Staff (Permanent & Temporary), Plant & Unit tripping	Energy Generated, Energy Generated Driest Month, Winter Peaking Capacity, Summer Peaking Capacity	Modified DEA efficiency model is presented & and improvement directions are proposed.
(Dedoussis et al., 2010)	DEA	20 Hydroelectric power plants in Greece	Power Capacity, Commissioning Date, Operation Time	Electricity Delivered, Availability, Scheduled and Unexpected Operation Interruptions	Results indicate that inefficient plants with less than 10 years of operation should decrease the annual operation time
(Sarica and Or, 2007)	DEA	64 thermal, hydro and wind generating plants in Turkey	Fuel Cost, Production, Operating Cost, Investment Cost, Construction Time	Availability, Environmental Cost, Production, Utilization Power Availability	Two efficiency indexes, reflecting operational and investment performance are defined and pursued.
(Iglesias et al., 2010)	DEA, SFA	57 Spanish wind farms from 2001-2004	Installed Capacity, Labour, Fuel	Electricity Generated	High correspondence between the results of technical efficiency obtained by both methods
(Hawdon, 2003)	DEA	International gas industry in 33 Countries 1998-1999	Employment, Length of Pipelines	Gas Consumption, Number of Customers	Recent developments in bootstrapping techniques are used to correct efficiency estimates for bias and to assess the uncertainty surrounding such estimates. The implications of these results for regulatory authorities are explored.

A.2 Empirical DEA Applications to Electricity Distribution

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Filippini et al., 2005)	SFA, COLS, DEA	59 Swedish electricity distribution utilities 1988-1996	Total Annual Costs, Number of customers, Load Factor, Service Area, Average Labor Price, Average Capital Price, Average Input Price, High-voltage network dummy Auxiliary revenues	Energy Delivered	Study concludes that benchmarking analysis should be used to support rather than to determine regulatory decisions.
(Farsi and Filippini, 2005)	SFA, COLS, DEA	52 electricity distribution utilities 1994	Total Annual Costs, Number of customers, Load Factor, Service Area, Average Labor Price, Average Capital Price, Average Input Price,	Energy Delivered	Considerable differences exist between parametric and non-parametric methods .
(Estache et al., 2004)	DEA, SFA	South American distribution companies 1994-2000	Number of Employees Distribution Network Transformer Capacity	Total Sales, Service Area, Customer Density, Demand Structure GNP per capita	Benchmarking could yield substantial efficiency results.
(Jamasb and Pollitt, 2003)	DEA, COLS, SFA	63 regional electricity distribution utilities Europe 1997-1998	OPEX, Total Expenditure, Network Length	Units Delivered No of Customers Network Length T&D Losses	Study finds SFA and COLS produce very comparable efficiency scores.
(Farsi and Filippini, 2004)	SFA	59 Swedish electricity distribution utilities 1988-1996	Total Annual Costs, Number of customers, Load Factor, Service Area, Average Labor Price, Average Capital Price, Average Input Price, High-voltage network dummy Auxiliary revenues Share of forest area	Energy Delivered	The results suggest that stochastic frontier models can be used to gain information about costs of individual firms.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Kumbhakar and Hjalmarsson, 1998)	OLS, SFA, DEA	Swedish retail electricity distributors 1970-1990	Number of Full-time Employees, Total Transformer Capacity ,	LV Units Delivered, HV Units Delivered, No. of HV Customers, No. of LV Customers	Privately owned firms were relatively more efficient in all models with evidence of scale economics.
(Whiteman, 1999)	DEA, SFA	7 Australian and 32 other Utilities 1994-1995	No. Full-time Employees, Hydro Power Capacity, Thermal Power Capacity	Electricity Generated	The results imply that the impact of microeconomic reform on economic growth
(Pollitt, 1995)	DEA, OLS	129 US transmission, firms,136 US, 9 UK distribution firms 1990	Labour, Length Transformer Capacity, Network Size	Maximum Demand, Network Size Distribution, No. of Customers, Sales-residents, Sales-non-residents, Service Area, Electricity Output	Results indicate no by evidence to state performance is affected ownership.
(Cullmann and Von Hirschhausen, 2008*a*)	DEA, SFA COLS	84 electricity distribution companies in Poland, Czech Republic, Slovakia, Hungary and Germany.	Number of workers, Length of Grid	Total Electricity Sales, Number of Customers, Inverse Density Index	The results suggest that the Polish distribution companies are still inefficiently small. The Czech Republic and Slovakia feature the highest efficiency.
(Goto and Tsutsui, 1998)	DEA	9 vertically integrated Japanese and 14 US utilities 1983-1993	Generation Capacity, Fuel (kCal), Labour, Power Purchases	Residential Sales (GWh), Non-residential (GWh)	Overall cost efficiencies of Japanese electricity utilities are consistently higher than the US utilities. The allocative inefficiency was the primary source of overall cost inefficiencies for Japanese utilities.
(Yu et al., 2007)	DEA	14 distribution networks UK 1990-2003	OPEX, CAPEX	Energy Delivered, Customer Number, Length of Line, Customer Interruption, Distribution losses	The results suggest that the utilities may not be sufficiently incentivised to achieve socially optimal input bundles under the current incentive scheme.
(Giannakis et al., 2005)		14 distribution operators in the UK	Operating Expenditure, Total Expenditure, Number of Interruptions, Customer Time Lost due to Interruptions	Total Number of Customers, Energy Delivered Total Network Length	The results also show that improvements in service quality have made a significant contribution to the sector's total productivity change.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Cambini et al., 2012)	DEA	115 electricity distribution zones Italy	Capital Costs, Operating Costs, Operating Costs Energy Not Supplied	Energy (MWh) Low Voltage Consumers	Claim that benchmarking models should include (monetary) measures of regulated outputs
(Growitsch, Jamasb and Pollitt, 2010)	SFA	7 European Countries	Total Expenditure, Customer Minutes Lost,	Number of customers, Units of energy (GWh) Country dummies, Customer density	The results emphasise that Quality of Service should be an integrated part of efficiency and economic analysis of regulated natural monopolies.
(Coelli et al., 2008)	DEA, SFA	92 French electricity distribution units 2003-2005	CAPEX, OPEX	Energy Supplied, Number of Customers, Network Length	The empirical results indicate that the inclusion of the quality variable has no significant effect upon mean technical efficiency scores obtained.
(Growitsch, Jamasb, Muller and Wissner, 2010)	DEA	131 Norwegian distribution network operators (DNO) from the period 2001 to 2004	SOTEX, TOTEX	Energy Supplied, Final Customer	The results indicate that internalising external or social cost of service quality does not have an important role in improving cost efficiency in Norwegian distribution utilities.
(Hougaard, 1994)	DEA	82 Danish electricity distribution utilities (EDUs) 1991	Number of Employees, Wages, OPEX, Losses, Capital Value	Network Size, Electricity Supplied, Number of Customers	There was significant potential for efficiency improvement among the firms, calculated efficiency scores are sensitive to model specification and rank order across models was rather robust.
(Burns and Weyman-Jones, 1994)	DEA, SFA	UK RECs in England 1973-1993	Number of Employees, Network Size, transformer capacity, customer density, share if industrial energy	Number of Customers, Domestic Customers, Commercial Customers, Industrial Customers, Max Demand	Evidence of Productivity Growth.
(DTe, 2000)	DEA	18 Dutch regional network utilities 1996	OPEX, OPEX and Tangible Depreciation	Units Distributed, No. of Customers, No. of Small Customers, No. of Large Customers, Network Length, No. of Transformers	The study investigated the choice of models and availability of data that will be used to estimate performance for regulatory purposes.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Jamasb and Pollitt, 2003)	DEA, COLS SFA	63 electricity distribution and regional transmission utilities in 6 countries	Total Cost, Operating Costs, Network Length, Energy Lost in Transmission	Units electricity Delivered, Number of Customers, Network Length	The results show that the choice of benchmarking techniques, model specifications, and variables can affect the efficiency scores, and the rank order of firms.
(Hattori et al., 2002)	DEA, SFA	Electricity distribution systems in the UK and Japan between 1985 and 1998	CAPEX, OPEX	Energy Delivered, Number of Customers, Length of Lines, Max Demand	The results suggest that the productivity gain in the UK electricity distribution has been larger than in the Japanese sector.
(Doraisamy, 2004)	DEA	UK electricity distribution network operators	Capital Inputs, Operating Expenditure	Total Customers, Total units distributed (GWh), Maximum demand (MW), Service Area, Quality of service measure(s)	The results showed evidence that there was scope for operating expenditure savings and capital savings across all the DNOs.
(Hjalmarsson and Veiderplass, 1992)	DEA	Swedish retail electricity distributors	Hours Worked, Low Voltage Power Lines, High Voltage Power Lines, Total Transformer Capacity	Low Voltage Electricity, High Voltage Electricity, No. of Low Voltage Customers, No. of High Voltage Customers	There was no significant difference in productivity associated with mode of ownership. Productivity growth in rural areas has been faster than in urban areas
(Giles and Wyatt, 1993)	DEA, Translog Cost Model	60 electricity authorities in New Zealand 1986-1987	Labour, Network Size, Transformer Capacity, Electricity Purchased	Units Sold	Economies of Scale is present
(Korhonen and Syrjanen, 2003)	DEA		OPEX	Units of Electricity Distributed, 3-year average of Total Interruption Time, Network Length, Number of Customers, Average Snow Depth in Winter, km^2 forest cover	The study provides an extensive framework for the selection of variables included in the efficiency analysis. The findings indicate considerable improvements to efficiency can be attained by distribution network operators.
(Salvanes and Tjotta, 1994)	Translog Cost Function	91 Norwegian electricity distributors 1991	Labour, Capital, Electricity Purchased	Electricity Supplied, Number of Customers	No evidence of economies of scale but significant evidence of economies of density

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Filippini, 1996)	Cost Function	39 Swiss distribution utilities 1988-1991	Labour, Load Factor, Purchased Power	Units Delivered, Load Factor, Service Area, No. of Customers	Presence of economies of scale for small and medium utilities and economies of density for different output levels.
(Von Hirschhausen et al., 2006)	DEA, SFA	307 German electricity distribution utilities	Labour, Capital, Network Size, Losses Peak Load	Energy Delivered, Inverse Density Index, Turnover, No. of Customers	The results suggest that returns to scale play but a minor role; only very small utilities have a significant cost advantage. East German utilities feature a higher average efficiency than West German.
(Yatchew, 2000)	Translog Cost Function	Electricity distribution utilities Ontario 1993-95	Total Cost, Network Length, Load Factor, wages	Energy Sales, No. of Customers	The data reveal substantial evidence of increasing returns to scale with minimum efficient scale being achieved by firms with about 20,000 customers. Larger firms exhibit constant or decreasing returns
(Perez-Reyes and Tovar, 2009)	DEA	14 distribution companies in Peru 19962006	No. of Employees, Monetary Value of Capital, Network Length, Distribution Losses, No. of Substations,	Annual Sales of Electricity, Number of Customers	The results indicate show that improvements in efficiency and productivity were higher in the first years following the implementations of the reforms within the sector.
(Nakano and Managi, 2008)	DEA	9 Japanese electricity companies	Employees, Fuel Consumed, Capital Stock	Electricity Produced	The results show that there is a positive effect of regulatory reforms on productivity. This productivity growth is mainly because of technological change.
(Pombo and Taborda, 2006)	DEA	12 electricity distribution companies in Columbia	Employees, No. of Transformers and Substations, Power lines Network	Total Sales, Total Customers	Plant efficiency and productivity increased after de reform, mainly in the largest utilities used as benchmarks in the DEA efficiency scores measures.
(Chunbo et al., 2011)	DEA	26 Chinese Power plants 2000-2008	Generating Capacity, Labour, Fuel Consumption	Electricity Generated	Total Factor Productivity (TFP) growth mainly comes from technological change; the technical efficiency of previously SPC managed power plants is converging to the better-performing independent power producers (IPPs).

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Abbott, 2006)	DEA	Australian State electricity sectors over the period 1969 to 1999.	Capital Stock, Labour, Fuel Materials and Services	Energy Supplied	The results indicate that there in the has been a substantial improvement performance of the industry since the mid-1980s.
(Ramos-Real et al., 2009)		17 Brazilian electricity distribution utilities 1998 to 2005	No. of Employees, Network Length, Power Lost due to Interruptions	Energy Delivered, No of Customers, Service Area	TFP index records a yearly positive growth rate of 1.3% in the whole period under analysis for all firms.
(Cullmann and Von Hirschhausen, 2008*b*)	DEA, SFA	32 Polish electricity distribution companies 1997 and 2002	No. of Workers, Length of Network	No. of Customers, Electricity Distributed, Inverse Density Index	The technical efficiency increased during of the companies has indeed the transition, while allocative efficiency has deteriorated.
(Hjalmarsson and Veiderpass, 1992)	DEA	289 Swedish retail electricity distributors 1970-1976	Hours Worked, LV Power Lines, HV Power Lines, Transformer Capacity	LV Electricity, HV Electricity, LV Customers, HV Customers	The study indicates a high rate of productivity growth, due to economies of density, when measured over the 17 year period.
(Bagdadioglu et al., 1996)	DEA	70 organisations in the Turkish electricity distribution sector	Manpower, Transformer Capacity, Network Size, General Expenses, Network Losses	No. of Customers, Electricity Supplied, Max Demand, Service Area	The early results show better technical and scale efficiency scores for the privately operated distribution organizations.
(Berry, 1994)	Translog Cost Function	169 US rural electric co-operatives and private utilities 1988	Capital, Labour, Fuel, Bulk Power Purchased	Power Sold: Industrial, Wholesale, Residential/ Commercial Customers	The rural electric co-operatives were found to be less efficient than the private electric utilities.
(Estach et al., 2002)	DEA, SFA	39 electricity distribution companies 1994-2000	No. of Employees, Distribution Length, Transformer Capacity	Total Sales, Service Area, Customer Density, Demand Structure, GNP per Capita	The most important result of this paper has been to show that yardstick or benchmark competition organized around measures of technical efficiency is possible, at least in a mild form.
(Mota, 2004)	DEA, SFA	14 private companies Brazil and 72 companies in the US 1994-2000	Operational Costs, Total Operational Costs	Total Sales, No. of Consumers, Kilometres of Distribution lines	The results suggest that capital costs should not be excluded from the benchmarking.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Sanhueza, 2003)	DEA	35 electricity distribution companies in Chile	O & M Costs, Capital Costs, No. of Workers, Remunerations, Not Sold Energy	Total Energy Sold, Max Demand, No. of Customers, Distribution Network	The adoption of the DEA methodology in the efficient firm regulation process gives more transparency.
(Zhang et al., 2002)		36 developing and transitional economies over from 1985-2003	Net Electricity Generation and installed generation capacity per capita of the population	Electricity Generation to Average Capacity	The empirical results presented show consistently that competition in electricity generation is more important than privatization or the establishment of independent regulation in bringing about performance improvements.
(Weyman-Jones, 1991)	DEA	12 public energy distribution companies in England and Wales	Total Value of Company Area Assets, Man-hours, Amount of Main Distributions in Service	Retail Sales to Domestic, Commercial, and Industrial Customers	The study finds only five technically are of the twelve boards are efficient, and that there wide divergences in performance.
(Pahwa et al., 2003)	DEA	50 electric utilities in the US	Distribution Losses, O&M Costs, Capital Expenditure, Transformer Capacity, Distribution Line Length	System Peak Total Sales No. of Customers	The results include performance efficiency, gaps in inputs and outputs of inefficient utilities, sensitivity-based classification of utilities, and a gap report.
(Economics, 1999)	DEA	Electricity distribution in New South Wales	Total O & M Costs, Route Kilometres, Transformer Capacity	Total Energy Delivered, Total Customers, Peak Demand	Productivity growth varied considerably among the NSW distributors over the three-year period from 1995-96 to 1997-98, but was in the order of 2% to 3% per annum on average
(Miliotis, 1992)	DEA, Econometrics	45 electricity distribution of Greek Public Power corporation	Network Length, Capacity of Installed Points, General Expenses, Administrative Labour, Technical Labour	No. of Customers Served, Energy Supplied, Service Area	The results indicate higher efficiency scores in urban areas but this is not supported by the econometric results. Both methods indicate the excess use of labour in less efficient utilities
(Grifell-Tatje and Lovell, 2003*a*)	DEA	9 Spanish distribution utilities 1995	LV Lines, MW Lines, HV Lines, Trans. Capacity HV to MV/LV, Trans. Capacity MV to LV	No. of LV Customers, No. of MV/HV Customers, Service Area, Units Sold, Service Reliability	The comparison of the utilities to ideal efficient model utilities designed by engineers show the ideal firm to be more efficient, on the whole.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Meibodi, 1998)	DEA, SFA	26 electricity distribution utilities 1995	No. of Employees, Labour, Network size, Transformer Capacity, Generating Capacity,	Sales Residential, Sales Industrial, No. of Residential Customers, No. of Industrial Customers	The empirical evidence suggests that public ownership of electricity production might have an adverse effect on technical efficiency.
(Tsutsui and Goto, 2009)	DEA	90 power companies in the US	Operation & Maintenance Costs Purchased Power Expenses	Electric Power Sales to Final Customers	Results reveal that the power generation divisions of the companies studied have significant influence on the overall cost.
(Hattori et al., 2005)	DEA, SFA	21 utilities, 12 UK regional electricity distribution companies and 9 Japanese electricity utilities 1985 and 1998	Total Expenditure	No. of Customers, Electricity Units Delivered Customer Density, Load Factor	The results suggest that the productivity gain in the UK electricity distribution has been larger than in the Japanese sector.
(Yunos and Hawdon, 1997)	DEA	27 distribution utilities Malaysia, Thailand and UK	Installed Capacity, Labour, Losses, Generation Capacity Factor	Gross Electricity Production	Evidence suggests that changes in the organization of electricity generation can be justified on efficiency grounds.
(Whiteman, 1995)	DEA	85 electricity systems in developing countries	Labour, Thermal Power, Hydropower, Nuclear Power, Other Generation	Electricity Output	Book
(Edvardsen and Forsund, 2003)	DEA	122 electricity distribution utilities from Denmark, Finland, Norway, Sweden and the Netherlands 1997	Total O & M Costs, Energy Lost due to Interruptions, Power Lines Network, Replacement Value	Number of Customers, Energy Delivered	The results point to Finland as the most productive country within the common technology.
(IPART, 1999)	DEA	219 Australian, New Zealand, UK, US distribution utilities 1995-1998	OPEX, Network Size, Transformer Capacity	Electricity Delivered, No. of Customers, Peak Demand,	The NSW utilities were, after adjustment of efficiency scores for the effect of environmental factors between 13 nd 14% less efficient than frontier firms.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Zhang and Bartels, 1998)	DEA, Monte Carlo Simulation	32 Australian power authorities, 51 New Zealand power boards, 173 discos in Sweden	No of Employees, Distribution Lines, Transformer Capacity	Total Number of Customers Served	Simulation results show that as sample size increases the estimated mean technical efficiencies decrease generally.
(Lo et al., 2001)	DEA	24 electricity distribution districts in Taiwan	Employment Expenditure, General Expenditure, Total Asset, Distribution Network, Transformer Capacity	Number of Customers, Energy Supplied	The empirical study showed that the TPC districts have good overall efficiency. Most of the inefficient districts suffer from scale inefficiency to a greater degree than technical inefficiency.
(Chien et al., 2003)	DEA	17 service centres involved in electricity distribution in Taiwan	No. of Staff, General Equipment,	No. of Customer, Distribution Length, Transformer Capacity	The results showed that the proposed reorganization alternatives have better efficiency scores.
(Jha et al., n.d.)	DEA	57 distribution centres in Nepal 2004-2005	Annual O & M, Transformer Capacity, Feeder Length, No. of Employees, Distribution Losses	Annual Energy Sales, Number of Customers	The analysis does not necessarily require a multi-period data set of DCs to have a proper discrimination in the results.
(Yang and Lu, 2006)	DEA	24 electricity distribution districts in Taiwan 2003	Employment Expenditure, Operating Expenditure, Distribution Length, Transformer Capacity	No. of Customers, Energy Sold, Energy Loss Rate	The findings indicate EDDs covering the high-tech industry park, on average, are more efficient than ones with no high-tech industry park. EDDs located in urban areas outperform those located in rural areas.
(Chen, 2002)	DEA	22 distribution districts in Taiwan	Labour, Capital, General Expenses	Energy Supplied, No. of Customers, HV Customers, LV Customers	The results benefit resource managers and administrators within the districts for cost management in the competitive electricity market.

Authors and Year	Models Employed	Sample Data	(I)Inputs	(O)Outputs	Contribution
(Bjorndal et al., 2008)	DEA	Norwegian electricity distribution companies 2008	Cottage Customers, HV Lines, Network Stations, Interface	Energy, Customers, Forest, Snow, Coast	Findings show that the two-sidedness of the weight restrictions and the large number of them, involving a large share of the output variables, may have unintended effects on the efficiency scores.
(Santos et al., 2010)	DEA	14 Portuguese electricity distribution companies 2002-2006	Operating Cost, Network Length, Transformer Capacity	Electricity Delivered, Total Interruption Time	The paper provides recommendations regarding the successful application of DEA for Performance improvement.
(Weyman-Jones, 1995)	DEA	UK electricity distribution	No. of Employees, Network Length, Transformer Capacity,	Residential, Commercial and Industrial Sales, Max Demand, Number of Clients, Network Length, Transformer Capacity, Total Sales, Population Density, Industrial Sales as proportion to Total Sales	Book
(Yu et al., 2009)	DEA	12 distribution networks in the UK	Customer Minutes, Operating Expenditure, Total Expenditure	Number of Customers, Energy Delivered	The results indicate that weather factors often do not have a significant economic and statistical effect on the overall performance of the utilities.
(Hattori et al., 2003)	DE, SFA	21 distribution companies - 12 from UK and 9 from Japan	Total Costs, Operating Costs, Density, Load Factor	Energy Sales, No. of Customers	The results suggest that productivity gain in the the UK electricity distribution has been larger than in the Japanese sector.
(Agrell et al., 2005)	DEA	238 electricity distribution concessions in Sweden	Operating Expenditure, Capital Expenditure, Net Losses	Peak Load, HV, LV Connections, Energy Delivered HV, LV, Climate Zone, Network Length	The findings contribute to the theoretical unification between firm-based DEA productivity models and micro-economic reimbursement theories.

APPENDIX B

Chapter Five - Data Sources and Models

B.1 Transmission System Characteristics

Transmission Lines		Transmission Stations	
	(km)		
400kV Overhead Lines	433	400kV Stations	4
400kV Underground Cables	2	220kV Stations	21
220kV + 275kV Overhead Lines	1,817	110kV Stations	31
220kV + 275kV Underground Cables	125	400/220kV Transformers	5
110kV Overhead Lines	4,654	275/220kV Transformers	3
110kV Underground Cables	433	220/110kV Transformers	44

B.2 Distribution System Characteristics

Subtransmission		Medium & Low Voltage	
220 kV S/Stns & 110kV Networks		**MV Networks**	**(km)**
220/110kV Stations	3	20kV Overhead - 3 phase	12,100
220/110kV transformer Capacity (MVA)	2,000	20kV Overhead - 1 phase	24,700
110kV Lines (km)	402	10kV Overhead - 3 phase Stations	14,900
110kV Cables (KM)	136	10kV Overhead - 1 phase	30,500
110kV Substations		20kV Cable	565
110/38kV	82	10 KV Cables	8523
110/MV	25	**MV/LV S/stns**	
110/38kV Transformer Capacity (MVA)	5,725	Pole mounted - 3 phase	19,206
110/MV Transformer Capacity (MVA)	1,130	Pole mounted - 1 phase	19,206
38kV Network		Ground Mounted	19,458
Overhead	5,666	**LV Network**	**(km)**
Cables	836	Overhead - 3ph	4,100
38kV S/Stns		Overhead - 1ph	53,000
No. of Stations	433	LV Cables	12,100
Transformer Capacity (MVA)	4,781	LV Minipillars	157,000

B.3 Names, locations and prevailing wind direction in Ireland from 1946-2010

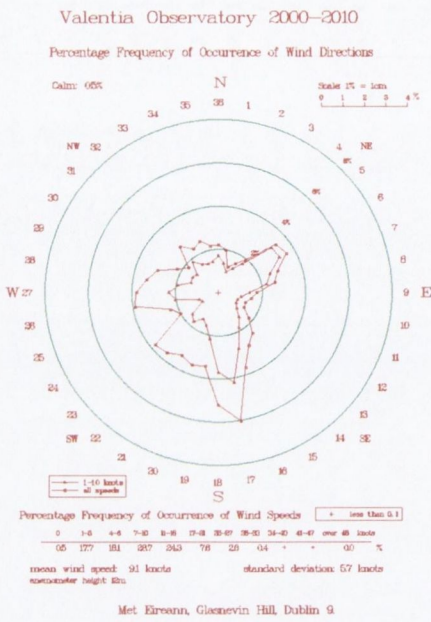


Fig. B.1: Valentia Wind Rose

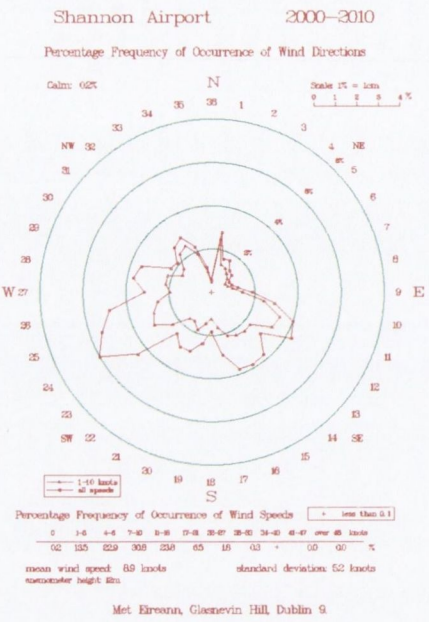


Fig. B.2: Shannon Wind Rose

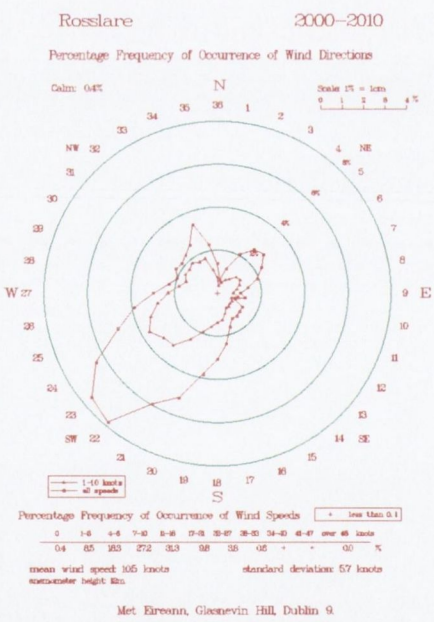


Fig. B.3: Rosslare Wind Rose

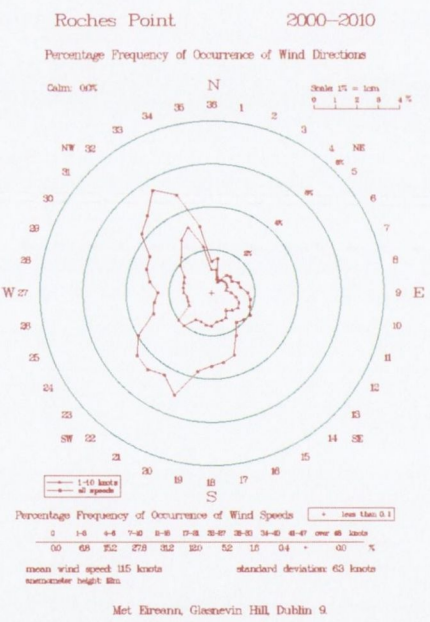


Fig. B.4: Roches Point Wind Rose

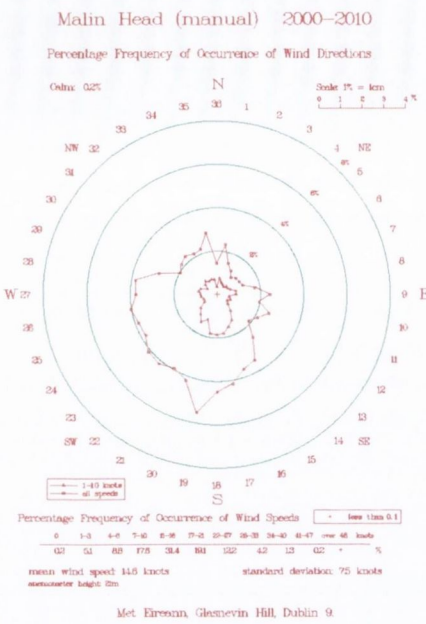


Fig. B.5: Malin Wind Rose

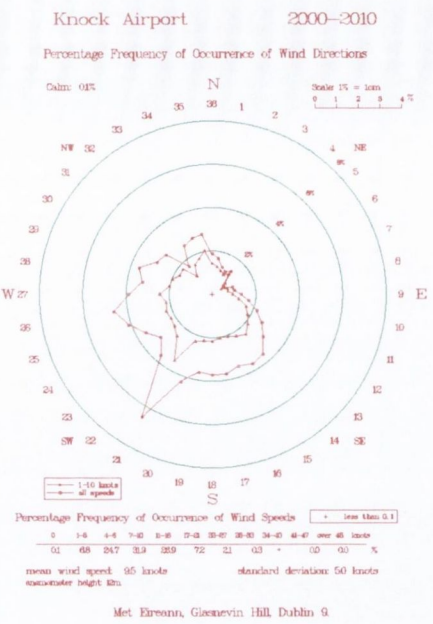


Fig. B.6: Knock Wind Rose

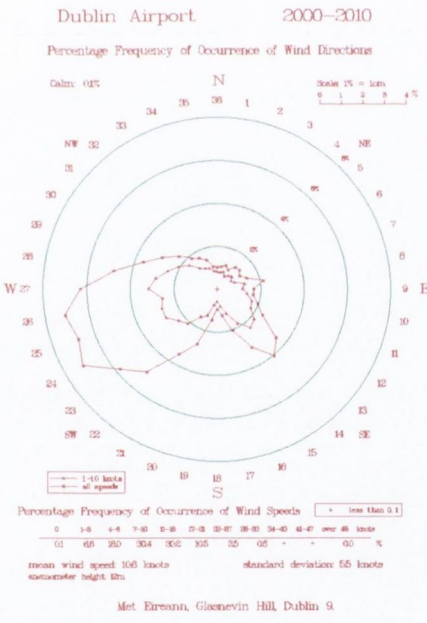


Fig. B.7: Dublin Airport Wind Rose

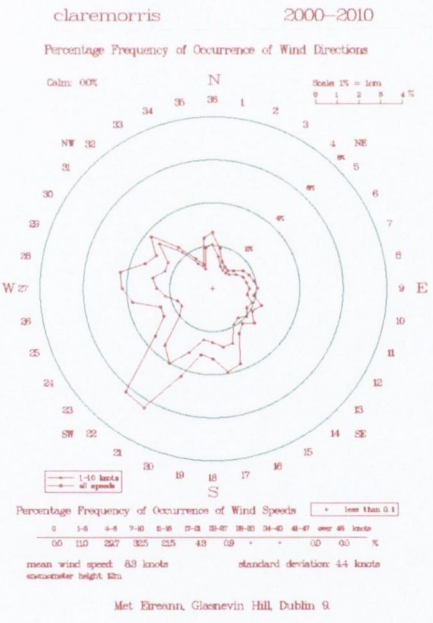


Fig. B.8: Claremorris Wind Rose

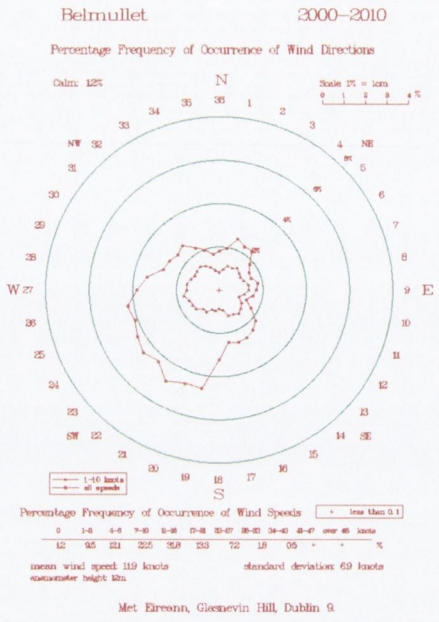


Fig. B.9: Belmullet Wind Rose

B.4 Application of DEA-Solver Pro Process

Once the data file in an Excel worksheet on an Excel workbook has been created. One must save the file and click open the "DEA-Solver Pro" explorer icon This begins DEA-Solver, then follow the following instructions on display otherwise if the file "DEA-Solver Pro" is not already open (loaded), click "Options" on the menu bar then select "Macro" and "enable this content" and the displaying Figure B.10 should appear.



Fig. B.10: DEA-Solver Start Up Screen

The DEA-Solver Pro proceeds with the following four procedural steps Figure B.11:

1. **Selection of DEA model**;
2. **Selection of a data set in Excel Worksheet**;
3. **Selection of a workbook for saving the results of efficiency computation and**;
4. **DEA computation**;

Figures B.11 and B.12 illustrates the procedure and model selection screen.

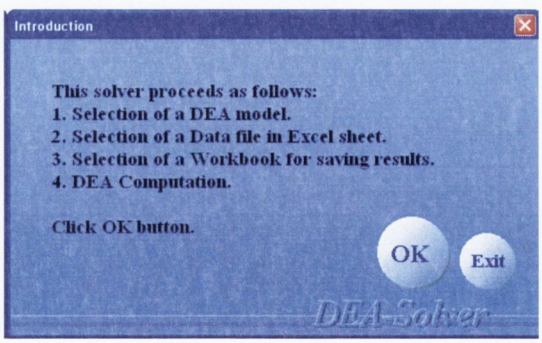


Fig. B.11: DEA-Solver Procedure Screen

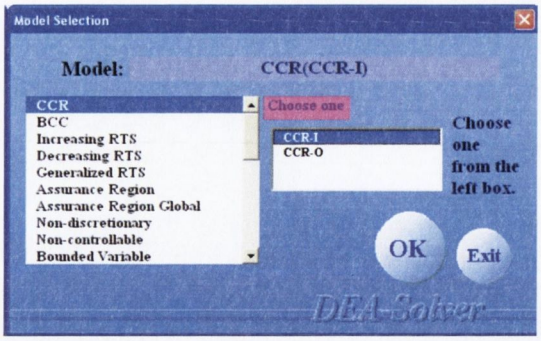


Fig. B.12: DEA-Solver Model Selection Screen

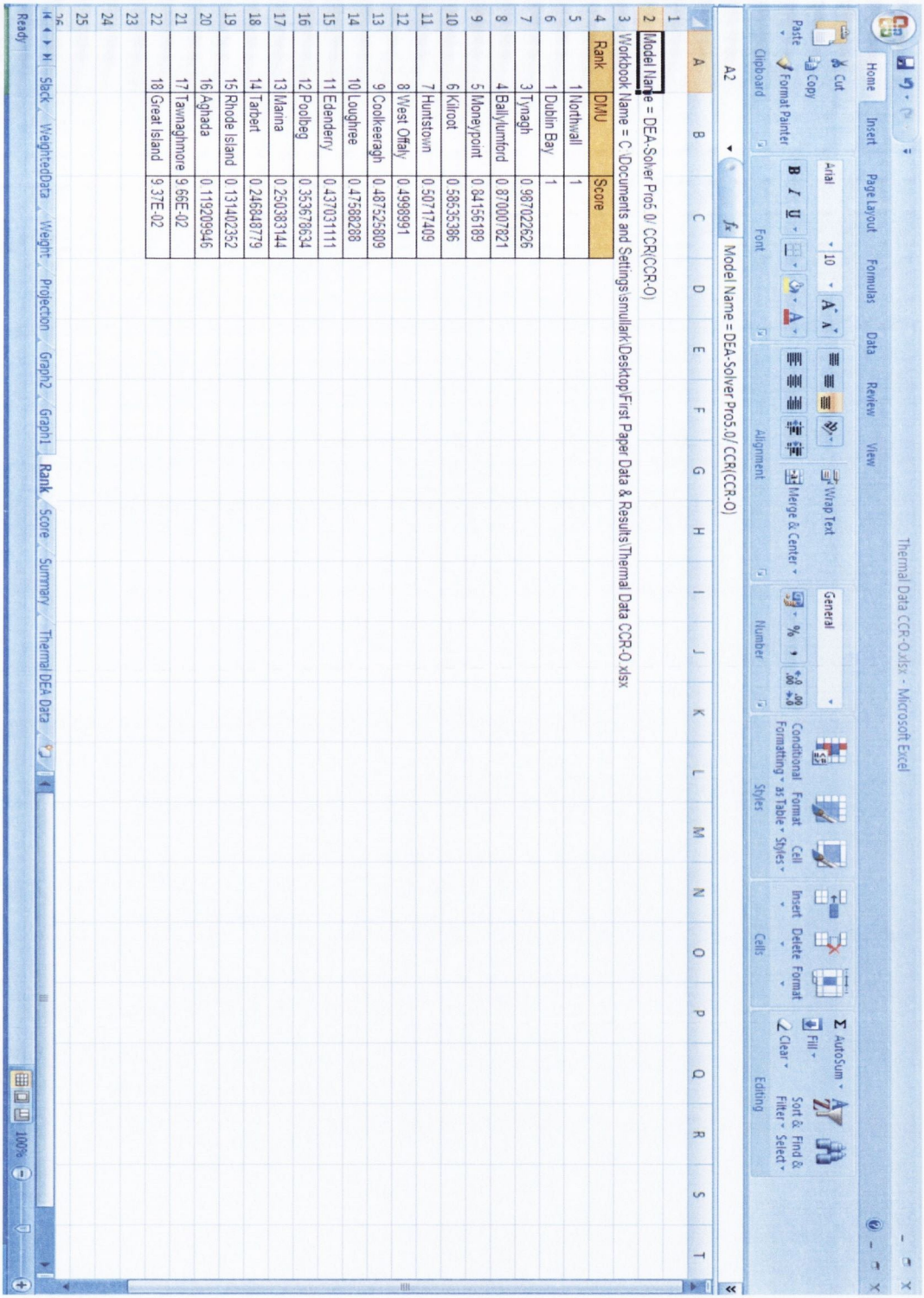


Fig. B.13: DEA-Solver Pro Results Workbook

The results of computation are stored in the selected Excel workbook (e.g. Figure B.13). The following worksheets contain the results of the efficiency analysis, although some models do

not have all of the following:

1. **Worksheet "Summary"**:
   This worksheet gives an overview of the model run (i.e. type of DEA model, inputs/outputs) and also displays statistics concerning the data.

2. **Worksheet "Score"**:
   This worksheet contains the DEA efficiency scores obtained by each DMU evaluated, and also the ranking reference set and lambda value of each DMU in the reference set.

3. **Worksheet "Rank"**:
   This simply displays the rank and efficiency score of each DMU in descending order/

4. **Worksheet "Projection"**:
   This worksheet illustrates the necessary adjustments needed for each DMU to be projected onto the efficiency frontier (i.e. the changes in inputs and outputs needed to make the DMU efficient).

5. **Worksheet "Weight"**:
   Outlines the optimal weights applied to $v(i)$ and $u(i)$ for inputs and outputs.

6. **Worksheet "Weighted Data"**:
   Displays the optimal weighted input/output values for the DEA model. (i.e. the original input/output data values multiplied by the optimal weights prescribed by DEA outlined in the "Weight" worksheet).

7. **Worksheet "Slacks"**:
   Illustrates the input excesses s^- and output shortfalls s^+ for each DMU (i.e. how much excess input/output is available that is not required)

8. **GraphSheets "Graph 1 and 2"**:
   These two worksheets illustrate the DEA efficiency scores in graphical form. "Graph 1" displays the scores of the DMUs in the order the were entered in the data file whereas "Graph 2" displays the scores in ascending order. These two graphs can be altered and redesigned by employing the graphic functions of Excel.

APPENDIX C

Chapter Six - Results and Evaluation of Efficiency Analysis

C.1 Sensitivity Analysis and Model Validation for National Wind Models

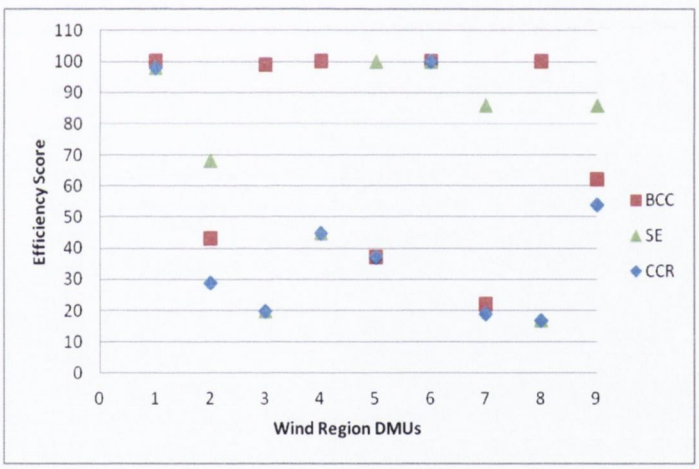


Fig. C.1: Base Case Wind Regions

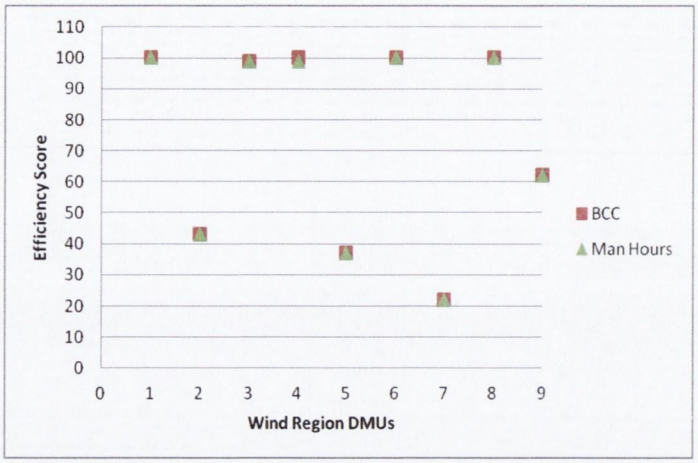


Fig. C.2: Man Hours Wind Regions Omitted

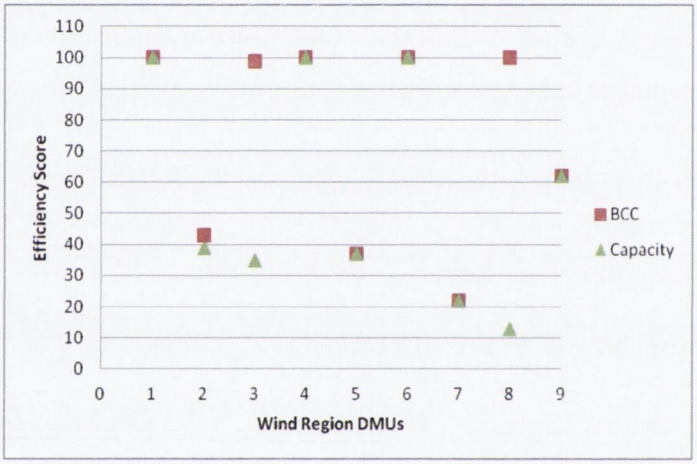


Fig. C.3: Installed Capacity of Wind Regions Omitted

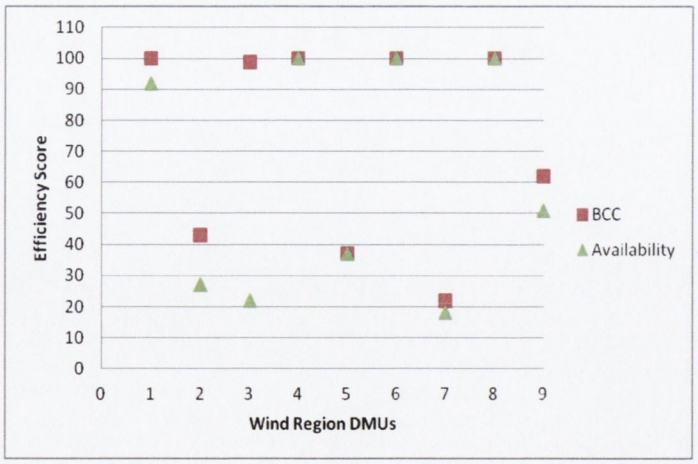


Fig. C.4: Availability Wind Regions Omitted

Table. C.1: Sensitivity Analysis of Wind Region Parameters

No.	Wind Regions	(PTE) BCC ϕ	Full Time Man Hours Omitted	Unit Rate Export Capacity Omitted	Wind Availability Omitted	Status
1	Region A	1	1	1	0.92	Robustly Eff.
2	Region B	0.43	0.43	0.39	0.27	Distinctly Ineff.
3	Region C	0.99	0.99	0.35	0.22	Significantly Ineff.
4	Region D	1	0.99	1	1	Robustly Eff.
5	Region E	0.37	0.37	0.37	0.37	Distinctly Ineff.
6	Region F	1	1	1	1	Robustly Eff.
7	Region G	0.22	0.22	0.13	1	Distinctly Ineff.
8	Region H	1	1	0.13	1	Marginally Eff.
9	Region I	0.62	0.62	0.62	0.51	Distinctly Ineff.

Note: Ineff. - Inefficient Eff. - Efficient

Table. C.2: Pearson Correlation Matrix for Wind Data

		Input 1 (I) Full Time Man Hours (O&M)	Input 2 (I) Unit Rate Export Capacity (MW)	Input 3 (I) Wind Availability (%)	Output 1 (O) Annual Production (MWh)
Full Time Man Hours	Pearson Correlation	1	.791*	.257	.470
	Sig. (2-tailed)		.011	.504	.201
	N	9	9	9	9
Unit Rate Export Capacity (MW)	Pearson Correlation	.791*	1	.367	.325
	Sig. (2-tailed)	.011		.331	.393
	N	9	9	9	9
Wind Availability (%)	Pearson Correlation	.257	.367	1	.402
	Sig. (2-tailed)	.504	.331		.284
	N	9	9	9	9
Annual Production (MWh)	Pearson Correlation	.470	.325	.402	1
	Sig. (2-tailed)	.201	.393	.284	
	N	9	9	9	9

Note: * Denotes Correlation is Significant at the 0.05 level

C.2 Sensitivity Analysis and Model Validation for National Hydro Models

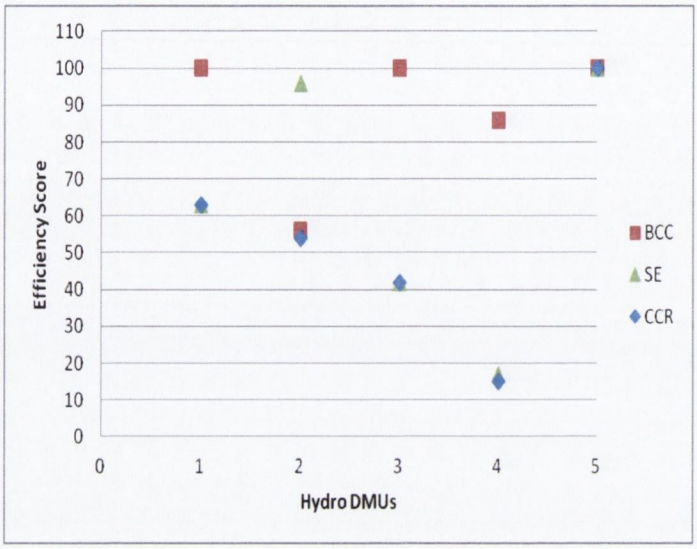


Fig. C.5: Base Case Hydro

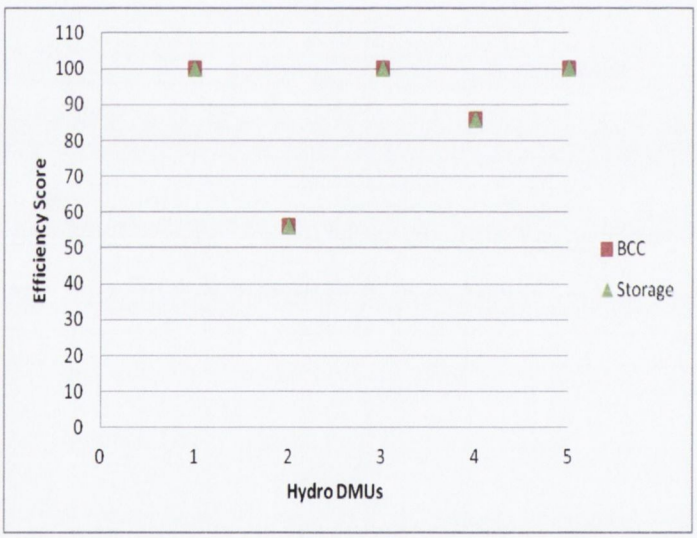


Fig. C.6: Storage Capacity Omitted

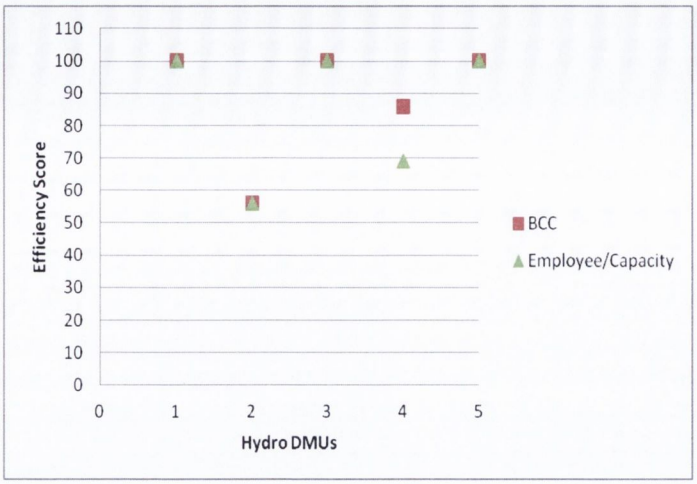


Fig. C.7: Employee/Unit Rate Export Capacity Omitted

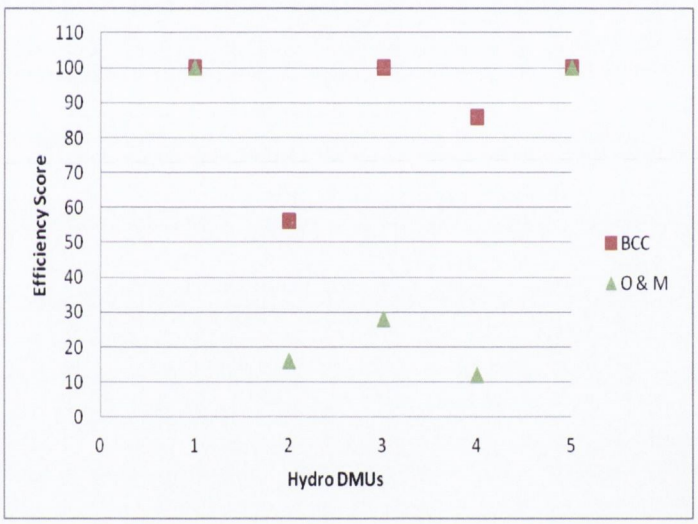


Fig. C.8: Operation and Maintenance Omitted

Table. C.3: Sensitivity Analysis of Hydro Parameters

No.	Hydro	(PTE) BCC ϕ	Storage Capacity Omitted	Employees/Unit Rate Export Capacity Omitted	O & M Omitted	Status
1	Ardnacrusha	1	1	1	1	Robustly Eff.
2	Erne	0.56	0.56	0.56	0.16	Distinctly Ineff.
3	Lee	1	1	1	0.28	Marginally Eff.
4	Liffey	0.86	0.86	0.69	0.12	Distinctly Ineff.
5	Turlough Hill	1	1	1	1	Robustly Eff.

Note: Ineff. - Inefficient Eff. - Efficient

Table. C.4: Pearson Correlation Matrix for Hydro Data

		Input 1 (I) Storage Capacity (MWh)	**Input 2** (I) Employee/ Export Capacity	**Input 3** (I) O & M Unit Rate (%)	**Output 1** (O) Annual Production (€/MW/yr)
Storage	Pearson Correlation	1	.221*	.153	.192
Capacity	Sig. (2-tailed)		.360	.403	.378
(MWh)	N	5	5	5	5
Employee/	Pearson Correlation	.221	1	.073	.432
Unit Rate	Sig. (2-tailed)	.360		.454	.234
Export Capacity	N	5	5	5	5
O & M	Pearson Correlation	.153	.073	1	.918*
	Sig. (2-tailed)	.403	.454		.014
(€/MW/yr)	N	5	5	5	5
Annual	Pearson Correlation	.192	.434	.918*	1
Production	Sig. (2-tailed)	.378	.234	.014	
(MWh)	N	5	5	5	5

Note: * Denotes Correlation is Significant at the 0.05 level