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Empirical Analysis and Improved Modelling of Natural Gas Demand in Ireland

Fionn Rogan BE MEngSc

Thesis submitted for the degree of Doctor of Philosophy
to the National University of Ireland, Cork

January 2013

Supervisor: Dr. Brian Ó Gallachóir
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Declaration

I hereby declare that this thesis is my own work and that it has not been submitted for another degree, either at University College Cork, or elsewhere. Where other sources of information have been used, they have been acknowledged.

Signature: ………………………………………….

Date: ……………………………………………………

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Executive Summary

Countries across the world are being challenged to decarbonise their energy systems in response to diminishing fossil fuel reserves, rising GHG emissions and the dangerous threat of climate change. There has been a renewed interest in energy efficiency, renewable energy and low carbon energy as policy-makers seek to identify and put in place the most robust sustainable energy system that can address this challenge. This thesis seeks to improve the evidence base underpinning energy policy decisions in Ireland with a particular focus on natural gas, which in 2011 grew to have a 30% share of Ireland's TPER. Natural gas is used in all sectors of the Irish economy and is seen by many as a transition fuel to a low-carbon energy system; it is also a uniquely excellent source of data for many aspects of energy consumption. A detailed decomposition analysis of natural gas consumption in the residential sector quantifies many of the structural drives of change, with activity ($R^2 = 0.97$) and intensity ($R^2 = 0.69$) being the best explainers of changing gas demand. The 2002 residential building regulations are subject to an ex-post evaluation, which using empirical data finds a 44 ±9.5% shortfall in expected energy savings as well as a 13±1.6% level of non-compliance. A detailed energy demand model of the entire Irish energy system is presented together with scenario analysis of a large number of energy efficiency policies, which show an aggregate reduction in TFC of 8.9% compared to a reference scenario. The role for natural gas as a transition fuel over a long time horizon (2005-2050) is analysed using an energy systems model and a decomposition analysis, which shows the contribution of fuel switching to natural gas to be worth 12 percentage points of an overall 80% reduction in CO_2 emissions. Finally, an analysis of the potential for CCS in Ireland finds gas CCS to be more robust than coal CCS for changes in fuel prices, capital costs and emissions reduction and the cost optimal location for a gas CCS plant in Ireland is found to be in Cork with sequestration in the depleted gas field of Kinsale.

Thesis Outputs

Journal papers

Rogan, F., Cahill, C.J., Gallachóir, B.P.Ó., (2012). Decomposition analysis of gas consumption in the residential sector in Ireland. *Energy Policy 42*, 19–36.

Rogan F. & Ó Gallachóir, B.P. Building Regulations – How Effective Are They At Delivering Energy Efficiency? (2012) *Energy Policy,* In review, submitted on May 28th 2012

Rogan, F, Cahill, C.J., Daly, H.E., Deane, J.P., Dineen, D., Heaps, C. & Ó Gallachóir, B.P., (2012), 'LEAPs and Bounds – A Hybrid Energy Demand and Constraint Optimization Model of the Irish Energy System' *Energy Efficiency,* In review, submitted on November 1st 2012

Chiodi, A., Gargiulo, M., Rogan, F., Deane, J.P., Lavigne, D., Rout, U.K., Gallachóir, B.P.Ó., (2012). Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system. *Energy Policy* 1–21.

Dineen D., Rogan F., Ó Gallachóir B.P. (2012) One energy efficiency programme but a range of possible energy savings. (In preparation)

Conference proceedings and presentations

Rogan, F., Gallachoir, B.O., (2011). Ex-post evaluation of a residential energy efficiency policy measure using empirical data. *Proceedings of the eceee (European Council for an Energy Efficient Economy) 2011 Summer Study,* 1769–1778. 6 – 11th June 2011, Belambra Presqu'île de Giens, France

Rogan, F., Cahill, C.J., Gallachóir, B.P.Ó Decomposition analysis of gas consumption in the residential sector in Ireland. (2010) *Proceedings of 9th YEEES* (Young Energy Economists and Engineers Seminar), November 26 – 27th 2010, Trinity College Dublin

Dineen D., Rogan F., Cronin W. and Ó Gallachóir B. P. (2011) Modelling residential energy savings due to Ireland's National Retrofit Programme using DEAP and LEAP. *Proceedings of IEW (International Energy Workshop) 2011,* July 6 -9th 2011, Stanford University, CA

Dineen D., Rogan F. and Ó Gallachóir, B. P. (2010) Bottom up modelling of energy savings due to the National Retrofit Programme for Ireland's Housing Stock *Proceedings of 9th YEEES (Young Energy Economists and Engineers Seminar)* November 26 – 27th 2010, Trinity College Dublin

Invited talks

Rogan F., Deane J.P., Cahill C., Dineen D, Daly H., Whyte K. and Ó Gallachóir B.P. (2011) LEAP OSeMOSYS Ireland. *Proceedings of IEW (International Energy Workshop) 2011,* Special Session on OSeMOSYS, July 9th 2011, Stanford University, CA

Rogan F. & Ó Gallachóir, B.P. (2011) Quantifying the Impact of 2002 Building Regulations. DIT Energy and Emissions Seminar, April 8th 2011, Dublin Institute of Technology, Dublin

Rogan F. & Ó Gallachóir, B.P. The Future of Gas in Ireland: A Perspective From Irish TIMES (2012) *UCC BGE Seminar.* November 13th 2012. Bord Gais Energy, Cork

Rogan F. & Ó Gallachóir, B.P. Building Regulations – How Effective Are They At Delivering Energy Efficiency?(2012) *ESRI UCC Energy Modelling Research Seminar: Informing Policy, Economic and Engineering Perspectives*, June 11th 2012, Economic and Social Research Institute, Dublin

Reports and submissions

Daly, H.E., Dineen, D., Rogan, F., Cahill, C. (2011) 'Bottom-Up Energy Demand Modelling - LEAP Ireland.' *Energy Forecasts for Ireland to 2020, 2010 Report*, Sustainable Energy Authority of Ireland, Dublin

Ó Gallachóir B.P., Deane J.P., and Rogan F. (2011) Irish Energy Policy UCC ERI Perspective. *Presentation to IEA Policy Review*, Sept 28th 2011, Department of Communications, Energy and Natural Resources, Dublin

Rogan F. (2012) Draft Building Control (Amendment) Regulations 2012, *Submission to Department of the Environment, Community and Local Government*, 24th May 2012

Units and abbreviations

BER	Building Energy Rating
BGE	Bord Gáis Energy
BGÉ	Bord Gáis Éireann
BGN	Bord Gáis Networks
BR	Building Regulations
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gasification Turbine
CCS	Carbon Capture and Storage
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalent
CSO	Central Statistics Office
DEAP	Dwelling Energy Assessment Procedure
DECLG	Department of Environment, Community and Local Government (formerly DEHLG)
DEHLG	Department of Environment, Housing and Local Government
DCENR	Department of Communications Energy and Natural Resources
DSM	Demand Side Management
EC	European Commission
eceee	European Council for an Energy Efficient Economy
EFOM	Energy Flow Optimization Model
EMEEES	Evaluation and Monitoring for the EU Directive on Energy End-Use Efficiency and Energy Services
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
ESD	Energy Services Directive
ESRI	Economic and Social Research Institute

ETP	Energy Technology Perspectives
ETS	Emissions Trading Scheme
ETSAP	Energy Technology Systems Analysis Program
EU	European Union
EV	Electric Vehicles
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GWh	Gigawatt Hours
GVA	Gross Value Added
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
INSHQ	Irish National Survey of Housing Quality
IPMVP	International Performance Measurement and Verification Protocol
ISSDA	Irish Social Science Data Archive
Kt	Kilo tonne
ktoe	Kilo tonne of oil equivalent
LCOE	Levelized Cost of Electricity
LEAP	Long Range Alternatives Planning System
LMDI	Log Mean Divisia Index
LNG	Liquefied Natural Gas
MARKAL	Market Allocation
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MJ	Megajoules
MPRN	Meter Point Reference Number
MRCI	Mean Rate of Change Index
Mt	Mega tonne

Mtoe	Mega tonne of oil equivalent
MURE	Mesures d'Utilisation Rationnelle de l'Energie
MW	Megawatt
NCCS	National Climate Change Strategy
NEEAP	National Energy Efficiency Action Plan
O&M	Operation & Maintenance
OSeMOSYS	Open Source Energy Modeling System
PC	Pulverized Coal
PET	Pan-European TIMES
PJ	Petajoules
RES-E	Renewable Energy Source - Electricity
RES-H	Renewable Energy Source - Heat
RES-T	Renewable Energy Source - Transport
SEAI	Sustainable Energy Authority of Ireland
TIMES	The Integrated MARKAL-EFOM System
TFC	Total Final Consumption
TGD	Technical Guidance Document
TPER	Total Primary Energy Requirement
TWh	Terawatt Hours

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1 Introduction

1.1 Background

The successes of industrialization have wrought the threat of human induced climate change upon the world. Decades of growing greenhouse gas (GHG) emissions have led to Carbon Dioxide equivalent (CO_2eq) concentrations in the atmosphere of 379 parts per million (ppm), nearly 100 ppm above pre-industrial levels. The impact in the past 100 years on global average temperature has been a rise of 0.74 degrees (Celsius)(Pachauri, 2007) and the world is now on a pathway where global temperatures could rise by 4.5-6.1 degrees by 2090 (Barker et al., 2007). This would have catastrophic implications for a majority of the world's population and in the Copenhagen Accord, the nations of the world agreed in principle to preserve GHG atmospheric concentrations at 450 ppm CO_2eq in order to limit global temperature increase to 2 degrees (UNFCCC, 2009). Although a successor to the Kyoto protocol comes into effect from January 1st 2013 (UNFCCC, 2012), it is without the participation of some the largest emitting countries[1].

CO_2 emissions from fossil fuel combustion in the energy sector have been the single largest contributor to GHG atmospheric concentrations, with fossil fuels accounting for 56.6% of global GHG emissions in 2004 (Barker et al., 2007). While all countries of the world are now engaged, to a greater or lesser degree, in climate change mitigation efforts to decarbonise their energy systems, the investment to-date has not been sufficient to put the world on a pathway of an increase in global temperature of no more than 2 degrees (IEA, 2012a). There are a plethora of technical solutions along the full energy supply chain from resource extraction, to fuel refining, to power generation and to energy end-use. A sustainable energy system is one that can meet the climate change mitigation requirements of being low carbon and that also satisfies the economic criteria of affordability. This goal has given rise to an increased level of analysis of the best combination of energy efficiency, renewable energy and low-carbon energy as policy makers seek to put in place an optimum energy mix in response to the climate change challenge (EC,

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[1] http://unfccc.int/kyoto_protocol/status_of_ratification/items/2613.php

2006). In this context, the vital role for evidence based analysis and techno-economic modelling of the full costs and implications of all potential energy solutions becomes clear.

The challenge to respond to climate change affects Ireland as much as any other country and Ireland, like many others, is grappling with the challenges of moving towards a sustainable energy system. While Ireland is in global terms, a very small contributor[2] to energy related GHG emissions, Ireland's per capita GHG emission intensity (approximately 14 t/capita in 2010) is one of the highest in Europe (EPA, 2012). Within the context of many European Union (EU) wide energy targets, Ireland has exhibited considerable leadership in the ambition of many of its policies and targets: Ireland already has the highest penetration of wind electricity in a single synchronous grid in the world (EirGrid et al., 2010) and it has targets to have 40% renewable electricity by 2020 (Clancy and Scheer, 2011). In the past two decades, Ireland has also deployed an increasing number of energy efficiency policies (DCENR, 2009) and while some of these policies have been successful (Rogan et al., 2011), many have not been sufficiently measured and verified for the true overall success rate of energy efficiency policy in Ireland to be evaluated. There have been a number of calls for more ex-post analysis of past energy consumption trends and historical performance of energy policies (Jacobsen and Kotchen, 2009; Koeppel and Ürge-Vorsatz, 2007; Hull et al., 2009), which are crucial for gaining an understanding of which energy policies work, or what needs to be changed, in order for these energy policies to become successful.

In the medium-term (2020), Ireland has committed to renewable energy source (RES) targets for the electricity (RES-E, 40%), transport (RES-T, 10%) and heat (RES-H, 12%) energy markets. While the RES-E targets are well supported by policy instruments, the same cannot be said for RES-T and RES-H targets, which to-date have been somewhat neglected in Irish energy policy. In the longer term (2050), Ireland has no energy policies or targets, but is currently finalizing a pathway for long terms emissions reduction (O'Donnell et al., 2012). The scope for bottom-up techno-economic modelling to inform both medium-term and long-term energy pathways is growing more apparent as the scale of the decarbonization challenge becomes more clear. A large amount of the energy modelling that

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[2] 0.14%

currently informs energy policy in Ireland is undertaken from an econometric perspective. While wholly suitable for modelling economic activity, in terms of modelling technology based energy measures and policies, the econometric approach has limitations. As the level of technical change in the energy system become more acute, there is a greater imperative for techno-economic modelling which is better equipped to model the structural step changes effected by energy efficiency and new energy technologies.

Ireland currently imports 88% of its energy requirement (Howley et al., 2012), raising concerns regarding future energy security. This thesis seeks to inform Ireland's response to these challenges. It presents both empirical analysis and techno-economic modelling of energy policies and technologies in Ireland. It provides an ex-post analysis of a key energy efficiency policy; a methodology for medium-term modelling of the combined impact of a number of energy efficiency policies and measures; a long-term analysis of the role of natural gas as a transition fuel to a low-carbon energy system; and an in-depth analysis of a key low-carbon technology: carbon, capture and storage (CCS). A visual summary of the thesis is shown in Figure 1-1

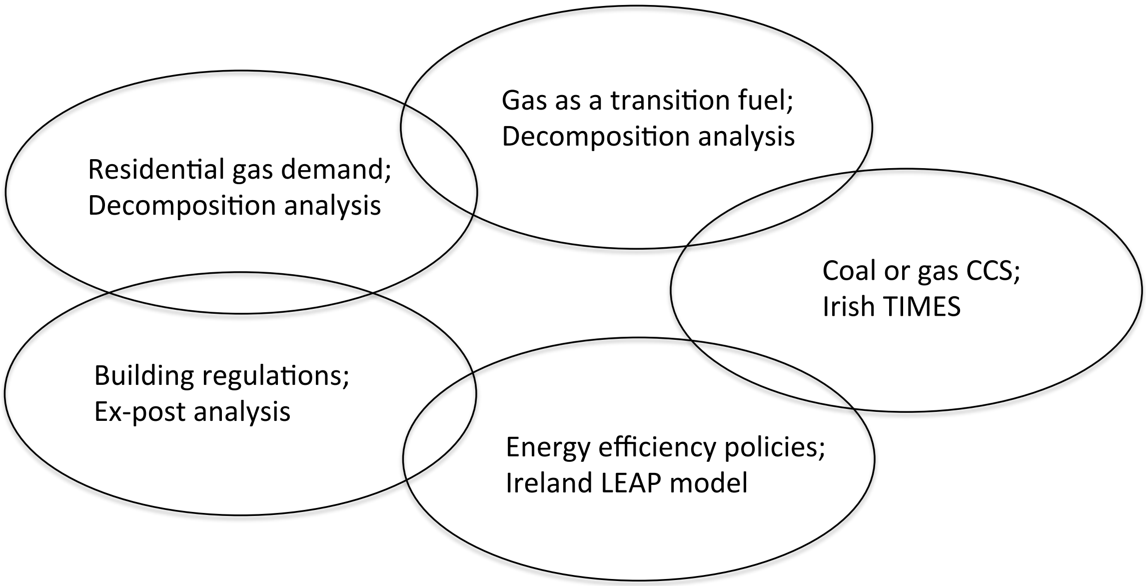

Figure 1-1 Thesis overview

This thesis has a particular focus on natural gas demand. In the past two decades in Ireland, natural gas total primary energy requirement (TPER) has grown at 5.1% per annum to become a fuel with the second (to oil) largest share (30%) in Ireland. In each sector of the economy, except for the transport sector, natural gas either has the largest share or second largest share of total final consumption (TFC). Over time, as natural gas has displaced coal and oil in the electricity, residential and commercial sectors, it has contributed to emissions reduction in Ireland (Howley et al., 2011). Natural gas currently has a key role in Ireland's energy system and in the medium term is expected to remain so, particularly since it has the lowest emissions of all fossil fuels, and is seen by many as a transition fuel to a low-carbon energy system (Baroni, 2010). Data on natural gas consumption, particularly in the residential sector is excellent (Cleirigh, 2008) and this provides an opportunity to analyse in-depth not only natural gas consumption trends, but also energy consumption trends that natural gas data gives a unique window into. In addition, there is an opportunity to use natural gas consumption data to analyse energy policies that would not otherwise be accessible to analysis.

1.2 Methodology

This thesis uses empirical analysis and techno-economic energy modelling to analyse in-depth aspects of Ireland's sustainable energy challenge. It focuses on natural gas demand and in some respect, on problems unique to natural gas, but it also uses natural gas consumption data to gain insights to consumption trends of all fuels. This section gives a brief outline of the methodologies used in this thesis, which uses a combination of modified existing methodologies and newly developed unique methodologies.

1.2.1 Empirical analysis

The importance of empirical analysis is that it is based on actual real-world data. Prior to their implementation, most energy policies will be subject to an ex-ante analysis in order to examine their potential impact; however, ex-post analysis of energy policies and energy consumption are essential for the success of the policy and the continuous improvement of future energy policy. In this thesis, decomposition analysis is used to quantify the impact of various drivers on changing energy consumption and changing CO_2 emissions. The methodology is applied to historic trends of natural gas demand in the residential sector and to changing CO_2 emission pathways in a long-term energy optimization model. Statistical analysis of metered gas consumption data is also employed together with modelling simulation of building energy rating data to conduct an ex-post analysis on the impacts of an important residential energy efficiency policy: building regulations.

1.2.2 Bottom-up techno-economic modelling

In the main, this thesis uses bottom-up techno-economic modelling of energy demand, together with scenario analysis in order to evaluate alternative energy pathways. Bottom-up modelling is the use of detailed energy-use data to model energy demand as it is consumed at the user level (e.g. space heating in terms of kWh/m^2 for a dwelling). It is primarily technical in nature, but incorporates some economic aspects as well: hence the term, techno-economic. Scenario analysis is the generation of a number of future projections of energy demand; their usefulness is not in their accuracy of forecast, but in the differences between the scenarios. Each scenario is typically an examination of either an individual energy technology, energy policy, or energy constraint and the results are presented in terms of performance relative to a reference scenario, which generally represents a baseline or continuation of current trends. Scenario analysis presents a range for future energy consumption, according to the deployment of various energy policies and technologies; it is seen as an aid to planners who want to devise the optimum energy system.

This thesis uses two energy modelling software tools:

- LEAP (Long Range Alternatives Planning System) is an energy demand simulation model developed by the Stockholm Environment Institute (SEI). LEAP uses scenario analysis to evaluate the individual and aggregate impact of energy policies and technologies for both the demand and supply side. The version of LEAP used in this thesis operates with the Open Source Energy Modelling System (OSeMOSYS), which optimizes the electricity generation sector.
- TIMES (The Integrated MARKAL-EFOM System) is long-term energy optimization model developed by the IEA-ETSAP (International Energy Agency – Energy Technology Systems Analysis Programme) community. It is a bottom-up,

technology-rich, energy systems model that over scenarios of medium and long-term time horizons, uses linear programming to identify the least-cost energy technology portfolio to satisfy a number of user constraints such as emissions reduction.

1.3 Thesis aims and objectives

This thesis sets out the aim to improve the evidence base underpinning energy policy decisions with a particular focus on natural gas, together with the following objectives:

-Analyse historic trends of natural gas demand in the residential sector and identify the key drivers in changing natural gas demand.

-Examine the impact of a key energy efficiency policy, residential building regulations with using empirical data.

-Model the impact of a number of energy policies in a bottom-up, techno-economic energy model.

-Examine the role of natural gas as a transition fuel to a low carbon energy system by using an energy systems model and a number of CO_2 constrained pathways.

-Model the potential in Ireland for CCS as part of a long term CO_2 mitigation pathway.

1.4 Thesis in brief

In addition to the introductory chapter, this thesis is presented in five chapters: Chapter 2 has been published in a peer-reviewed scientific journal. Chapter 3 has been published in peer-reviewed conference proceedings and is currently in review in a scientific journal. Chapter 4 is currently in review in a scientific journal. Part of Chapter 5 has been published as part of a co-authored paper in a peer-reviewed scientific journal. Chapter 6 is in final preparation for imminent submission to a scientific journal.

With reference to the overview in Figure 1.1, the main body of the thesis is summarized as follows:

Chapter 2 presents a decomposition analysis of gas consumption in the residential sector in Ireland. It uses the Log Mean Divisia Index I methodology to decompose end-use natural gas consumption into five effects (activity, intensity, weather, dwelling size, building regulations) and the relative contribution to changing natural gas demand of each of these five effect is analysed for the period 1990 to 2008. This chapter provides an initial indicative assessment of the 2002 Building Regulations which are analysed in more depth in the following chapter.

Chapter 3 is an in-depth evaluation of an energy efficiency policy, residential building regulations. Using metered gas consumption for a treatment group constructed to the regulations and a control group not constructed according to the regulations, an analysis is made of effectiveness of the energy efficiency aspect of the dwellings. Using a simulation model and a national database of Building Energy Rating assessments, evaluation is also made of the compliance aspect of the building regulations. Some of the results from this policy analysis are used to inform the policy modelling work in the following chapter.

Chapter 4 presents a bottom-up energy demand model for Ireland. This model was originally commissioned by SEAI (Sustainable Energy Authority of Ireland) and built by UCC's Energy Policy and Modelling Group to contribute to Ireland's 2010 energy forecast report. This chapter presents the first use of LEAP-OSeMOSYS (Open Source Energy Modelling System) for optimizing the electricity sector of a country model.

Chapter 5 presents the results of an energy systems model in terms of the potential for natural gas to operate as a transition fuel to a low carbon energy system. For the time horizon 2005-2050, scenarios for an 80% cut in CO_2 emissions and 95% cut in CO_2 emissions are used to examine the role of natural gas in each sector of the economy. The analysis also uses a decomposition analysis to examine the relative contribution of fossil fuel switching, energy efficiency and renewable energy to overall CO_2 emissions reduction. The key technology for gas as a transition fuel, Carbon Capture & Sequestration, is analysed in more detail in the following chapter.

Chapter 6 presents a techno-economic analysis of the potential role for mitigating CO_2 emissions that CCS can play in Ireland. It compares coal and gas CCS using a number of different metrics including sensitivity analysis of fuel prices and capital costs of capture. It examines the most cost-optimum location for a CCS site in Ireland and examines the impact of a security of supply scenario.

Chapter 7 presents conclusions of the thesis and some recommendations arising.

1.5 Role of Collaborations

This thesis comprises my own work and was written by me, but it involved collaboration at many junctions. With the exception of Chapter 5, all chapters have been published, submitted or prepared for submission to a scientific journal with me as the lead author. Dr Brian Ó Gallachóir, my supervisor, has advised on all aspects of this thesis. The rest of the chapters are as follows:

Chapters 2 and 3 are entirely my own work.

Chapter 4 is based on a paper for which I was the lead author in collaboration with a number of co-authors: sub-sections on industry and transport are based on work done by Caiman Cahill and Hannah Daly respectively, and which were co-written with me; the sub-section on the residential sector is based on collaborative work led by a colleague Denis Dineen, and co-written with me; Paul Deane provided advice on inputs to the electricity generation sector; Mark Howells and Manuel Welsch provided advice on aspects of OSeMOSYS; Charlie Heaps advised on LEAP and Morgan Bazilian on energy systems modelling.

Chapter 5 contains a decomposition analysis which was done by me and which has been published in a paper with me as a co-author (Chiodi et al, 2012). This chapter includes some additional analysis and text of my own. Chapter 6 is my own work and was written entirely by me. It received advice on Irish TIMES from Alessandro Chiodi and Maurizio Gargiulio, and Morgan Bazilian provided advice on aspects of CCS in Ireland and the comparison of coal vs. gas CCS.

2 Decomposition Analysis of Natural Gas Demand in the Residential Sector

Abstract

To-date, decomposition analysis has been widely used at the macro-economic level and for in-depth analyses of the industry and transport sectors; however, its application in the residential sector has been rare. This chapter uses the Log-Mean Divisia Index I (LMDI-I) methodology to decompose natural gas consumption trends in the gas-connected residential sector in Ireland from 1990 to 2008, which despite an increasing number of energy efficiency policies, experienced total final consumption growth of 470%. The analysis decomposes this change in gas consumption into a number of effects, examining the impact over time of market factors such as a growing customer base, varying mix of dwelling types, changing share of vacant dwellings and changing size of new dwellings. It also examines the impact of building regulations policy and other factors such as the weather. The analysis finds the most significant effects are changing customer numbers and changing intensity; the analysis also quantifies the impact of building regulations within the context of other effects. By comparing the historical impact on gas consumption of policy factors and non-policy factors, this chapter highlights the challenge for policy-makers in achieving overall energy consumption reduction.[3]

Keywords: decomposition analysis; residential sector gas consumption; energy efficiency policies

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[3] Chapter published as Rogan, F., Cahill, C.J., Gallachóir, B.P.Ó., 2012. 'Decomposition analysis of gas consumption in the residential sector in Ireland' *Energy Policy 42*, 19–36.

2.1 Introduction

In Ireland from 1990 to 2008, natural gas TFC, for all sectors of the economy grew by an average annual rate of 6.1%, the highest rate for any fuel in Ireland during that period; in 2008, natural gas accounted for 12.4% of Ireland's TFC. In the residential sector, natural gas TFC grew by an average annual rate of 10.2%, growing from a 5.2% share in 1990 to a 21% share in 2008 (Howley, Dennehy, et al., 2009b). Ireland's natural gas import dependency went from 0% in 1990 to 92% in 2008 (Howley, Gallachoir, et al., 2009). The EU has also experienced growth in natural gas TFC and import dependency: over the period 1990 to 2008, natural gas TFC in the EU12 grew at an average annual rate of 3% (Eurostat, 2010); concurrently, the EU expanded to 27 member state countries and from a low of 45.6% in 1998, import dependency climbed to 62.3% in 2008 (Eurostat, 2011), as illustrated in Figure 2-1.

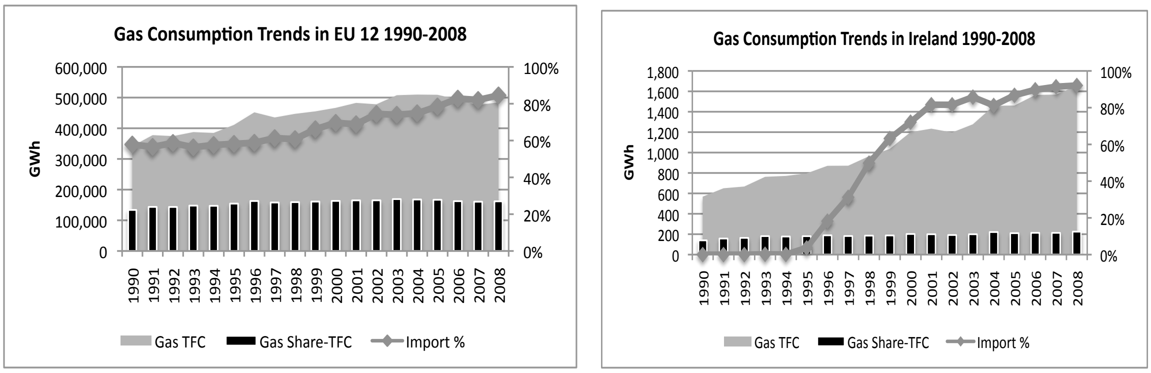

Figure 2-1 Gas trends in EU12 & Ireland 1990-2008 (data source: (Eurostat, 2010))

The negative consequences of Europe's import dependency became acutely apparent during the Russia Ukraine gas crisis in 2008. The second EU strategic energy review was published following this crisis and focused on security of supply (European-Commission, 2008), proposing a significant upgrade to gas infrastructure in an attempt to address the volatility of EU gas supply. Other EU energy policies that also seek to reduce EU dependence on imported gas include a focus on energy efficiency (notably the Energy Services Directive (ESD) (EC, 2006) and Energy Performance in Buildings Directive[4] (EC, 2010)) and renewable energy (Renewable energy Directive (EC, 2009a)). However, it remains the view of both the

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[4] In 2008 energy in buildings comprised a 25% share of final energy consumption in the EU27

EU and IEA that natural gas will have a bridging role between the energy past and future (Vinois, 2010; Baroni, 2010).

2.1.1 Policy trends

The residential sector is a significant energy user and represents a significant opportunity for energy efficiency improvement in Ireland. It has been the focus of increased policy activity, as can be seen from the MURE[5] database, a centralized storehouse listing energy policies for all sectors of the economy for all EU member countries[6]. For 1990-1999, the MURE database lists five energy- end-use policies in Ireland's residential sector; for 2000-2008, fourteen policies are listed (MURE-II 2011)[7]. In 2006, as obliged by the Energy Services Directive (EC, 2006), Ireland prepared a National Energy Efficiency Action Plan (NEEAP), which contained many of the same policies. A particular focus has been on improving the energy performance of new homes. Ireland's NEEAP had building regulations (BR) contributing a 48% share of the residential energy savings target for 2020, making it the most significant type of policy measure in the residential sector. Until 2008, most of the other policies listed in MURE were either niche policies (e.g. fuel poor dwellings, appliance efficiency, renewable energy grants) or pilot policies (low carbon homes, smart metering). The only policy to address existing dwellings, focusing on the largest energy end-use category of space heating was an information campaign, promoting behavioural change towards efficiency in the home. Post 2008, there has been an extensive retrofitting scheme aimed at improving the energy efficiency of the existing dwellings stock (DCENR, 2011).

2.1.2 Literature review

Despite the increased number of policies in Ireland, there has been a limited number of empirical analyses of the energy performance of the dwelling stock (O'Doherty et al., 2008) or of the impact of energy efficiency policies generally (Hull et al., 2009) (Rogan and O'Gallachoir, 2011). It is particularly pertinent that such research be done since Ireland has one of the most inefficient housing stocks in Northern Europe

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[5] Mesures d'Utilisation Rationnelle de l'Energie

[6] The MURE database is maintained by the national energy agencies of each EU member state; in Ireland, this is Sustainable Energy Authority of Ireland (SEAI)

[7] A full list of all energy efficiency policies in the residential sector in Ireland for the period 1990-2008 can be found in Appendix A

(Healy, 2004) and in recent times has experienced an above average level of new builds (DEHLG, 2010). There have been two previous analyses on residential natural gas TFC in Ireland. Hull et al. (2009) used a 10% anonymized sample and a more detailed sample of 48 dwellings to conduct a preliminary analysis on the impact of building regulations, dwelling type, changing dwelling size and gas tariffs. The study produced results that were "not conclusive" but suggested a "substantial rebound effect and/or a degree of non-compliance with historic building regulations"; the authors recommended further work, particularly ex-post analyses of energy efficiency policies. In an examination of the impact of a national energy efficiency advertising campaign on natural gas TFC in 2006 and 2007, Diffney et al. (2009) found no significant impact on gas consumption.

A number of other analyses have been carried out on aspects of energy consumption in the Irish residential sector. Scott (1997) did a regression analysis on ownership of household energy saving appliances in Ireland with a focus on the reasons for their low take-up. Clinch et al. (2001) constructed a model of the Irish housing stock to model the energy and emissions impact of home insulation energy efficiency measures. O'Doherty et al. (2008) conducted a regression analysis on energy appliances and energy saving features in Irish dwellings. Lyons et al. (2009) calculated expenditure and own price elasticities for fuels in the household sector. Two Sustainable Energy Authority of Ireland (SEAI) reports, Energy in the Residential Sector (O Leary et al., 2008) and Energy Efficiency in Ireland (Dennehy et al., 2009), analyzed energy consumption in the residential sector and included a decomposition analysis of four effects (size, diffusion of central heating, technical efficiency & behaviour) which impacted the energy consumption of the dwelling stock between 1995 and 2006.

A number of these analyses on gas and energy consumption in the residential sector have highlighted the need for further analysis of factors impacting energy consumption. This further analysis is important for a number of reasons: (i) measuring the efficacy of energy efficiency policies is important for designing better future policies; (ii) there is an obligation to report energy savings under the European Energy Services Directive (EC, 2006) and (iii) in view of the growing volume of energy efficiency policies, more ex-post analyses are required to sufficiently model current and future energy demand. It is in this context, that an expanded decomposition analysis is seen as a powerful analytical tool.

2.1.3 Decomposition analysis

A collaborative report between the IEA and the IAEA recommended the use of decomposition to study changes in energy demand in all sectors, including the residential sector (IAEA et al., 2005) and the IEA has demonstrated the usefulness of decomposition analysis by comparing nine countries for five different effects (Taylor, 2009). This chapter uses the Log-Mean Divisia Index (LMDI) decomposition analysis methodology. Decomposition analysis was first used in the late 1970s to examine the impact of changes in product mix on energy intensity and consumption. It has since broadened its scope to include analysis of energy supply and demand, energy-related emissions, material flow and dematerialization, monitoring of national energy efficiency trends and making cross-country comparisons of energy performance (Ang, 2004).

A survey of decomposition studies in 2000 found 124 studies in the literature (Ang and Zhang, 2000), which focused largely on the industry sector, with studies focusing on the economy as a whole, and a smaller number focusing on the transport sector. Decomposition papers focused on the residential sector are rare, just two currently exist in the literature (Unander et al., 2004; Achão and Schaeffer, 2009). Decomposition analysis in Ireland has been carried out on industry (Cahill et al., 2010; Cahill and Gallachóir, 2010) and on the economy as a whole (O' Mahony et al., 2012). This represents the first decomposition analysis on the residential sector and focuses on natural gas demand. The analysis carried out here is readily replicable in other countries to quantify the policy and non-policy factors affecting natural gas demand trends in the residential sector.

A number of papers have included the residential sector in broader analyses: Munksgaard et al. (Munksgaard et al., 2000) analyzed the impact of direct and indirect household consumption on emissions in Denmark, Wachsmann et al. (Wachsmann et al., 2009) did a structural decomposition analysis of energy demand in Brazil which included the residential sector, Donglan et al. (Donglan et al., 2010) examined changing emissions in rural and urban household sectors in China, and Kumbaroğlu (Kumbaroğlu, 2011) examined emissions in Turkey.

2.1.4 Analysis objectives

Over the time scale 1990-2008, this decomposition analysis seeks to quantify the impact of a number of policy and non-policy factors on natural gas TFC. As the table in Appendix A shows, there was a growing volume of energy efficiency policy measures over this period; however, for most of the period, the focus was on BR[8] for new dwellings, with little emphasis on the existing dwellings stock. By appropriate manipulation of the available data, this chapter provides a preliminary analysis of the dominant energy efficiency policy for the period: the 2002 BR. Other energy efficiency policies occur too late in the analysis period to be examined, do not address space heating of existing dwellings or are not readily quantifiable within a top-down methodology such as decomposition analysis, which is not typically used to evaluate specific energy efficiency policies. Although decomposition analysis is not an ex-post policy analysis tool, it can give an indicative quantification of the absolute and relative impact of the 2002 BR policy within a framework that also quantifies non-policy market effects (changing number of dwellings, changing share of vacant dwellings, dwelling size, type of dwellings) and intensity effects (weather effect and intensity effect).

This chapter is focused on the natural gas cohort of the residential sector because in terms of a source of data, metered gas consumption is a uniquely excellent source (Cleirigh, 2008), providing accurate consumption data and many other details of dwelling type and location as described in section 2.3. This chapter seeks to incorporate this additional data to make a detailed analysis of the natural gas consuming residential sector. It is due to a lack of data for other fuels (oil, solid fuels, electricity), that these other sectors have not been included. The generality of the results will be seen within the context of the known differences between the national dwelling stock and the gas dwelling stock (Conniffe, 2000).

The chapter is organized as follows: section 2.2 discusses the trends from 1990 to 2008 of natural gas TFC, the gas network and the dwelling stock. Section 2.3 gives an overview of index decomposition analysis, outlines the LMDI-I methodology, describes how the formula was developed to capture five effects and lists the data sources used. Section 2.4 presents the results, section 2.5 has a discussion and section 2.6 concludes.

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[8] In 1991, 1997, 2002 & 2008

2.2 Residential natural gas sector: 1990-2008

2.2.1 Gas consumption trends

During the period 1990 to 2008, Bord Gáis Éireann (BGÉ) was the only retailer of piped natural gas to the residential sector in Ireland. In 1990, residential gas TFC was 142 ktoe, a 5.2% share of overall residential TFC; throughout the period that followed, 1990 to 2008, Ireland underwent a sustained economic boom during which GDP grew by 182% and TFC for all fuels in all sectors of the economy grew by 85% (Howley, Dennehy, et al., 2009b). Residential natural gas TFC grew by an average annual rate of 10.2%, the highest rate for any fuel in the residential sector during that period and by 2008, natural gas had a 21% share of overall residential TFC (Howley, Dennehy, et al., 2009b). Contained within these overall trends of growth in residential gas customers and natural gas TFC is a more complex interweave of trends that don't all tally with the macro trend of constant growth. Starting in 2000, average annual consumption of the natural gas dwelling stock began to decline, see Figure 2-2.

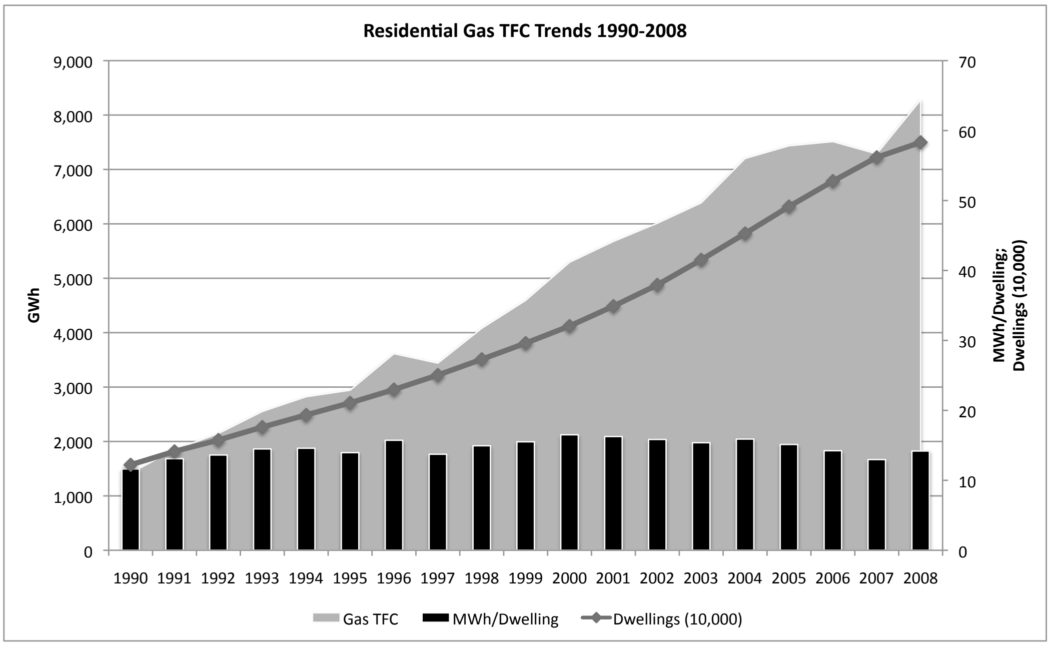

Figure 2-2 - Residential gas consumption trends in Ireland 1990-2008

2.2.2 Gas transmission and distribution network

Starting in 1990, BGÉ had 139,000 residential customers, approximately 14% of all dwellings in Ireland; in this year, over 90% of all gas connections were in the urban areas of Cork and Dublin. In 1993, an interconnector with the UK made landfall on the east coast of Ireland and over the rest of the decade, the gas transmission and distribution network expanded along the northeast coast, the southeast coast and west into the rapidly growing towns in the Greater Dublin Area[9]. In the early 2000s there was continued expansion around the existing urban areas of Limerick and Cork and in the towns along the existing Cork-Dublin pipeline. By 2004, the Seven Heads gas field off the south coast had been opened, a second interconnector with the UK had been constructed, and a pipeline between Galway and Dublin had been completed, see Figure 2-3. By 2008, natural gas residential customer numbers had grown by 342%, at a constant annual growth rate of 9%, to reach 616,000, approximately 39% of all dwellings in Ireland.

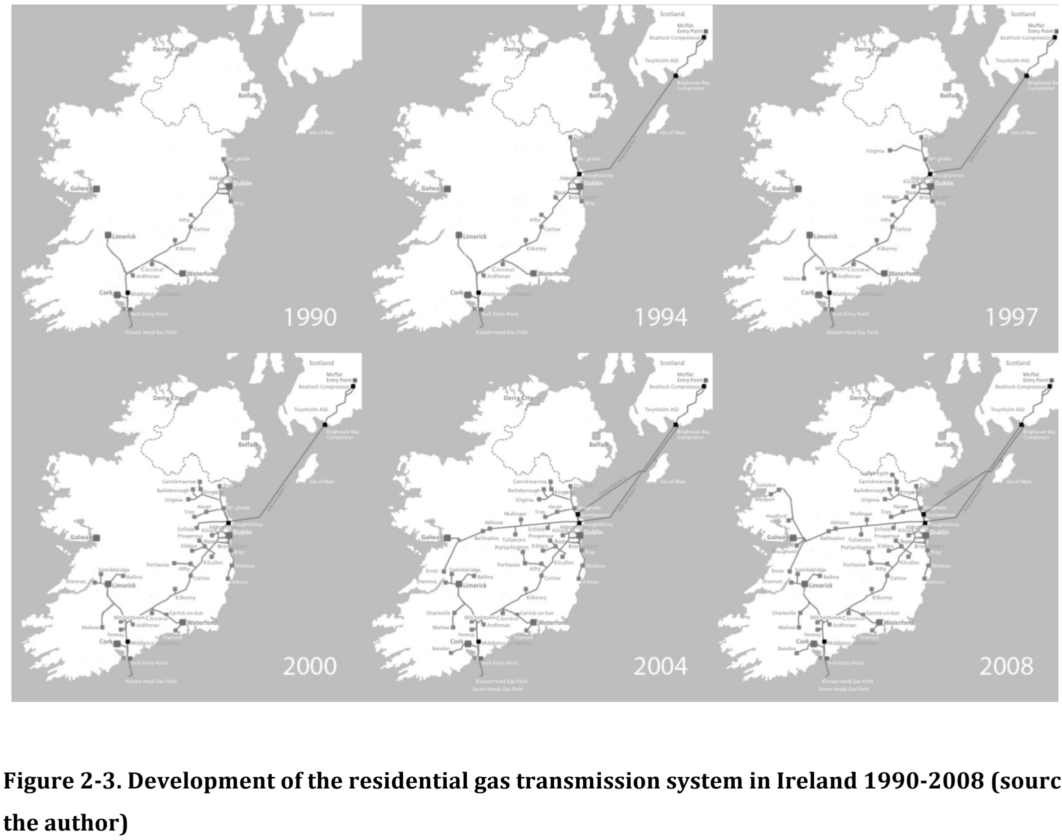

Figure 2-3. Development of the residential gas transmission system in Ireland 1990-2008 (source: BGÉ & the author)

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[9] Greater Dublin Area refers to Dublin county and the three counties (Meath, Kildare & Wicklow) that border it.

2.2.3 Gas dwelling stock trends

In Ireland's residential sector, from 1990 to 2008, there was an 86% increase in dwellings, concentrated in the latter decade (DEHLG, 2010). In addition to the effect on energy demand of more dwellings was the effect of which types of dwellings (semi-detached, detached, apartments) were constructed, something that over the period varied considerably (see Table 2-1). Other structural effects impacting energy demand were the number of vacant dwellings, which increased rapidly and according to a 2010 study could be as high as 17.4% of all dwellings (Williams et al. 2010). While the total vacancy rate for the gas dwelling stock is more stable, the per dwelling vacancy rate shows considerable variation (see Table 2-2).

Table 2-1– Share of dwelling types for national & gas dwelling stocks (data source: (DEHLG, 2010) & BGÉ data set)

Dwelling Types		**1990**		**2000**		**2008**	
National DW Stock	Gas DW Stock	National	Gas	National	Gas	National	Gas
Detached	**Detached**[10]	49%	17%	47%	20%	43%	20%
	Bungalow		0.2%		0.1%		0.1%
Multi-Scheme	**Semi-Det**	50%	50%	46%	57%	46%	58%
	Terraced		26%		19%		18%
Apartment	**Apartment**	1%	7%	7%	5%	12%	4%

Table 2-2 – Vacancy rates by dwelling type for gas dwelling stock

Dwelling Type	**1990**	**1993**	**1996**	**1999**	**2002**	**2005**	**2008**
Bungalow	58%	53%	35%	32%	26%	22%	13%
Detached	11%	15%	12%	11%	10%	10%	11%
Apartment	37%	33%	29%	37%	38%	38%	38%
Semi-Det	12%	13%	11%	11%	12%	11%	11%
Terrace	19%	18%	18%	18%	20%	21%	23%
Total	15%	15%	14%	14%	14%	14%	14%

2.3 Methodology and data

The first methodology sub-section gives an overview of index decomposition analysis and some of the different decomposition methodologies that currently exist; it describes some of the properties that distinguish the different methodologies and how these differences are used to choose a particular

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[10] BGÉ Detached dwellings are two-storey only whereas National Detached dwellings are one & two storey and include bungalows

methodology for any given analysis. This serves as a background for why the LMDI-I method was chosen in this analysis. The second sub-section outlines the decomposition methodology chosen for this case study, LMDI-I; it describes the effects chosen and the formulae used to calculate the results. It also includes a description of the data used for the analysis and some of the assumptions that accompany the data.

2.3.1 Index decomposition analysis

Methodologically, all index decomposition techniques use some version of price index theory in how they relate the value of a change to a particular base year. Beyond this common foundation, there are many different index decomposition techniques, all with their own advantages and disadvantages. The growth in the number of studies using decomposition has been paralleled by a growing diversity of methodologies (see Figure 2-4).

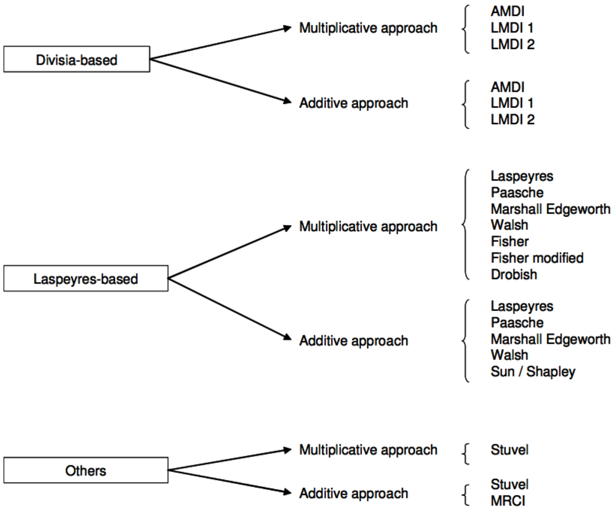

Figure 2-4 - Taxonomy of decomposition methodologies (source: (Granel, 2003))

Index decomposition properties

Five key properties which distinguish different decomposition techniques are (i) base year type (fixed or rolling); (ii) form of presentation (multiplicative or additive); (iii) weighting type (e.g. base year or logarithmic change); (iv) the presence or absence of a residual and (v) consistency of aggregation.

Fixed base year vs. rolling base year

All decomposition techniques analyze change over time relative to a base year and all techniques employ either a fixed base year or a rolling base year. The fixed base year method is simpler, but provides fewer results and has been found to produce erroneous results. The rolling base year, or chained decomposition is far more popular. It provides substantially more information, and while it is more prone to compounding errors by cumulating them each year, it has been found to provide more reliable results in general (Granel, 2003).

Multiplicative vs. additive

Most decomposition methodologies offer a choice of either multiplicative or additive, with a few techniques only offering one form. The multiplicative form presents relative changes by giving the results in the form of a ratio with the original base year always having a value of 1. Additive decomposition presents absolute change and so presents results in the original units of the analysis.

Weightings

When choosing the rolling base year, appropriate weightings for each year must be calculated. How these weightings are calculated is one of the key defining differences between decomposition methods and it can be a determining factor in the presence or absence of a residual in the results. For example, Laspeyres methods use weights determined by base year values, whereas some Divisia methods use weights calculated according to the laws of logarithmic change - the former has a residual, whereas the latter does not.

Residual

The presence or absence of a residual is a key factor distinguishing methods. This is especially the case if a decomposition analysis is investigating effects that have a small impact; if the decomposition analysis results include a residual that exceeds the size of certain effects, this casts doubt on the validity of the results. Many of the earlier decomposition methods produced results that included a residual whereas more recent methods have found ways to remove, reallocate or simply produce results without a residual.

Consistency of aggregation

Another factor distinguishing decomposition techniques is consistency of aggregation, i.e. are aggregated sub-sectoral decompositions consistent with sectoral decompositions? This property is a significant enabler of decomposition with many effects or decomposition at a very micro-level.

2.3.2 Different decomposition methodologies

The taxonomy of decomposition methodologies in Figure 2-4 embodies many on the different properties listed above. The Divisia grouping, based on divisia index numbers, includes the arithmetic mean and log mean methods. The former is a simple methodology, which leaves a residual, whereas the log mean method provides perfect decomposition. There are two versions of the log mean technique: LMDI-I and LMDI-II. LMDI-I has the unique and useful consistency-in-aggregation property. The LMDI-I method has become increasingly popular as a decomposition technique in recent years; it has been used for both energy demand analyses and energy-based emissions analyses in academic studies and has also been adopted by national energy agencies in Canada and Australia (Cahill et al., 2010).

The conventional Laspeyres method has fallen out of favour with researchers recently as it tends to leave a large residual (Ang and Liu, 2007). Other methods in the Laspeyres grouping have been modified to provide a perfect decomposition, but the formulas and results grow more difficult as more effects are included. Other methods have been developed, such as (Sun, 1998), that re-distribute the residual. The Other category (see Figure 2-4) has a number of effective but somewhat specialized methodologies, such as Stuvel which is only available for two factors and Mean-Rate-of-Change Index (MRCI) (Chung and Rhee, 2001), which is only available for additive decomposition.

It has been noted that the results of different decompositions analyses for the same data, but with different methodologies, will offer slightly different results. In a case study by Granel (2003) this discrepancy was quantified and shown to be very small; it was found that the same data set subjected to the different decomposition methodologies contained some differences but they were all below 1% and were considered negligible.

2.3.3 Decomposition methodology – LMDI-I

As described in section 2.1, the motivations for this analysis are to add to the existing body of empirical analyses of residential sector energy consumption (O'Doherty et al., 2008; Hull et al., 2009) with a focus on quantifying the impact of the most significant policy (2002 BR) within the same quantitative framework as market factors (changing dwelling size, varying share of dwelling type and vacant dwellings) and intensity factors (such as weather). Based on the motivations of the study and the data available, the additive form of the LMDI-I was chosen as the most appropriate decomposition methodology for the following reasons:

1. LMDI-I has perfect decomposition, i.e. it produces results with no residual.
2. In terms of transparency, the additive form of LMDI-I is deemed simplest to interpret because it presents results in the same units as the consumption data (GWh in this study).
3. The LMDI-I formula does not increase in complexity as it is expanded, there is no disincentive decomposing to many effects.
4. The consistency-in-aggregation property, which is unique to LMDI-I, means a decomposition within multiple sub-sectors can be done.
5. Finally, LMDI-I has a strong theoretical foundation (Ang and Liu, 2001), making it robust and adding confidence to its results.

Section 2.3.4 is a description of the five effects that are decomposed. It also describes the two sub-sectors within which, the decomposition calculations were done before being aggregated to give the final results.

2.3.4 Five effects

1. *Activity Effect:* How changing customer numbers (Q) impacted gas consumption, see Figure 2-2.
2. *Intensity Effect:* How changing consumption per dwelling, intensity (I), impacted overall gas consumption. The intensity effect has been adjusted for weather and size and this makes it different to the intensity trend shown in Figure 2-2.
3. *Building Regulations Effect:* How the 2002 BR impacted gas consumption: the 2002 BR (legislation from 2003) stipulated an energy efficiency improvement of 20% compared to the 1997 BR. Allowing a gradual phase-in

and adjusting for the distorting impact of the connection year, the 2002 BR are first examined in 2004.

4. *Weather Effect:* The weather effect (W) was calculated as the changing share that weather adjusted gas consumption has of total non-weather adjusted gas consumption.
5. *Size Effect:* The size effect (S) was calculated as the changing share that size adjusted gas consumption has of non-size adjusted gas consumption.

All decomposition analyses will have an activity, intensity and structural effect; depending on data availability, the intensity and structural effect can be further disaggregated as per the wishes of the analyst. Previous studies (Gaslink, 2009; Rogan, 2009) have indicated that dwelling size and domestic building regulations were impacting gas consumption, but to what extent was unknown; it was therefore the intention of the analysis to quantify these latter effects. Due to the perfect decomposition property of LMDI, there is no theoretical limit to the number of effects that can be decomposed for; however, one principle guiding the choice of effects in this exercise was for the effects to be as independent of each other as much as possible. In addition to the effects described above, the data set enabled the following list of effects, which were not included in the final analysis: regional effect (addition of new towns, counties to gas network); dwelling type; bedroom number; building age. Early decomposition analyses were done, which included these effects, but in each instance it was found that either an insignificant amount of information was added to the overall analysis, or that the particular effect contained the same information as another effect, e.g. the regional effect was largely the same as the activity effect. Lack of data also prevented analysis of certain effects such as income and price effects, which is discussed below.

2.3.5 Two sub-sectors

Vacant Dwellings: Using the metered gas consumption data set, all dwellings were categorized as either permanently occupied or temporarily vacant: a permanently occupied dwelling has consumption every year whereas a temporarily vacant dwelling has zero consumption for at least one entire year at any time during the 1990-2008 period. The vacant dwelling rate for gas-connected dwellings was more stable than the national vacancy rate but according to dwelling type exhibited significant variation, see Table 2-2.

Dwelling Type: The gas consumption data set categorized all customers into five dwelling types: detached, bungalow, apartment, semi-detached and terraced. A comparison of shares between national dwelling types and BGÉ dwelling type shares is shown in Table 2-1.

The aggregated general form of the five effects is shown in Equation 2-1.

$$\Delta E = E_t - E_{t-1} = \Delta E_{activity} + \Delta E_{intensity} + \Delta E_{2002BR} + \Delta E_{weather} + \Delta E_{size}$$

Equation 2-1

In formula (1) ΔE is the total change in gas consumption between year t and t-1 and $\Delta E_{\text{activity}}$, $\Delta E_{intensity}$, ΔE_{2002BR}, $\Delta E_{weather}$ and ΔE_{size} are the five effects, the sum of which is ΔE. The more specific form for the decomposition of the five effects in each sub-sector is shown in Equation 2-2.

$$\Delta E = \sum_{ijk}^{n} \frac{(e_t^{ijk} - e_{t-1}^{ijk})}{(\ln e_t^{ijk} - \ln e_{t-1}^{ijk})} \times \left\{ \ln\left(\frac{Q_t^{ijk}}{Q_{t-1}^{ijk}}\right) + \ln\left(\frac{I_t^{ijk}}{I_{t-1}^{ijk}}\right) + \ln\left(\frac{BR_t^{ijk}}{BR_{t-1}^{ijk}}\right) + \ln\left(\frac{W_t^{ijk}}{W_{t-1}^{ijk}}\right) + \ln\left(\frac{S_t^{ijk}}{S_{t-1}^{ijk}}\right) \right\}$$

Equation 2-2

In Equation 2-2 e is the change in energy in each sub-sector, i is the index for occupied or vacant sub-sector, j is the index for the five dwelling type categories and k is the index for the pre and post different BR category. The two sub-sectors create three levels, which are shown in Figure 2-5. Within both the permanently occupied dwellings and the temporarily vacant dwellings (Level 2), the five effects are separately decomposed for each of the five dwelling types (Level 3). The values for each of the five effects are then summed to the aggregated level (Level 1).

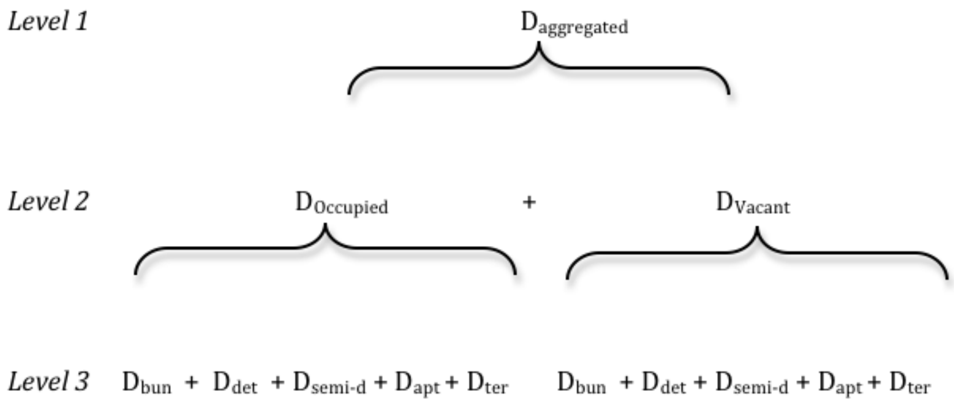

Figure 2-5 - Levels of disaggregation for different sub-sectors

2.3.6 Data

This chapter made use of three data sources:

1. *BGÉ Metered Consumption Readings*
2. *Met Éireann Annual Degree Days*
3. *Central Statistics Office Floor Size*

BGÉ Metered Consumption Readings: The author was provided with a data set of metered consumption readings for 10% of residential natural gas customers for each year between 1990 and 2008. For each customer, the data set included (i) the metered consumption for each calendar year; (ii) an anonymized town level address; (iii) the type of dwelling; (iv) the number of bedrooms in the dwelling and (v) the date the dwelling was connected to the gas grid. This data set enabled calculation of the impact of changing customer numbers, varying dwelling type, changing share of vacant dwellings and the impact of BR. Prior to the data set being used in this analysis, 1% of entries: large, small or negative, were trimmed. Also removed, was the first connection year of data, due to partial consumption during that year. Finally, some entries weren't labelled with bedroom number or dwelling type and so these were also removed.

The main limitation of this data set is that for new connections, there is no distinction between connection to a new dwelling and to an existing dwelling. Therefore, a key assumption has been made that the year of connection is the same as the year of construction. Of all the effects examined, this assumption has implications for the Building Regulation effect only, since that effect uses the year of construction to determine which building regulations the dwelling was constructed to. Although it is known that the great majority of new connections were to new dwellings, the decomposed Building Regulation effect must remain a preliminary figure. A more robust analysis of building regulations is carried out in the next chapter.

Met Éireann Annual Degree Days: Degree day data for weather stations in Ireland was acquired, which enabled a regional weather adjustment on a county-by-county basis (EC, 2005). A regional, rather than a national weather adjustment was particularly important due to the differences between the gas-connected dwelling stock and the national dwelling stock (e.g. the gas dwelling stock is more heavily weighted to urban locations and it includes a smaller share of apartments). The weather adjustment was applied to the space-heating share (i.e. non-base load) of the consumption data. The base load values were derived from the average consumption values for July and August for the entire dwelling stock, unfortunately base load values for different dwelling types were not available. By taking the difference between weather adjusted gas consumption and non-weather adjustment gas consumption, it was possible to isolate the weather effect.

The focus in this analysis is on yearly gas demand so the main weather variable used is average annual temperature; day-to-day and peak dynamics are not examined. This is the basis for the degree days weather correction that is used by Eurostat (EC, 2005) and SEAI (O Leary et al., 2008) and is applied here. Other studies, particular those which examine daily and peak changes in gas consumption have used more complex climate corrections such as lagged degree day variables, humidity and rainfall. While degree days is expected to capture most of the variation in gas consumption due to weather, a comparison of the intensity effect and weather effect will enable further examination of whether this is the case.

Central Statistics Office Floor Size: Data on floor size of new dwellings was acquired from the Central Statistics Office (CSO) from a database of successful planning permission applications, based on population averages (CSO, 2012). While this data is the best data on dwelling floor area in Ireland at present (OLeary et al., 2008) there are a number of caveats that accompany it:

1. Not all dwellings that apply successfully for planning permission are built
2. The year planning permission is granted is not necessarily the same year that the dwelling is constructed and connected to the gas network; there is a lag of between one and five years
3. There is no distinction between fuel type of dwelling so any dwelling size differences between gas and non-gas dwellings are not captured

To account for the lag between year of planning permission application and construction, a one year lag was applied to the floor size data and due to the spikiness of the original data set, a three year moving average for floor size was used. Using date of application, dwelling type and county, this data can be linked to other data on dwelling energy consumption. Like weather adjustment, the floor size adjustment was applied only to the space heating share of gas consumption, this was because space heating is proportional to floor area, whereas water heating is more linked to the occupancy of the dwelling. The base year for the floor size adjustment was 1990. Due to the availability of the floor size data, the adjustment was applied to three dwelling types only: detached, semi-detached and apartments. The dwellings that were excluded: terraced and bungalows only accounted for 12% of dwellings and in each case were shrinking as a dwelling category share. The adjustment was applied nationally from 1990 until 2000, and on a county-by-county basis from 2001 to 2008. By size adjusting the gas consumption of new dwellings, this data set enabled calculation of the size effect for the gas consuming stock.

2.4 Results

The GWh figures referred to in the results and discussion section are from the 10% sample data set and are not GWh consumption figures for the entire BGÉ residential customer base. For the 10% sample data set, the average yearly change in consumption was an increase of 8.9% with extremes ranging between an increase of 40.4% in 1991 and a decrease of 8.3% in 1997, see Table 2-3. The aggregate change in gas consumption and the five decomposed effects are shown in Figure 2-6.

The analysis looks at the aggregate trends for the 19-year period (Figure 2-6), the trends as they cumulate over time (Figure 2-7), trends within specific groups of years (Figure 2-8) and the impact of individual effects (Figure 2-9 to Figure 2-15). Since the decomposition was done at a disaggregated sub-sectoral level, it was also possible to investigate the impact of occupied or vacant status and varying dwelling type on each of the five effects; the results for this are shown in two tables in Appendix A. Where possible, trends in the data are verified against known trends in the dwelling stock and gas network as described in Section 2.2. Finally, any unexplained or outstanding trends in the data that the decomposition analysis does not account for are outlined.

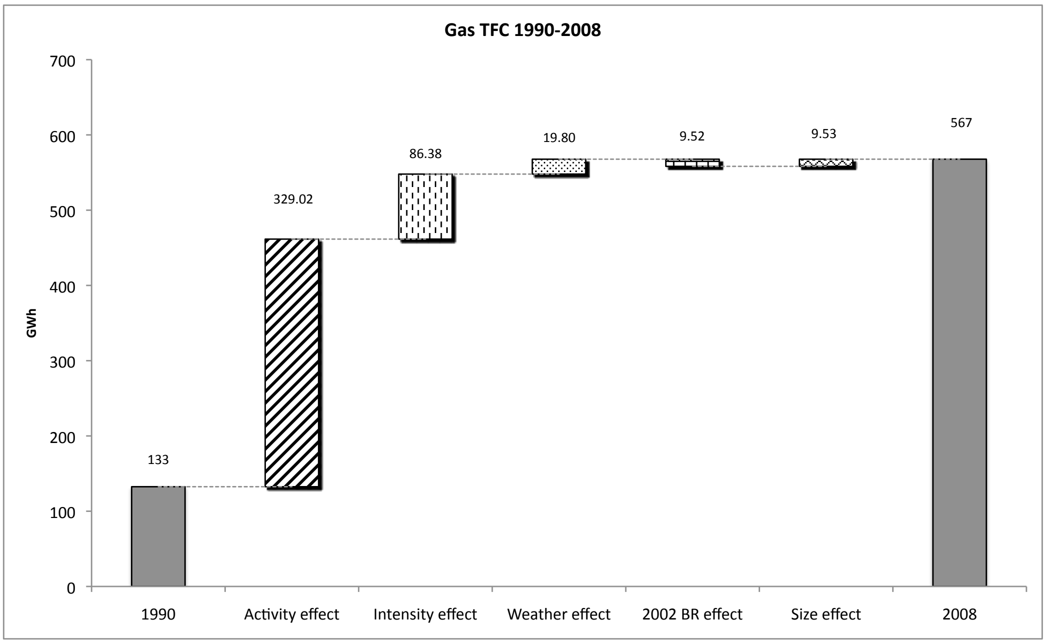

Figure 2-6. Aggregate decomposition of gas consumption 1990-2008

In the 19 year period in its cumulative entirety, the dominant effects were activity (329 GWh) and intensity (86.4 GWh), which by 2008 had a 72% and 19% share respectively; the other effects: weather (19.8 GWh), size (9.5 GWh) and 2002 BR (-9.5 GWh) made up the remaining 9%. The impact, or lack of impact, of the smaller effects is more apparent when analyzing shorter time periods or individual years.

The intensity effect is the associated change of average gas consumption per dwelling. It is driven by a large number of factors, which vary from year to year.

Some of the intensity effect is driven by the changing share of dwellings, e.g. in the early 1990s, the increased number of older terraced dwellings, with their large variation in average consumption contributed to the rising intensity effect. In later years, the share of terraced dwellings intensity effect falls over time as more semi-detached were added to the gas dwelling stock. The changing share of vacant dwellings, particularly in the years 2004 – 2008, also drives the intensity effect. A certain amount of the intensity effect is driven by changes in gas price; household income; dwelling internal temperature; dwelling occupancy. Lastly, a certain amount of the intensity effect is attributable to uncaptured weather effect.

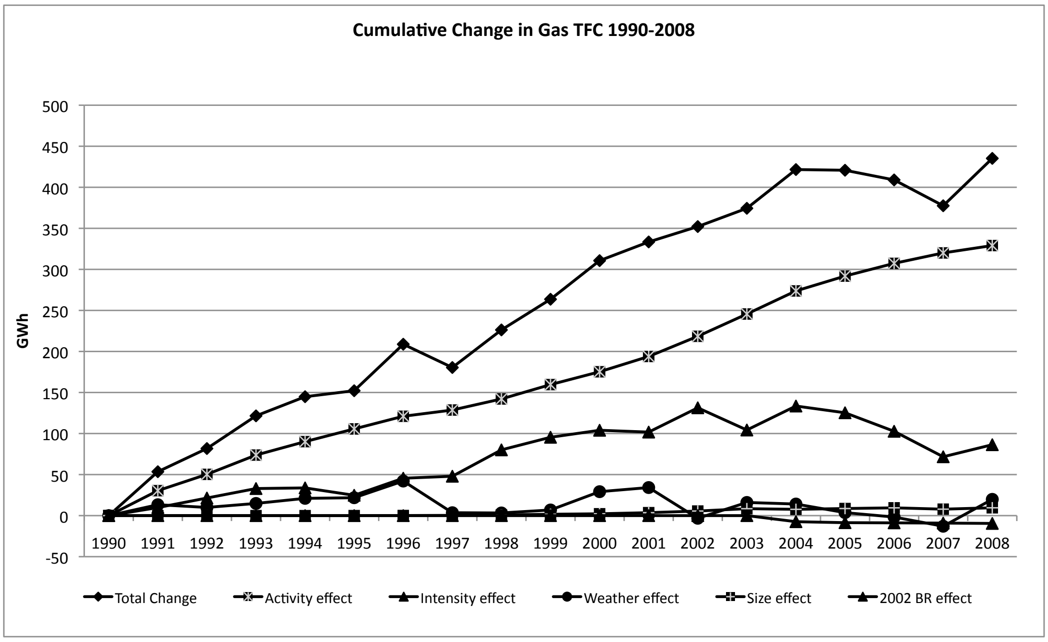

Figure 2-7. Accumulating decomposition of gas consumption 1990-2008

Within the aggregate trends shown in Figure 2-8, six separate groupings of years were analyzed. These sets were primarily based on grouping years of similar growth rates together (see Table 2-3). The years 1990–1994 each had high growth in gas consumption; the years 1995–1997 had low growth, high growth then negative growth in a pattern which implied one year was influencing the next; for each year in the period 1998–2000, growth was greater than 10%; during the years 2001–2004 the growth rate fell below 10%; for every year during 2005–2007, growth was negative; finally, 2008 saw an 11.3% growth in gas consumption. These year groupings and their associated effects are shown in Figure 2-8.

Table 2-3 – Growth and average annual growth rates (%) in gas consumption for six time periods, 1990-2008

	Growth	Average Annual Growth Rate		Growth
1990-1994	109	20.3	**1990**	-
			1991	40.4
			1992	15.2
			1993	18.6
			1994	9.2
1995-1997	12.8	4.1	**1995**	2.6
			1996	19.9
			1997	-8.3
1998-2000	41.6	12.3	**1998**	14.6
			1999	10.4
			2000	11.9
2001-2004	25	5.7	**2001**	5.1
			2002	4
			2003	4.6
			2004	9.3
2005-2007	-8	-2.7	**2005**	-0.2
			2006	-2.1
			2007	-5.8
2008	11.3	11.3	**2008**	11

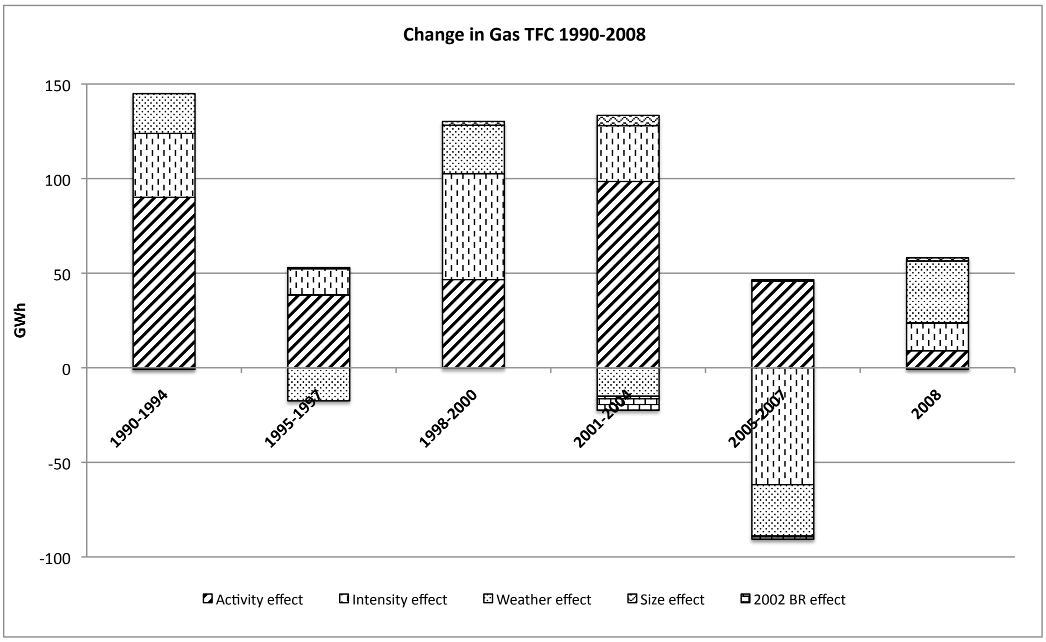

Figure 2-8. Decomposition analysis of gas consumption for six time periods during 1990-2008

Table 2-4 – Total change & decomposed change in gas consumption (GWh), 1990-2008

	Total		Activity	Intensity	Weather	Size	2002 BR	Total
1990-1994	144.9	**1990**	-	-	-	-	-	-
		1991	30.4	9.8	13.3	0	0	53.5
		1992	19.9	11.6	-3.3	0.1	0	28.2
		1993	23.5	11.5	4.9	-0.1	0	39.8
		1994	16.4	0.8	6.2	0	0	23.3
1995-1997	35.6	**1995**	15.5	-9	0.8	0	0	7.3
		1996	15.4	20.8	20.3	0.1	0	56.6
		1997	7.6	2.4	-38.6	0.2	0	-28.4
1998-2000	130.2	**1998**	13.5	32.1	-0.3	0.5	0	45.8
		1999	17.5	15.3	3.6	0.9	0	37.3
		2000	15.6	8.5	22.3	0.6	0	47.1
2001-2004	111	**2001**	18.6	-2.2	5	1.3	0	22.8
		2002	24.6	29.6	-37.4	2	0	18.7
		2003	27.1	-27.1	19.3	2.9	0	22.2
		2004	28.1	29.2	-1.9	-0.8	-7.4	47.2
2005-2007	-44.1	**2005**	18.1	-8.2	-10.5	1	-1.2	-0.8
		2006	15.5	-22.6	-5.4	0.9	-0.2	-11.8
		2007	12.7	-31	-11.2	-1.6	-0.3	-31.5
2008	57.7	**2008**	9	14.7	32.8	1.7	-0.4	57.7

The correlation between change in consumption per dwelling (Figure 2-2) and summed intensity effect and weather effect is almost perfect (0.96); the correlation between change in consumption per dwelling and intensity effect alone is lower, but still high enough to be considered significant (0.65). Some of the volatility in the intensity effect is therefore misattributed weather effect that isn’t captured by the regional degree-days methodology. The particular spikiness in 2002, 2003 and 2004 occurs alongside a large increase in the activity effect for the same time period. During these years, large numbers of new dwellings were being simultaneously added to the dwelling stock. An examination of a separate, more time-disaggregated, data set of bi-monthly gas readings indicates that initial gas bills (after first connection) tend to be estimates, until actual customer readings give the correct reading. It is probable therefore that when large numbers of dwellings were connected simultaneously, large overestimates in one year were corrected in the following year, leading to a significant volatility in the intensity effect.

2.4.1 1990-1994

For 1990–1994, nearly all effects were positive and the total increase in gas consumption for the period was 144.9 GWh, see Table 2-4. Activity and intensity were the largest effects: both of these trends (Figure 2-9 & Figure 2-14) were in part due to a 1990 ban on bituminous coal in Dublin, which along with a targeted marketing campaign to recruit new customers (Hull, 2008) enlarged the number of dwellings connected to the gas network. Examination of connections according to dwelling type revealed a high proportion of terraced dwellings, which had significantly higher average consumption than the terraced dwellings connected in the 1980s. The weather effect, which was positive in three out of four years contributed most of the remaining share of changing gas consumption. The size effect for this period was 0.1 GWh in 1993 and -0.1 GWh in 1994 making it cumulatively zero for the period.

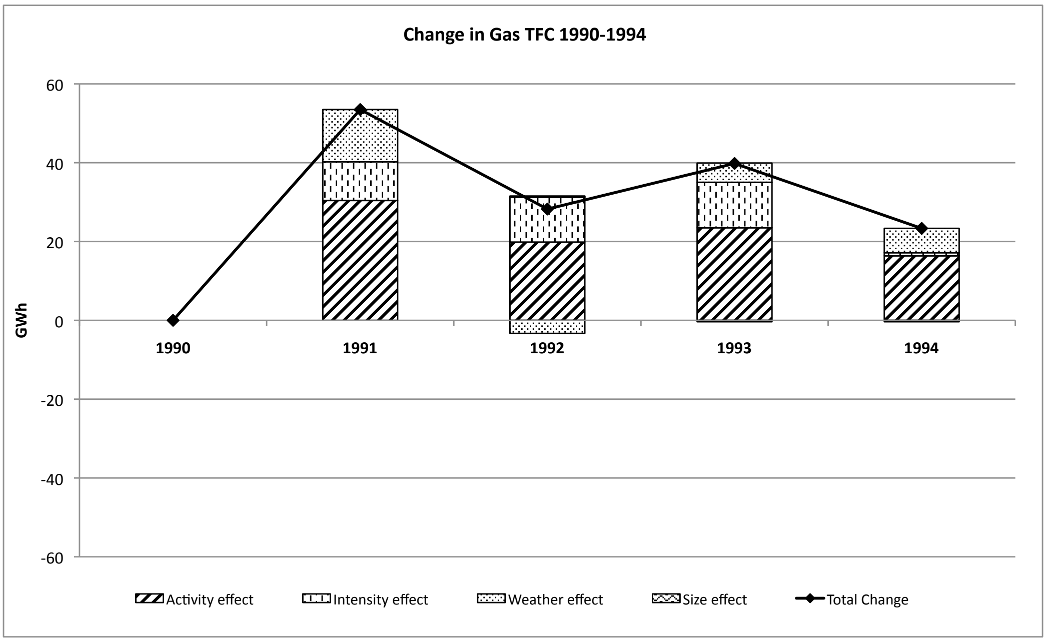

Figure 2-9. Decomposition of gas consumption 1990-1994

2.4.2 1995-1997

This period marked a break with the trend of consistent growth in the previous period, see Table 2-3. The primary reason for the sharp rise in consumption in 1996 and fall in consumption in 1997 was the weather effect, which had an exaggerated impact because the activity and intensity effects were small, see Figure 2-10. As shown in Figure 13, the activity effect decreased in magnitude each year (1995, 1996 & 1997) and in 1997 reached its second lowest rate in the entire analysis period. According to the dwelling type disaggregation, the intensity effect for terraced dwellings for this period was similar in magnitude to other time periods, but due to the declining intensity effect in detached and semi-detached dwellings, the terraced dwelling share was much larger. For this period, the size effect was positive but negligible, see Table 2-4.

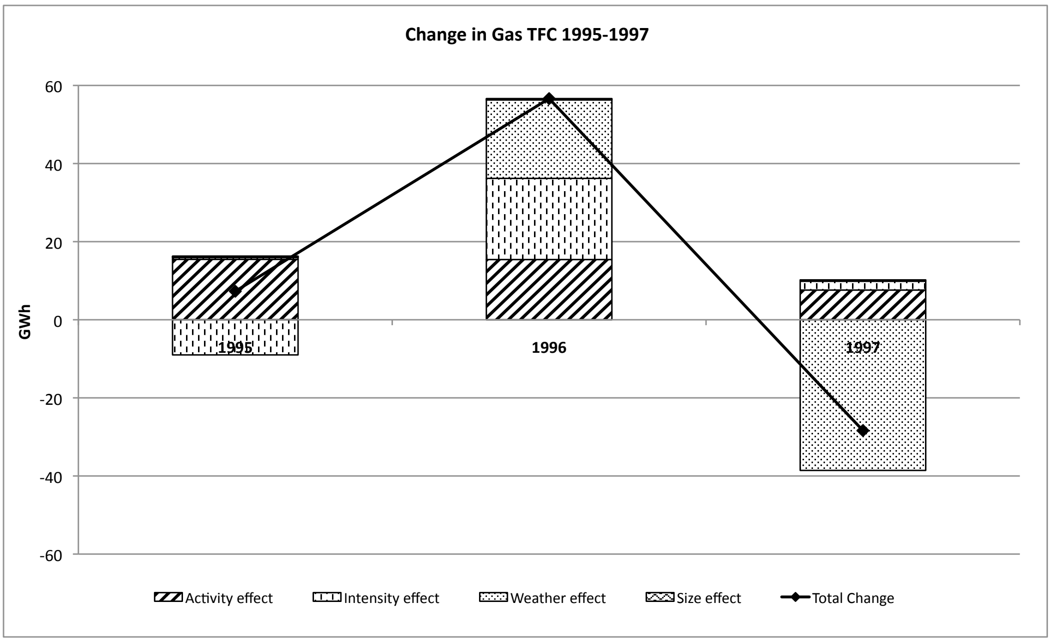

Figure 2-10. Decomposition of gas consumption 1995-1997

2.4.3 1998-2000

1998–2000 was a period of consistent growth in gas consumption. Every year had a positive activity effect. As can be seen in Figure 2-3, the gas network was expanding into the rapidly growing area outside Dublin county (Greater Dublin Area) at this time. However in 1998, and for the first time in the entire analysis period, the intensity effect was larger than the activity effect, see Figure 2-11. Analysis of the intensity effect, shows it was concentrated in semi-detached dwellings. It is not known why the intensity effect is so high in 1998, but it was observed that the intensity effect for 1997 was very low and that an average value for the two years is normal, indicating perhaps a displaced effect from 1997 to 1998. The weather effect had a large impact in 2000, reflecting the cold weather that year. The size effect, although small again, was growing; compared cumulatively to the previous period, it was nearly seven times bigger, see Figure 2-8. This a combination of economic growth driving larger dwellings and the fact that many of the dwellings connected during this period were in the GDA outside Dublin county, where dwellings tend to be larger than in Dublin.

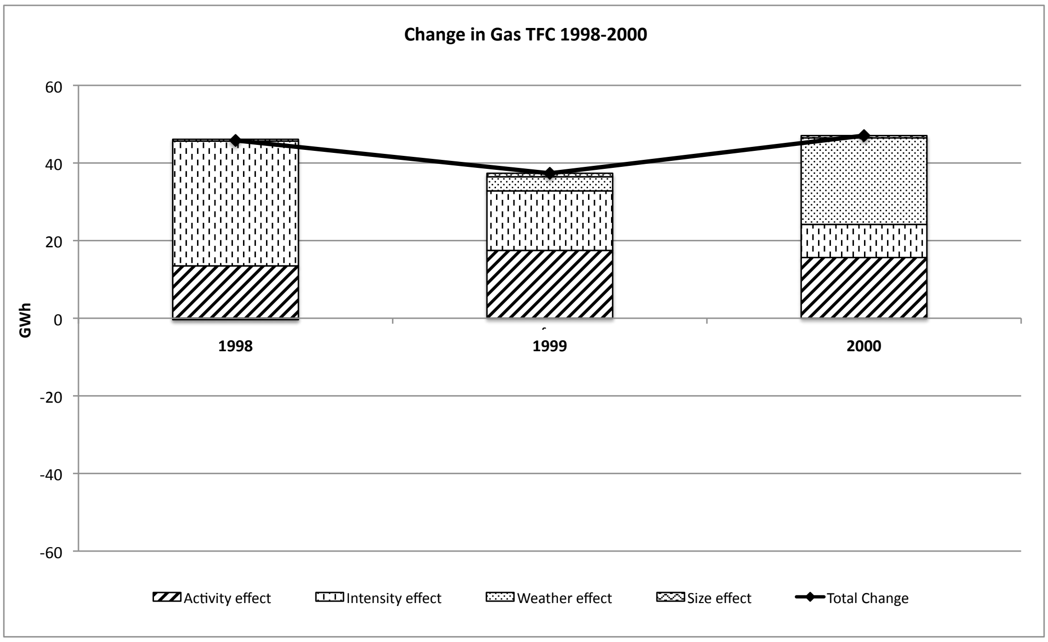

Figure 2-11. Decomposition of gas consumption 1998-2000

2.4.4 2001-2004

For 2001–2004, average annual consumption growth declined to 5.7%. The activity effect was positive and it grew in three out of the four years, see Figure 2-12; this trend can also be seen in Figure 2-3, which shows the gas network expanding into many new towns during this period. Analyzed by dwelling type, the increase in activity was concentrated in semi-detached dwellings (81%). While there was volatility in the intensity effect (see Figure 2-12), the cumulative impact for the period was in the same range as the cumulative impact for preceding periods. The growing number of semi-detached dwellings showed in the intensity effect with an enlarged semi-detached share (49%) in comparison to the terraced dwellings share (30%) which continued to decline.

The weather effect also had a substantial impact in 2002 and 2003, and was similar to 1996 and 1997, when the weather effect alternated between a large positive and a large negative impact. The 2002 BR first came into full effect in 2004, after a phase-in period of one year. In this year, the 2002 BR effect reduced gas consumption by 7.2GWh (see Figure 2-12) and compared to 2003, reduced overall gas consumption by 1.5%. At the end of the four year period, the cumulative size effect was 5.4 GWh, which almost completely cancelled out the gas reduction due to the 2002 BR.

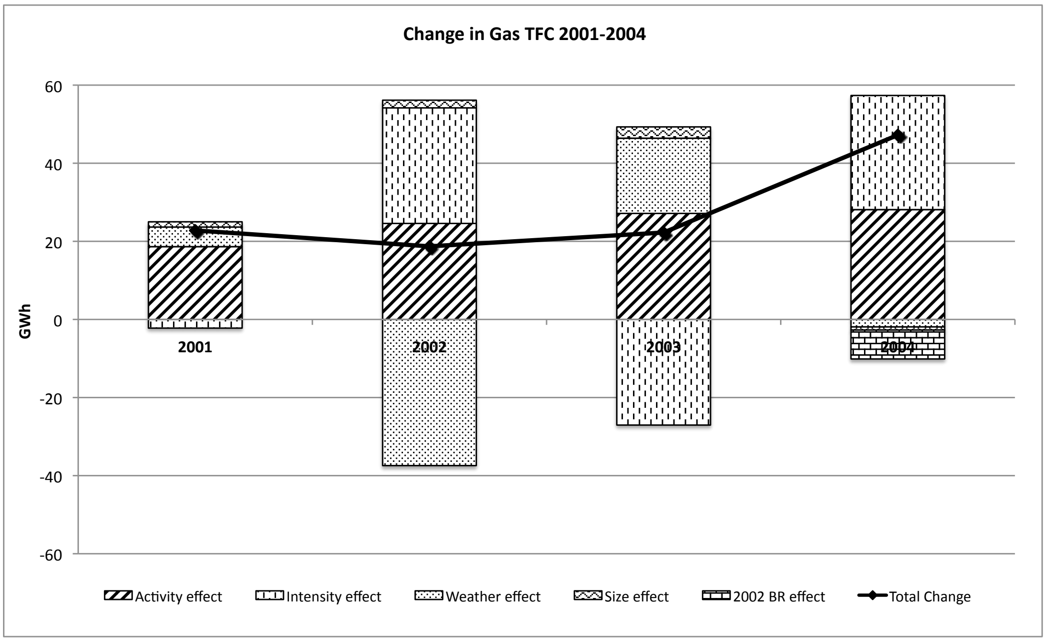

Figure 2-12. Decomposition of gas consumption 2001-2004

2.4.5 2005-2008

In each year between 2005 and 2007, gas consumption decreased, see Figure 2-13. The three drivers of this consumption were a shrinking positive activity effect, a growing negative intensity effect and a consistently negative weather effect. Between 2005 and 2007, the activity effect exceeded the overall change in gas. In other time periods, when the activity effect was large, it was concentrated in occupied semi-detached, whereas in this time period, there was a sharp fall-off in the semi-detached contribution and the relative share of detached dwellings increased. The declining intensity effect was negative across all dwelling types and was most pronounced in semi-detached dwellings and detached dwellings. Compared to its initial impact in 2004, the 2002 BR effect was much diminished in 2005 and 2006 with the dwelling size effect effectively cancelling it out.

In 2008, the final year of the analysis period, overall gas consumption increased by 11.3 % which was largely because of the change in weather. Population weighted national degree days for 2008 were 5% above long term average degree days and nearly 20% higher than the average for the previous two years. The activity effect was positive but continued its downward trend for the fourth year in a row; in 2008, it was at its second lowest absolute value for the entire analysis period.

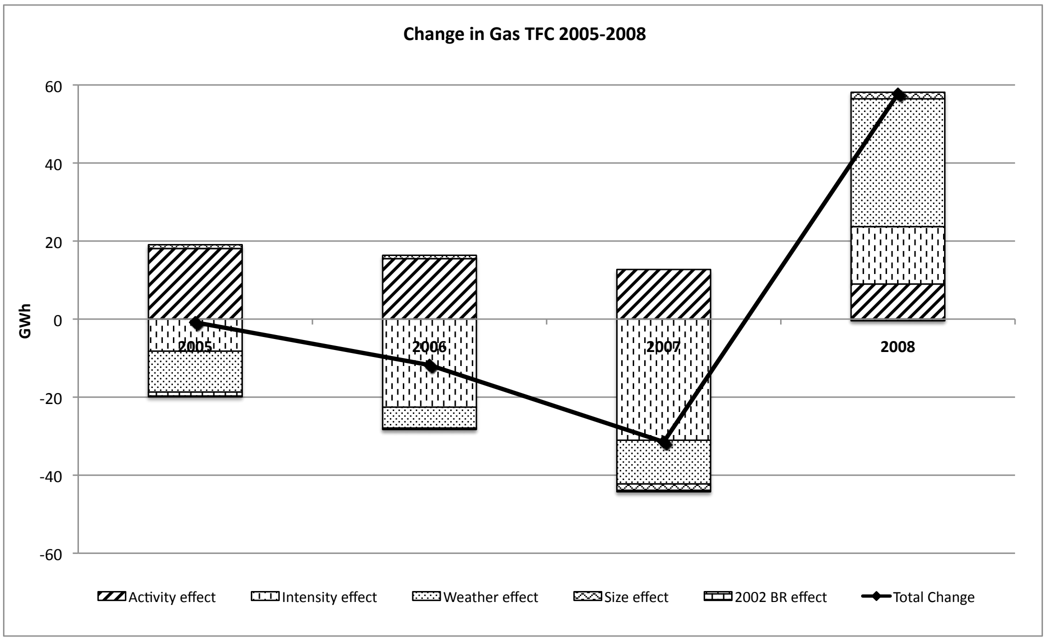

Figure 2-13. Decomposition of gas consumption 2005-2008

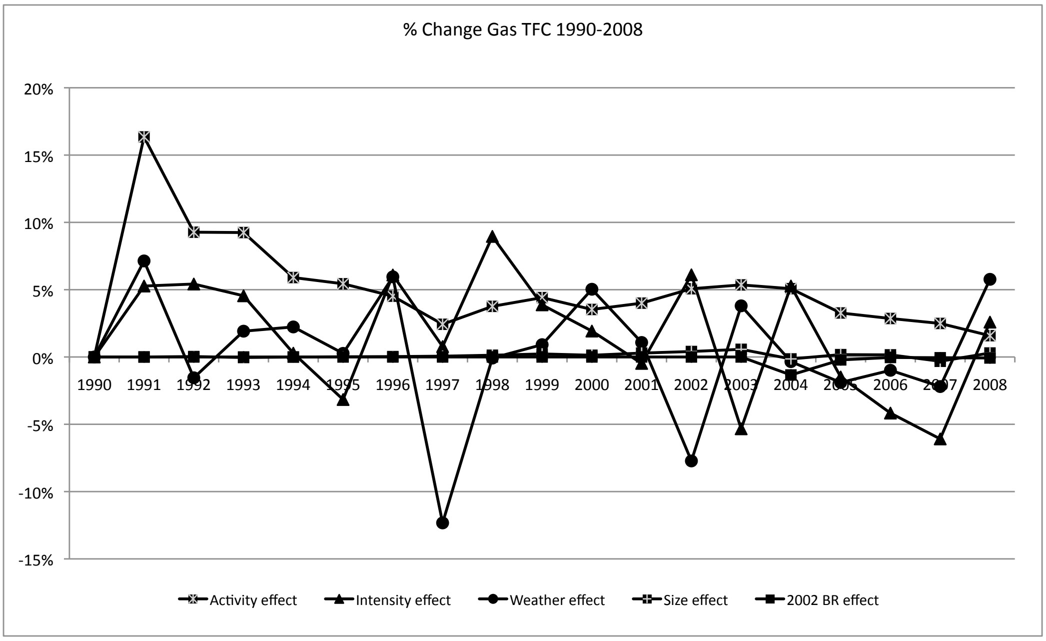

Figure 2-14. % change in decomposed effects for gas consumption 1990-2008

2.5 Discussion

2.5.1 Activity effect

The activity effect had the largest cumulative impact of the five effects and it was also the best explainer ($R^2 = 0.97$) of cumulative change in gas consumption. Over the entire analysis period, the activity effect had a diminishing growth rate. Large activity effects between 2002 and 2004 were closely tied to the expansion of the national gas network during this time. Its declining rate of growth post-2005 made it a contributory factor to the overall decline in gas consumption between 2005 and 2007. Of all the dwelling types, semi-detached dwellings were the only positively correlated dwelling type with activity effect. This reflected their high (60%) share of new connections, which during most of the 1990-2008 period grew as more new dwellings were connected. The existence of vacant dwellings within the activity effect was small, but not negligible; in the first decade vacant dwellings had an average share of 7%, in the second decade this share grew to an average of 15%.

While it has been possible to determine the impact of dwelling type and vacant versus occupied status, due to a limitation of the data set, it has not been possible to determine the impact of fuel switching, i.e. existing dwellings converting to gas. Oil central heating greatly increased its share of overall dwellings during this time (O Leary et al., 2008) and it is known that gas was the fuel of choice for new dwellings (BGN, 2002). In a decomposition analysis of electricity consumption in the residential sector in Brazil (Achão and Schaeffer, 2009) also found a high activity effect; it is a finding appropriate to a rapidly growing economy.

2.5.2 Intensity effect

The intensity effect was the second largest effect and on a year-to-year basis, alongside the weather effect, it was the effect most likely to explain change in gas consumption ($R^2 = 0.688$). In certain years, the driver of intensity effect was clear, e.g. in the early 1990s, the increased number of older terraced dwellings, with their large variation in average consumption drives the rising intensity effect. In later years, the share of terraced dwellings intensity effect fell over time as more semi-detached were added to the gas dwelling stock. As the share of vacant dwelling increased, the share of intensity effect due to vacant dwellings increased and this is most in evidence in 2004 – 2008.

The purpose of the intensity effect in this analysis was to distinguish it from the weather and size effect. As noted in section 2.3, certain assumptions and limitations accompany the data meaning that both the weather and size adjustments are imperfect and are potential underestimates, i.e. the weather effect was based only on degree-days and cannot capture factors such as humidity or rainfall; size adjustments were not applied to a small portion of the dwelling types (bungalow and terraced) and were only nationally applied from 1990-2000. Therefore, a small amount of the intensity effect could be due to uncaptured weather and size effects.

In certain years, it is not entirely clear why the intensity effect was changing; this is due to the intensity effect being a function of all the non-captured effects such as the direct economic effect of price and income, changing internal temperature and the impact of changing occupancy effect. While other studies have concluded that natural gas demand is quite inelastic to price (Diffney et al., 2009), the period from 2004 to 2008 saw a consistent rise in price, which appears to be well correlated with the reduced gas demand across all dwellings in 2005-2007. Without linked data sets, or more detailed data, it is unfortunately not possible to further examine the influence of price, income or occupancy on gas consumption. Stemming from this shortcoming, a recommendation is made at the end of this thesis to link more data-sets together in order to examine the impact of these metrics. However, it is known that households with piped gas tend to have higher incomes, in part because such dwellings tend to be in urban areas (Watson et al., 2003).

Dwelling occupancy changed considerably over the period and it is possible that a record low unemployment rate (CSO, 2011), which led to low day-time occupancy of the dwelling, all things being equal, would have led to lower average energy dwelling consumption. The impact of changing internal temperature has also not been investigated due to a lack of adequate data.

2.5.3 Weather effect

It has been stated that the weather effect can explain 90% of natural gas variation (Diffney et al., 2009); in this decomposition analysis, for explaining year-on-year variation, the weather effect had effectively the same R^2 (0.686) as the intensity effect R^2 (0.688). In two years (1997 & 2008) the weather effect was larger than all other effects and determined the overall trajectory of total change in gas consumption. While in any given year the weather effect could be sufficiently large to counter the change in gas consumption due to the activity effect, the cumulative weather effect is also of interest. As shown in Figure 2-7, the intensity effect fell for four consecutive years and for the period 2005-2007. As shown in Figure 2-15, degree days for the period trended down and concomitantly, so did the cumulative weather effect. This result suggests that rising surface temperatures in Ireland since the 1980s (Met-Éireann, 2011) are having a reducing effect on gas consumption over time.

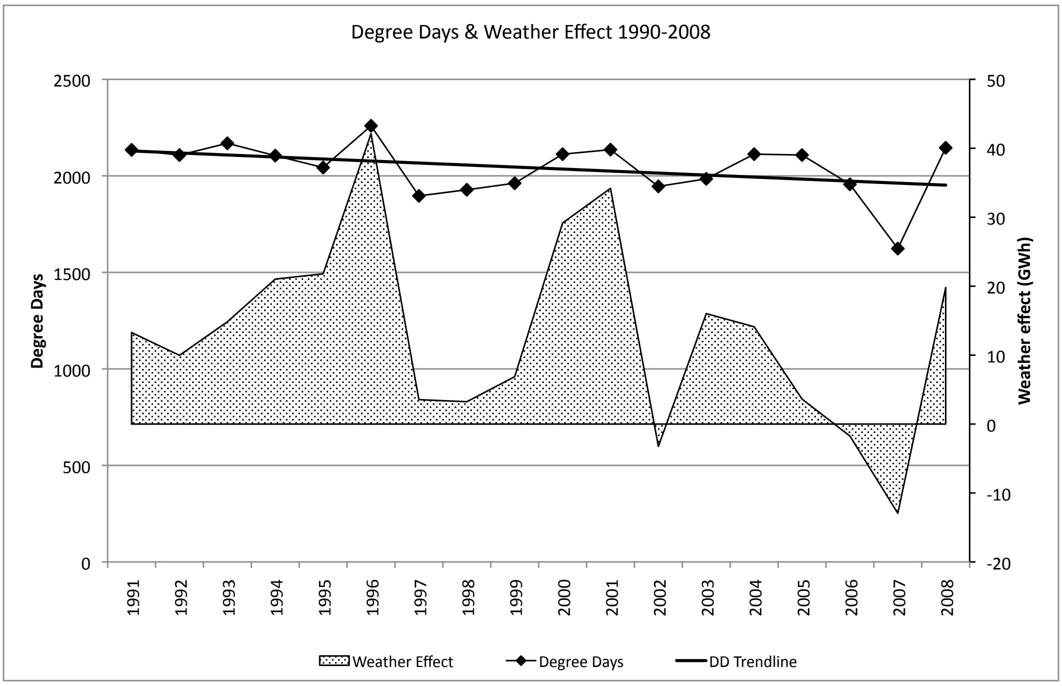

Figure 2-15. Decomposed weather effect and degree days 1990-2008 (data source: (Met-Éireann, 2011))

2.5.4 Size effect

In all years the size effect was small and for fifteen out of nineteen years it was positive; while there is a general trend of increasing size effect, which peaks in 2003, there is a significant fall-off thereafter with two negative years in 2004 and 2007. The cumulative impact of the size effect was 9.5 GWh, over 2% of the total change in gas consumption. As has been stated, the size effect is potentially an underestimate since it wasn't applied for bungalow and terraced dwellings which together represent 12% of the dwellings in the data set.

Other analyses have found a significant size effect. In a comparative decomposition analysis of energy use in Norway, Denmark and Sweden, Unander (2004) concluded that dwelling size was the most important structural effect and determined it to be closely aligned to incomes, in situations of both rising incomes and stagnating incomes. The size effect is to some extent an affluence effect in that larger dwellings tend to have higher incomes (Watson et al., 2003).

Determining the precise reasons for the change in dwelling size are beyond the scope of this analysis, but it is probable that two factors which led to the negative size effects (in 2003 & 2007) are the changes to stamp duty exemptions for first time buyers in 2004 and economic pressure on land throughout the entire period. In 2003 all dwellings eligible for stamp duty exemption had to meet two criteria: (1) floor area below 125m^2 and (2) a sale price below €190,500 (Revenue, 2010). In 2003, the average dwelling sale price was €224,567 (DECLG, 2009)18% above the dwelling price threshold. In 2004, when the average price of a new house was €249,191 (DECLG, 2009), stamp duty exemption for first time buyers was increased to €317,500 (Revenue, 2010). While this change applied to all dwellings, only semi-detached dwellings decreased in floor area from 131m^2 in 2001 to 119.1m^2 in 2004. By decreasing the floor area of new dwellings to below 125m^2, the number of dwellings eligible for first time buyer, stamp duty exemption was significantly increased. The second factor in the declining floor areas for semi-detached could be economic pressure on land prices which during the analysis period rose continuously.

2.5.5 2002 BR effect

Over the period 2004-2008, the 2002 BR reduced gas consumption cumulatively by 9.5 GWh, which compared to gas TFC for the same period, was a 0.3% reduction. Comparing the average intensity of dwellings before and after the 2002 BR are introduced, the fall in gas consumption is approximately 10%, which falls short of the 20% target reduction set by the 2002 BR. The decomposition analysis shows that the impact of the 2002 BR declines over time (see Figure 2-13) indicating that the persistence of savings is weak.

There are multiple possible reasons some of which could be newer dwellings being added to the BR group, rebound & higher comfort levels amongst earlier BR dwellings and non-compliance with BR; however, it is not within the scope of this decomposition analysis to give a robust assessment of the multiple factors affecting the implementation of the 2002 BR except to highlight the need for more ex-post analysis of this policy. In terms of interaction with other effects: dwelling size effect over the entire analysis period is cumulatively positive (9.5 GWh) and so effectively negates the 2002 BR effect (-9.5 GWh). The dwelling size effect is likely to be replicated in the national dwelling stock and so it is probable that a similar reduction in 2002 BR effect is occurring because of larger dwellings nationally.

While a decomposition analysis does not have the scope for a full ex-post analysis on a policy such as 2002 BR, it can outline apparent savings, the development of these savings over time and the interaction of the policy with other dynamic factors in the dwelling sector. This process has raised questions, which have helped frame a more comprehensive ex-post analysis of the 2002 BR policy, which has been undertaken in Chapter 3.

2.6 Conclusions

This chapter has examined the impact of changing customer numbers, average consumption per dwelling, the 2002 BR, the weather effect, the size effect, varying dwelling type and changing share of vacant dwellings on gas consumption in the residential sector in Ireland from 1990 to 2008. The activity effect was the largest of the five effects and the most significant underlying cause was the growing number of semi-detached dwellings. The intensity effect had the second largest impact; some of the reasons are clear (i.e. dwelling type), some have been isolated (weather and size) and some of reasons remain unclear. The 2002 BR had a negative impact on gas demand, but the extent of that impact is declining over time and is being negated by the positive dwelling size effect, which for the entire analysis period is equal to the 2002 BR effect. Overall, the impact of vacant dwellings is small. The weather effect in particular years had a dominating effect, but over time its impact is waning. This decomposition analysis has been able to outline many key trends and highlight areas for further examination such as 2002 BR and the role of policy in impacting energy consumption. Decomposition is used to analyse the results of an energy systems model in Chapter 5.

In terms of policy, the focus on building regulations as a key policy for effecting energy reduction in the residential has serious shortcomings. Even within the context of a rapidly expanding dwelling stock, the majority category of existing dwellings are not addressed by such an approach to energy efficiency policy. In addition, the preliminary analysis in this chapter suggests that building regulations as a policy are underperforming, their impact is diminishing over time and that other factors such as dwelling size are cancelling out their impact. Ex-post analyses of policies such as the 2002 BR are vital if they are to be successfully implemented. At the time of writing, a large scale retrofitting programme, the Better Energy

Homes scheme is being rolled out; it remains to be seen what the impact of this policy will be.

While this analysis has hypothesized, but not confirmed, that economic conditions in the form of price, income and occupancy are influencing gas consumption (manifest through the intensity effect), in the period post 2008, it would be possible to examine to some extent if this is case: under a recession, the intensity effect would be expected to decline. Other changes to gas market post-2008 are the increased number of suppliers. In the analysis period 1990-2008 there was only one, but post 2009 there are three suppliers with an element of price competition. There has been a significant amount of customer switching to take advantage of favourable price; the impact of this on gas consumption is unknown.

3 Ex-Post Analysis Of Residential Building Regulations

Abstract

Until 2008, Ireland had a relatively high turnover rate of its dwelling stock; this was an outcome of a boom in housing construction. In 2008, according to CSO data: 66% of permanently occupied dwellings had been constructed prior to 1996; 10% had been constructed between 1996 and 2000; and 24% were constructed between 2001 and 2008. This chapter presents an ex-post evaluation of residential building regulations for new dwellings in Ireland using empirical data. The analysis focuses on the energy savings that can be attributed to the energy efficiency part of the regulations. According to an ex-ante evaluation, the 2002 Building Regulations were expected to achieve a 20% reduction in dwelling energy consumption compared to the previous building regulations in place since 1997. This analysis uses metered natural gas consumption data to quantify the actual impact of the 2002 Building Regulations as compared to a control group of 1997 Building Regulation dwellings. The results focus on gas-connected, semi-detached dwellings in Dublin and find a substantial shortfall in the expected energy savings with a statistically significant reduction in energy consumption of 11.2±1.9 % compared to an ex-ante prediction of 20%. A separate analysis on the level of compliance with the 2002 Building Regulations, for gas connected semi-detached dwellings in Dublin, finds a 13±1.6% level of non-compliance, higher than the guideline value for non-compliance of 10%.[11]

Keywords: ex-post analysis; residential sector energy efficiency policy; building regulation compliance

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[11] Rogan, F., Gallachoir, B.O., (2011). Ex-post evaluation of a residential energy efficiency policy measure using empirical data. *Proceedings of the eceee (European Council for an Energy Efficient Economy) 2011 Summer Study,* 1769–1778. 6 – 11th June 2011, Belambra Presqu'île de Giens, France

3.1 Introduction

Between 1990 and 2008, final energy consumption in the EU12 grew by 15.7% and in Ireland by 79.5%; during the same period, energy growth in the household sector was 16.4% in the EU12 and 31.5% in Ireland (Eurostat, 2010). There are now in place ambitious policy targets that seek to address this energy growth: the 2006 Energy Services Directive (ESD) has committed all EU27 member states to a 9% reduction in total final energy consumption by 2016 (EC, 2006) and the 20/20/20 climate package has set a target for each member state to reduce its energy demand by 20% by 2020 (European-Commission, 2008). While both these targets are currently indicative, the most recent directive has mandated for indicative targets together with binding measures (EU, 2012). According to the Irish NEEAP drawn up to meet these energy efficiency targets, there will be a significant contribution from the residential sector and a substantial contribution made as a result of building regulations (BR), also referred to as building codes, for new dwellings (DCENR, 2009).

In recent years, across both the developed and developing world, more and more countries have been adopting mandatory BR (Janda, 2009). Many countries have successfully used new dwelling BRs to address growing energy demand; e.g. the US state of California has historically one the strictest building code regimes in the world (IEA, 2008) and this has helped California maintain per capita electricity use at relatively flat levels (Chang, 2006). In Ireland, residential BR incorporating a minimum standard of energy efficiency have been in place since 1979 (O Leary et al., 2008). Over time, the scope of the Irish BR have steadily widened and their stringency has steadily increased: the 2002 BR were designed to achieve a 20% reduction in energy consumption compared to the 1997 BR (DEHLG, 2002), revised regulations introduced in 2008 were designed to achieve a 40% savings compared to the 2002 BR (DEHLG, 2008), which were followed by the 2011 BR designed to achieve 60% dwelling energy savings, again compared to 2002 BR (DECLG, 2011).

Currently, residential BR constitute a major part of Ireland's energy savings targets with this policy measure alone projected to account for 14.4% of Ireland's total NEEAP energy savings in 2020 (DCENR, 2009). These are ambitious targets, yet there has been to-date no publically available ex-post evaluation of how efficacious Irish BR have been at achieving their target energy efficiency improvement; at the same time, concerns have been raised about the effectiveness of Irish BR (Thornton, 2008) and there have been a number of high profile cases of BR failure (Power and Hogan, 2012). Ireland's NEEAP modelled historical energy savings for the 2002 BR for the period 2002-2008, however it was not based on empirical data (Rogan, 2009). This gives rise to the research question: what has been the empirical impact of the 2002 BR in Ireland in terms of energy savings? This chapter attempts to answer that question, by quantifying the energy savings of the 2002 BR using empirical data and using the 1997 BR as the baseline. A second research question arises: what has been the level of compliance with the 2002 BR? These two questions will form the basis of the quantitative ex-post evaluation of the 2002 BR contained in this analysis.

This chapter is organised as follows: Section 3.2 presents a review of BR as an energy efficiency policy and a review of some methodologies for evaluating polices such as BR. Section 3.3 describes the data used in the analysis and section 3.4 outlines the methodologies used to evaluate the 2002 BR in terms of achieved energy savings and levels of compliance. Section 3.5 presents results, section 3.6 contains a discussion of the results and section 3.7 contains conclusions.

3.2 Building regulations

This section reviews the importance of BR as an energy efficiency policy, summarises the key kinds of BR and lists some of the key factors in successful BR. It also contains a summary of BR in Ireland, how the policy achieves energy savings, how compliance is calculated, some issues that have been raised regarding enforcement and some enforcement methodologies together with a literature review of some pertinent case studies. The functions of BR clearly extend well beyond energy efficiency and include building structure, fire safety, drainage and many other important aspects of building; the focus of this chapter is restricted to the elements of BR[12] relating to energy efficiency only.

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[12] Part L: Conservation of Fuel and Energy

3.2.1 Building energy efficiency

Globally, energy consumption in buildings represents nearly a third of TFC (IEA, 2011b). Many disparate factors contribute to this energy demand and changing composition, some of which were outlined in the previous chapter using a decomposition analysis. In terms of policy options, the energy efficiency standard of the building codes is one of the biggest determinants of the overall energy performance of a building. The energy consuming lifetime of a typical building is long – in Ireland over 50% of dwellings are over 40 years old (CSO, 2007a). Since changes made at the design stage are much cheaper and easier to implement than changes made during the functional life of the building, BR for new dwellings are one of the most important policy types in the residential sector (Laustsen, 2008). In considering the energy balance over the building lifetime, and comparing it with other policies, BR are most likely to have negative costs. Other advantages exhibited by BR are that from a consumer point of view, they have no large investment cost, have low transaction costs, and neither imperfect information nor lack of information such as a lack of interest in energy issues affects their implementation (Haney et al., 2010).

3.2.2 Building regulation types

While international reviews have found many varieties of BR, in terms of specifying energy efficiency standards, a basic distinction exists between prescriptive BR and minimum performance BR; the former being generally regarded as easier to enforce and the latter as more encouraging of innovation (Vine, 1996). There are many different roads to BR implementation and while this diversity can make comparisons and guidelines for best practice difficult, some regimes have been identified as more successful than others: for example, in Scotland there is a certificate system for compliance and a requirement for auditing of the compliance process (Thornton, 2008) and in California there is an mandatory audit requirement (Haney et al., 2010). Regarding the myriad BR regimes, there is unanimity that the degree of BR enforcement is the biggest determinant of BR success (Deringer et al., 2004; Hitchin, 2008; Haney et al., 2010); a frequent addendum to this conclusion is that not enough resources are currently given over to the enforcement process (Hitchin, 2008). Adequate measurement and verification of BR programmes are vital to successful enforcement, but just like ex-post analyses of energy efficiency policies in general (Hull et al., 2009), these studies are difficult to find (Koeppel and Ürge-Vorsatz, 2007). A review of some of the BR studies found is in section 3.2.3.

Building regulations in Ireland

In Ireland over the past 40 years, the energy efficiency aspect of residential BR has steadily improved (O Leary et al., 2008). For each set of BR, the legislation documents are accompanied by a Technical Guidance Document (TGD), which contains practical and detailed information on dwelling design, construction and standards for a host of building properties such as maximum heat loss values for separate building elements, thermal bridging limits, maximum air filtration rates, minimum insulation thickness, etc. The TGD also contains details on how compliance with the BR can be demonstrated.

The 2002 BR succeeded the 1997 BR, and contained building element U-values which, by being more stringent than the previous BR, provided for a 20% reduction in dwelling energy consumption (DEHLG, 2002), see Table 3-1. In terms of demonstrating compliance with the 2002 BR, the 2002 BR TGD contained two prescriptive methodologies and one minimum standard methodology for meeting the new energy standard; respectively, these are: (i) maximum individual U-values for separate building elements, (ii) a maximum average U-value for the entire building, and (iii) a heat energy rating standard, which relates the maximum permitted kWh/m^2/yr to the quotient of building heat-loss area (m^2) and building volume (m^3), see Table 3-2 (DEHLG, 2002).

Table 3-1: U-values for 1997 BR & 2002 BR

U-value (W/m^2 K)	1997 BR	2002 BR
Windows/Roof-lights	3.3	2.2
Doors (average for all doors)	3.3	2.2
Floor (ground or exposed)	0.45	0.25
Walls (exposed)	0.45	0.27
Roof	0.25	0.22

Table 3-2: Heat energy rating method for BR compliance

Maximum Permitted Heat Energy Rating (kWh/m^2/yr)	102.5	101.4	99.0	92.6	88.2	83.8	81.6
Dwelling Heat Loss Area/Building Volume (m^{-1})	1.25	1.2	1	0.8	0.6	0.4	0.3

The 2002 EU Energy Performance of Buildings Directive imposed a number of requirements on Ireland, one of which was an updated methodology for evaluating BR; in Ireland, the Dwelling Energy Assessment Procedure (DEAP) was developed to meet this requirement. The 2005 BR were updated to incorporate the DEAP methodology for assessing BR (DEHLG, 2006a). In 2007, the DEAP software programme also became the default methodology for determining the energy asset rating, or Building Energy Rating (BER) of a dwelling (DEHLG, 2006a). The DEAP programme is used in the analysis in this chapter and will be discussed in more detail in section 3.4.

Building regulation enforcement

In terms of their target energy standard, Irish BR are on a par with the UK and just below Scandinavian countries (EURIMA, 2007). This reflects the momentum of EU legislation, which has been driving improved building energy efficiency standards for many years. The same cannot be said of BR enforcement in Ireland, which uniquely does not have a requirement that all new dwellings be inspected for compliance: only 12-15% of all dwellings are required to be inspected. By contrast, in many other EU countries there is a requirement for 100% inspection (Thornton, 2008). Within the 12-15% of dwellings that are inspected, there is a large emphasis on fire safety, often to the detriment of other factors (Rogerson et al., 2005). In addition, Irish Building Control officers are regionally based and while there is a central Building Control Authority, there is a lack of formal training, procedures and consistency in approach for Building Control officers (Thornton, 2008). Issues with building control are not unique to Ireland and have been recorded in England and Wales (Pan and Garmston, 2012); however, Ireland is one of only two countries in the EU where no completion certificate is required (Hitchin, 2008). At the time of writing, there are currently in place plans to revise Building Control procedures in Ireland (DECLG, 2012). The explicit impact on dwelling energy consumption of some of the current BR enforcement shortcomings will be assessed in this chapter.

3.2.3 Building regulation evaluation methodologies

This section reviews the legislation requiring BR evaluation and some of the recommended and competing methodologies for evaluating BR. It also contains a literature review of studies, which have examined the impact of BR in other countries.

ESD on Energy End-Use Efficiency

For Ireland the first specific obligation to report on energy savings achieved due to energy efficiency policies came from the 2006 ESD on Energy End Use Efficiency (EC, 2006). The ESD required each member state to prepare a NEEAP that would achieve a 9% reduction in energy consumption in 2016, relative to 2008. As part of this plan, rigorous measurement on the progress towards the 9% reduction target must be reported on an interim (2011) and final (2016) basis (EC, 2006). This report is required to have “a thorough analysis and evaluation of the preceding [N]EEAP”, which will include “the final results with regard to the fulfilment of the energy savings” calculated according to a framework that measures energy with bills or energy sales data, is normalized for weather, occupancy, etc. and accounts for uncertainty in a statistically quantified way (EC, 2006). While the ESD requires a certain degree of rigor, it doesn’t contain specific detail on measuring and verifying energy savings from particular types of policies. In November 2006, the Evaluation and Monitoring for the EU Directive on Energy End Use Efficiency and Energy Services (EMEEES) project was specifically launched for this purpose (EMEEES, 2009).

EMEEES

The goal of the EU funded EMEEES project was to produce harmonized indicators that enable cross country comparison, as stipulated in the ESD (EC, 2006). The EMEEES project produced a detailed description of how to evaluate and report on BR: savings are to be calculated with respect to a baseline that effectively excludes autonomous development of energy efficiency; the baseline is the situation in a member state at the moment when the BR are implemented for the first time and is not dynamic; a time-lag, with a default value of two years, must be taken into account for new BR to take effect in building production; non-compliance with the building code should also be taken into account and a default value of 10% is recommended unless empirical data can substantiate a more accurate figure; square metres of conditioned floor space is the preferred unit of measurement rather than dwellings or buildings as a unit; and the rebound effect is not to be taken into account (Maas and Monne, 2009). Unlike the ESD, the EMEEES guide does not contain any detail on expressing uncertainty in a statistically quantified way.

European Ex-Post Evaluation Guidebook

The European Ex-Post Evaluation Guidebook for DSM and EE Service Programmes was produced by SRC International in 2002 and was co-authored by a committee of mostly European energy experts (International, 2001). It doesn't contain measure-specific methodologies, but it does contain methodologies that can be adapted to different measures depending on the level of accuracy that is required and the amount of data that is available. The Guidebook proposes a two-way taxonomy of evaluation methods. The first method is an *engineering simulation*, which is best used to quantify the ex-ante impact of a measure. The second method is *statistical* with a number of variations: the simple comparison can be a time-series comparison, which is expressed as the 'same people at different times', or a cross-sectional comparison, which is expressed as 'different people at the same time'. There is also a weather-adjusted comparison and the last statistical method suggested is a multivariate analysis, which the Guidebook deems the most accurate method (International, 2001).

IPMVP

The International Performance Measurement & Verification Protocol (IPMVP) is an international standard maintained by the Efficiency Valuation Organization and is much used verifying energy efficiency savings (Vine, 2005). Volume III, Part I is "Concepts and Practices for Determining Energy Savings in New Construction," a 34-page report on evaluating the efficacy of building standards for energy savings for both commercial and residential buildings (EVO, 2006).

Volume I of IPMVP "Concepts and Options for Determining Energy and Water Savings" contains an extensive appendix for quantifying uncertainty in energy efficiency programmes (EVO, 2007).

Ex-post evaluations

Case studies of residential energy efficiency are more commonly focused on retrofitting and improvement of existing dwellings rather than BR for new dwellings; despite the importance of BR as an energy efficiency policy, there has been to-date a shortage of case studies examining their ex-post impact (Jacobsen and Kotchen, 2009). This chapter addresses this knowledge gap. The papers that do exist, offer differing results of dwellings both over-achieving and under-achieving their BR target savings. This divergence of results is in part due to variation in local characteristics and it also highlights the need for more ex-post analysis, since there is little certainty about how BR will achieve their ex-ante targets.

In a US study that examined the period from 1979 to 1988, the authors concluded that the building codes under investigation had no effect on energy consumption; this result was deemed to stem in-part from the codes not being strict enough (Jaffe and Stavins, 1995). A study on BR based on a sample of Florida dwellings in a single town for both gas-connected and electricity-connected dwellings found that the actual dwelling performance was "reasonably close" to the predicted improvement of 4%, as calculated by an engineering simulation. The authors noted that the state of Florida is "known to have generally strict enforcement of building codes" (Jacobsen and Kotchen, 2009). In a study of German dwellings after 1961, it was concluded that dwellings were under-achieving their energy targets because their insulation levels were far below the technical simulation (Schuler et al., 2000). In a study of BR in Denmark, a 7% level of savings was found against an ex-ante prediction of 25% (Kjaerbye et al., 2011).

While many countries such as the UK (Haney et al., 2010), Netherlands (Koeppel and Ürge-Vorsatz, 2007), parts of the USA (Dastur, 2004) and China (Maas and Monne, 2009) have noted having an issue with BR compliance, case studies on BR non-compliance are also rare. A detailed study of a sample of dwellings in England and Wales found failures in enforcement led to “poor” levels of BR compliance (Pan and Garmston, 2012). Vine (Vine, 1996) conducted a survey of compliance with BR in three US states and found evidence for varying levels of compliance that corresponded with the existence or absence of utility-sponsored residential new construction programmes, which offers credits to builders to exceed the minimum BR standards. For space heating in Austria, Haas and Biermayr (Haas and Biermayr, 2000) determined a 20-30% rebound value and in the context of the rebound effect value “eating into” energy savings, concluded that BR remain one of the most important energy policies.

3.3 Data

In this chapter, the evaluation period for the 2002 BR was from 2004, when they were deemed to be fully implemented, until 2008, when a newer set of BR, introduced in July 2008, had superseded them. Four separate data sets were available for this four year evaluation period:

- Metered natural gas consumption
- Building energy ratings
- Dwelling floor area
- Degree days

Bord Gáis Networks (BGN) provided the author with a data set of metered consumption for all residential natural gas customers for each year between 1990 and 2009: in 1990, there were 139,000 customers and in 2009, 566,000 customers. Unlike the data set described in Chapter 2, this data set contains all gas customers, and is in statistical terms a population rather than a sample. This data-set contains the same additional ancillary data as the 10% sample described in the previous chapter.

3.3.1 Metered natural gas consumption

Data preparation: Prior to using this data in our analysis, some filtering and preparation was necessary: firstly, to remove outliers, 2.5% of the largest and 2.5% of the smallest values were trimmed from the data set; then, any values less than 575 KWh were removed to account for dwellings that only use gas for cooking[13]; finally, vacant dwellings were identified as dwelling without consumption or with zero consumption for any full year and were removed. *Assumptions:* It was assumed that the year-of-connection to the gas network, as specified in the above data set, was the same as the year-of-construction of the dwelling. The caveats with this assumption will be discussed further in section 3.4.1.

3.3.2 Building energy ratings

Since 1st January 2007, all new dwellings for sale or for rent in Ireland must have a Building Energy Rating (BER). On 1st January 2009, this requirement was extended to include all existing dwellings for sale or for rent (DEHLG, 2006a). SEAI is the supervisory authority responsible for managing the BER process and as part of this role they retain records of every BER assessment. An anonymised database of all BER records for the period September 2007 to February 2012 was provided to the author. Each entry was generated first in DEAP, according to the BER methodology, and then compiled into the database of 229,017 records. A list of the main parameters used by the DEAP methodology to calculate the energy rating of a dwelling is contained in Appendix B.

This data set included nearly every field contained in a BER assessment and as a sample, represents 14% of all pre-2009 dwellings in Ireland. However, it is not a random sample and due to the fact that BERs have been a requirement for new dwellings for four years and existing dwellings for only two years, the data set is far more representative of newer dwellings, i.e. dwellings constructed between 2001-2008 are a 21% sample whereas dwellings constructed between 1971-1980 are an 11% sample. Due to the prevalence of newer dwellings, there is also a probability that in terms of dwellings being either owner-occupied or tenant-occupied, there is a different distribution in the BER data set than in the national dwelling stock. However, the analysis in this chapter is focused on the standard of the initial construction of each dwelling, which is assumed to be unaffected by the dwelling subsequently being either owner-occupied or tenant-occupied.

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[13] Based on http://www.carbonfootprint.com/energyconsumption.html

Data preparation: A considerable amount of data filtering was required before the BER database could be used as a data set. This was done in collaboration with SEAI and a full list of the removed entries is in Appendix B. The approach generally was to remove outliers that differed substantially from the average; erroneous values were also identified and removed.

3.3.3 Dwelling floor area

The same data on dwelling floor area that was used in Chapter 2 is also used in this analysis. Similarly, the adjustment is only applied to base load (water heating) values from average metered consumption of July & August because the floor area adjustment is only applied to the space heating load, which is assumed to vary linearly with floor area.

3.3.4 Degree days

In order to weather correct the natural gas consumption data, degree day data for Ireland was retrieved from Met Éireann. The weather correction methodology employed is from Eurostat's "Temperature correction of final energy consumption" (EC, 2005) and like the dwelling floor area adjustment, it was only applied to the space heating load for each dwelling.

3.4 Methodology

The methodology chosen to evaluate the 2002 BR has two parts and reflects the two research questions introduced in section 3.1. The first part compares the metered gas consumption data of two appropriate groups of dwellings: one (treatment) group of dwellings, built to the 2002 BR and a second (control) group, built to the previous regulations, which in this analysis are the 1997 BR. The key to this approach is normalizing the two groups of dwellings for all energy-significant differences and in this way quantifying the actual impact of the BR. This sheds light on the operational energy performance of houses, which incorporates both the technical aspects (i.e. BR compliance) and behavioural effects of householders. The second part of the methodology examines the asset energy performance of the dwellings built to the 2002 BR, using the BER data set. The purpose of this step is to assess the level of compliance with the 2002 BR.

For both parts of this methodology, the analysis was restricted to semi-detached dwellings. The semi-detached dwelling is not intended to be representative of other dwelling types, it was chosen for investigation as it represents the largest share (41% in 2008) of new dwellings (DEHLG, 2010). In Ireland, the semi-detached dwelling is typically two-storey, has one or two walls adjoined to another dwelling, has three to four bedrooms and its average size ranges between $90m^2$ and $140m^2$. Although the dwelling type (semi-detached) and fuel consumed (natural gas) is the same in both parts of the methodology, because the first part is using consumption data and the second part is using BER data, the two methodologies give different energy consumption results for ostensibly the same dwelling type. This is because the two data sets are generated separately to each other and for alternative purposes than this current analysis; for annual dwelling consumption, the metered consumption data set, for a semi-detached dwelling in 2006 has an average, weather corrected value of 13.17 MWh, whereas the BER data set, for the same dwelling type, has a value of 14.04 MWh. The purpose of the BER calculation is to derive an 'asset rating' that makes the dwelling comparable to other dwellings. As such, it has standardized assumptions regarding occupancy, heating periods and internal temperature for the building and hence does not directly match the metered consumption figures.

There are limitations with using the BER data set to model an estimate of actual energy consumption and it is recommended that a better relationship between the BER data set and the metered consumption data set be undertaken. Many parts of the methodology employed are in accordance with the BR evaluation methodologies reviewed in section 3.2.3. Microsoft Excel 2008 and IBM PASW 18 were used for data filtering and statistical testing respectively.

3.4.1 Part I – 2002 BR empirical impact

A group of dwellings that have not adopted the policy (i.e. a control group) are compared with a group that have adopted the policy (treatment group). This methodology is a composite of the cross-sectional comparison and the weather-adjusted comparison methods described in the European Ex-Post Evaluation Guidebook. Fundamental to this approach is that the two groups "share a wide variety of characteristics" (International, 2001). Working from the metered gas consumption data set, the control group and treatment group were examined for the same year of consumption (2006) and both groups were defined by the same dwelling type (semi-detached), bedroom number (three) and location (Dublin). Differences between the groups were minimized as much as possible and a number of statistical tests were then applied to quantify the differences due to the impact of the 2002 BR.

Part of the reason for choosing the dwelling type category of three-bedroom, semi-detached in Dublin was to minimize the uncertainty associated with the assumption that the dwelling connection year is equal to the dwelling construction year. As discussed in Chapter 2, while the majority of new connections were to new dwellings, some existing dwellings were connected as well. As shown in Figure 2-3, when the gas grid was being extended to the centre and west of Ireland, there was a significant increase in the number of new connections, some of which would have been existing dwellings. Because the gas grid in Dublin has been in place longer than anywhere else in the country, it is assumed that the level of connections for existing dwellings is small and that it did not increase during the years of this analysis. Interviews would have been beneficial to elucidate the difference but unfortunately, data-confidentiality was paramount; the data received was anonymised and it was not possible to conduct interviews with the occupants of the dwellings under examination.

Control and treatment groups

Year of connection to the gas network is the key difference between the groups, by which the impact of the building regulations is pinpointed. The control group, dwellings built to 1997 BR, is chosen as dwellings connected in 1998. The 1997 BR themselves allow six months for implementation (DEHLG, 1997), so a one-year lag is applied to allow that set of BR come fully into force. It should also be noted that there is no difference in terms of U-value requirements between the 1997 BR and the previous 1992 BR. The treatment group, dwellings built to the 2002 BR, is defined as dwellings connected in 2004; although the 2002 BR were legally in force from 1st January 2003, there was a waiver for certain dwellings completed after this date if planning permission had been granted before the 1st January 2003 cut-off point (DEHLG, 2002), so 2004 is deemed to be an appropriate year when the 2002 BR were fully implemented. The population of the control group is 5,011 and the population of the treatment group is 6,035. All of the original dwellings from the control group (connected in 1998) and the treatment group (connected in 2004) are found to be still connected in 2006. The metered consumption data sets are populations as stated in section 3.3, so both the control group and treatment group include all dwellings in their respective categories.

Group differences

The control group and treatment group were defined so as to share as many characteristics as possible. Additional work from other data sources was undertaken to investigate any other differences between the two groups and where possible, these differences (such as floor area) are normalized; the goal is to exclude all differences except that due to BR. Possible differences due to secondary heating fuel types and retrofitting work on the baseline data were also investigated. For floor area, the planning permissions data set is used and for weather correction, degree days are used. Due to a lack of surveys, it is not possible to characterize the two dwelling groups according to their occupants in terms of energy behaviour and income levels.

Secondary heating fuel types

It is necessary to investigate whether the gas consumers in each group used other heating types as well, i.e. were their dwellings only partially heated by natural gas? Since the metered consumption data set does not contain information on non-gas heating sources, a separate data set was utilized. For semi-detached dwellings in Dublin, with natural gas as the main heating type, the BER database contains a 10% sample for 1998 dwellings and a 3% sample for 2004 dwellings. For each dwelling assessed, it contains data on fuel types used as main and secondary, space and water heating. For dwellings built in 1998, a 60.5% share also have natural gas as a secondary space heating fuel; for the same dwellings built in 2004, a 60.4% share have natural gas as a secondary space heating fuel. This tiny difference, suggests that both the control group and the treatment group dwellings had a very similar share of natural gas in their secondary fuel mix.

Retrofitting

It is vital to this method, that both groups should not be different in terms of the potential impact of retrofitting, and hence this was investigated. A national housing survey done in 2002 found that below 3% of dwellings after 1998 had retrofit works carried out (Watson et al., 2003). Although there is some time between 2002 & 2006, it is felt that any retrofitting work will be concentrated in older, less efficient dwellings and so the potential impact of retrofitting on either the control group or treatment group is expected to be minimal.

Dwelling floor area

Since the primary data source in this analysis, the metered gas consumption, does not contain any linked data field on floor area this was externally sourced and then linked to the consumption data. There are six years between the control group and the treatment group, and the average floor areas for houses in Ireland increased by 6% during this time (CSO, 2010), making it essential to normalize the two groups for floor area. As outlined in section 3.3, certain properties of the planning permission database, the source of the floor area data, add uncertainty to the final result; however, investigation of the data set for the two connection years, dwelling type and location of interest showed that the floor area correction necessary for these two years was negligible.

Weather correction

In weather terms, 2006 was a mild year, with 1,971 national degree days and so required minimal weather correction. As per the approach used by Eurostat (EC, 2005) a regional weather adjustment is applied to the data, rather than a nationally weighted average. This enables a weather correction specific to the Dublin region, one of the defining properties of the control and treatment groups. The weather correction is applied to Dublin as a whole, with no climatic variation within the Dublin region in this analysis. The degree days for Dublin airport for 2006 were 2,124, 8% higher than the nationally weighted degree day figure for Ireland in 2006.

Data distribution

Comparing the mean values of the control and treatment groups requires a parametric test, for which the two data groups need to be normally distributed. An initial visual assessment of both the control group and treatment group showed that both distributions were negatively skewed and had long positive tails. A square-root transformation of the data reduced both skew and kurtosis, bringing the latter into the normal range (<+2 & >-2), see Table 3-3. This transformation, combined with the large number of data points (>5000) and the predictions of the Central Limit Theorem, indicate that the use of parametric tests to compare the means of the two groups was appropriate.

Table 3-3. Measures of skewness and kurtosis for untransformed and square-root transformed data

	1997 BR (untransformed)	**1997 BR (sqrt)**	**2002 BR (untransformed)**	**2002 BR (sqrt)**
Skewness	1.26	0.063	1.402	0.313
Kurtosis	3.589	0.805	3.889	0.74

T-test & Z-test

An independent sample T-test was performed in IBM PASW18 at 5% significance level. The T-test includes measurements of standard error and thus enables the calculation of precision as required by the ESD (EC, 2006) and recommended by the IPMVP (EVO, 2007). This comparison effectively pinpoints the differences between the groups in terms of the BR impact. An F-test characterized the two data samples as having unequal variance. Therefore, a T-test for unequal variance was conducted on the full data population for both the untransformed data and the square-root transformed data. In order to verify the robustness of the initial result, a number of additional statistical tests were done. These included T-tests for both the untransformed data and square-root transformed data at different sample sizes (80%, 60%, 40% 20%, 10% & 5%). For each sample size, equal variance T-tests or unequal variance T-tests were done as appropriate. Finally, and although on some occasions it broke the assumption of equal variance for both groups, a Z-test was applied to all the samples. This range of tests enabled a higher degree of confidence to be placed in the final result.

3.4.2 Part II – 2002 BR compliance

A separate methodology and data source is used to quantify the level of compliance of the 2002 BR; the methodology is an engineering simulation and the data source was the BER database. The baseline for an assessment of non-compliance with the 2002 BR is full compliance with the same regulations. This is modelled by calculating the energy consumption of a dwelling according to full compliance with the maximum allowable U-values and default assumptions regarding hours of occupancy and internal temperatures. Comparing this baseline to the empirical situation, as determined when the BER database is used, enables the quantification of the level of BR compliance.

DEAP

As described in section 3.2, DEAP is the official programme used in Ireland to determine the BER of an individual dwelling and its compliance with the 2005, 2008 or 2011 BR. The 2005 BR are specified in U-values terms, the same as the 2002 BR. The only difference between these two sets of regulations is a minimum boiler standard required by 2005 BR and the use of the DEAP software to measure compliance. DEAP is an engineering simulation programme that calculates the energy performance of a dwelling using a large variety of input data for such parameters as floor area, dwelling orientation, glazing area, building element U-values, heating controls, etc (a more complete list can be found in Appendix B). It incorporates standardized values for occupancy, internal temperature and heating usage patterns. It also incorporates many calculation methodologies and data tables from the equivalent UK programme, Standard Assessment Procedure (SAP).

DEAP was released in 2006 and according to the DEAP manual "Much of the calculation procedure […], the accompanying tabulated data and the documentation […] is drawn or adapted from" SAP (Kavanagh, 2008). An extremely detailed description of the differences can be found in the document, "Invitation To Tender For The Supply Of Dwellings Energy Assessment

Procedure (DEAP) Software For The Purposes Of Implementing The Energy Performance Of Buildings Directive (EPBD) In Ireland" (DEHLG, 2006b). In summary, there are minor differences in the calculations associated with the draught lobby, u-values for windows (no curtain correction), standardized number of occupants, storage losses, hot water heat gains and losses, lighting gain methodology, mean internal temperature, thermal heat mass, solar radiation data (Irish based), heating season, heating controls, additional fuel types (peat) and the displaced emission factor for electricity.

Simulating full and actual compliance

Two types of simulation were carried out: one representing the baseline situation of full compliance and the other approximating the reality of actual levels of compliance. The two simulation types shared characteristics that were not stipulated by the BR, but that do determine energy consumption, e.g. floor area, dwelling orientation, number of chimneys and open flues, living area percentage. A subset of the BER database, semi-detached, gas connected dwellings constructed in Dublin in the period 2004 - 2006, was generated. From this subset, average values for all BER parameters were data mined and used to populate the both the 2002 BR (full-compliance) simulation and the 2002 BR (actual-compliance) simulations.

Full compliance

Four simulations were run to account for the three methods that exist to demonstrate BR compliance. The four simulations were:

1. *Elemental heat loss:* Compliance according to maximum average U-values per building element (windows, doors, roof, walls, floor)
2. *Elemental heat loss + permitted openings variation:* Compliance according to maximum average U-values per building element with permitted variation of average U-values and combined area of external doors, windows and roof lights
3. *Overall heat loss:* Compliance according to a maximum level of building fabric heat loss as expressed by a maximum average U-value for all building elements combined

4. *Heat energy rating:* Compliance according to the maximum permitted kWh/m2/yr as specified by the quotient of building heat-loss area (m2) and building volume (m3)

The U-values used in the full-compliance simulation are in Table 3-4.

Table 3-4: U-values used for BR Compliance

U-value (W/m^2 K)	1. Elemental	2. Elemental + Openings	3. Overall Heat Loss	4. Heat Energy Rating
Windows/Roof-lights	2.2	2.56	1.5	1.4
Doors (Avg for all doors)	2.2	2.56	2.1	1.4
Floor (Exposed)	0.25	0.25	0.37	0.22
Walls	0.27	0.27	0.37	0.25
Roof	0.2	0.2	0.25	0.22

Actual compliance

To account for the uncertainty from using average U-values from the BER database, five separate simulations were done. The uncertainty stems from how accurately U-values recorded in each BER assessment represent the actual heat loss of that building element. For the design and construction stage, a variety of methods for calculating the U-values of a building element are contained in the TGD of the BR (DEHLG, 2002). For BER assessments however, concerns have been raised about the reliance on default values (Thornton, 2008) and the fact that some BER assessors, in the absence of actual heat-loss tests, will choose the default U-values for the building element type or set of BR. Discussions with various building experts[14] concluded that the dwelling elements most likely to be accurate are roof[15] and windows[16] and those least likely to be accurate are

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[14] Informal and unstructured discussions were held with Shay Kavanagh (BER technical expert, works for SEAI), Jim Scheer (SEAI), Kevin O'Rourke (SEAI) and Rodger O'Connor (Chartered Engineer, extensive experience in construction). Audience discussion with experts at the following conferences also informed aspects of this analysis: DIT Energy and Emissions Seminar (2011), UCC-ESRI Joint Seminar (2012), eceee (European Council for an Energy Efficient Economy) conference (2011). Email correspondence was conducted with Sean Armstrong (DECLG).

[15] Roofs are seen as the easiest building element to visually inspect and physically measure

[16] Concerns about the use of manufacturer U-values for the non-frame part of the window were raised

wall[17]. In order to mitigate the uncertainty from using mean U-values, the median and modal U-values were recorded from the BER database and together with the 40th and 60th percentile values, were used in a sensitivity analysis. The five simulations for the actual-compliance situation are distinct according to the method of calculating the building element U-values:

1. *Mean U-values*
2. *Median U-values*
3. *Modal U-values*
4. *40th percentile U-values*
5. *60th percentile U-values*

The U-values used for the actual-compliance simulation are in Table 3-5.

Table 3-5: U-values used for BR Empirical

U-value (W/m^2 K)	Mean	Median	Mode	40th Percentile	60th Percentile
Windows/Roof-lights	2.49	2.7	2.7	2.39	2.7
Doors (Avg for all doors)	2.7	3	3	3	3
Floor (Exposed)	0.38	0.37	0.41	0.37	0.41
Walls	0.45	0.37	0.37	0.37	0.37
Roof	0.28	0.26	0.25	0.25	0.26

These different simulations produced figures of average energy consumption for a fully-compliant dwelling and an actually compliant dwelling and the difference between them provides a quantified level of non-compliance. The range of values between mean, median and mode values and the sensitivity analysis enabled the final result for non-compliance to be expressed as a confidence interval which captures some of the uncertainty in the calculations.

3.5 Results

The two part methodology produced two key results. The first result was for the comparison between the metered consumption of the control group and the metered consumption of the treatment group; this result indicated to what extent the 2002 BR have achieved the target of a 20% reduction in dwelling

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[17] Without specialized equipment or invasive practices, wall U-values are difficult to calculate

energy consumption. Unlike more recent building regulations (2008, 2011), the 20% target is not explicitly cited anywhere in the NEEAP; however, energy savings based on this improvement are in NEEAP. The 20% comes from the author's calculations for the average energy performance for a typical dwelling built according to the u-values in the 1997 and 2002 building regulation TGD. The 20% is an average figure, for there are a number of ways to calculate compliance with BR; more recent BR have an updated method for achieving an explicit 40%, or 60% that is not applicable to 2002 BR.

The second result quantified the level of non-compliance with the 2002 BR; this empirical result will be compared to the default level of non-compliance found in the EMEEES report on BR (Maas and Monne, 2009). Non-compliance is defined in dwelling energy terms as the degree to which minimum standards of building element u-values and building heating controls are adhered to; this non-compliance is measured under standard assumptions of occupant behaviour and as such, it only evaluates the technical state of the building: i.e. the presence or absence, in part or in whole, of various technical building properties.

3.5.1 Part I – 2002 BR empirical impact

According to the independent sample T-test, for a gas connected, three-bedroom semi-detached dwelling in Dublin, the difference in average gas consumption during 2006, for a dwelling constructed to 1997 Building Regulations to a dwelling constructed to 2002 Building Regulations was substantially below the expected improvement. The target saving per dwelling was 2.97MWh, whereas the mean saving, with 95% confidence was just 1.67MWh ±17%. While the target improvement per dwelling was a 20% reduction, what was achieved was a 11.2±1.9% improvement, as shown in Table 3-6.

Table 3-6. Part 1 – 2002 BR empirical impact results

	1997 BR (MWh)	2002 BR (MWh)	ΔMWh	Δ%
Actual	14.84	13.17	1.67	11.2±1.9%
Target	14.84[18]	11.87	2.97	20%

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[18] Actual performance of 1997 BR assumed as baseline

Further tests were run to verify the robustness of the result:

- T-tests of square-root transformed data
- T-tests of samples at 80%, 60%, 40% 20%, 10% & 5% for:
  - Untransformed data
  - Square-root transformed data
- Z-tests for:
  - Full population of untransformed data
  - All samples sizes for untransformed data

In all cases the square-root transformed data was within 1 percentage point of the untransformed result, which was well within that result's confidence interval, see Table 3-7.

Table 3-7 – Results for t-test for untransformed & square-root transformed data

Sample (%)	% Delta (untransformed)	Confidence Interval (percentage points)	% Delta (sqrt)	%Δ untransformed & sqrt (percentage points)
N	11.2%	1.9%	11%	0.2%
80%	11.7%	2.1%	11.3%	0.4%
60%	12.3%	2.4%	12.0%	0.3%
40%	11.3%	3.0%	11.1%	0.2%
20%	12.4%	4.3%	12.1%	0.3%
10%	13.6%	6.2%	12.6%	1.0%
5%	13.6%	8.3%	12.6%	0.9%

For nearly all sample sizes, the majority of the tests were within the confidence interval of the initial T-test. As the sample size decreased, the confidence interval range increased with lower certainty stemming from the smaller samples. The confidence interval range of the 5% sample was more than four times larger than the confidence interval of the full population range, see Table 3-8. Below a sample size of 5%, both the t-stat and the p-value exceeded the critical values for the T-test.

Table 3-8. Test range of uncertainty for untransformed data

Sample (%)	% Delta	Lower Limit	Upper Limit	Range (% points)
80%	11.7%	9.6%	13.9%	4.3%
60%	12.3%	9.9%	14.7%	4.9%
40%	11.3%	8.3%	14.3%	5.9%
20%	12.4%	8.1%	16.7%	8.6%
10%	13.6%	7.3%	19.8%	12.5%
5%	13.6%	5.2%	21.9%	16.7%

For each case of the Z-test, the result was within 3% of the T-test, see Table 3-9.

Table 3-9. T-test and Z-test results

Sample (%)	Critical Value	T-test	P-value	Z-test	P-value
80%	1.96	10.699	0.000	10.699	0.000
60%	1.96	9.868	0.000	9.868	0.000
40%	1.96	7.406	0.000	7.406	0.000
20%	1.96	5.663	0.000	5.663	0.000
10%	1.96	4.373	0.000	4.266	0.000
5%	1.96	3.199	0.001	3.152	0.001

The discrepancy between the actual improvement (11.2±1.9%) and the target improvement (20%) will be discussed in section 0; the uncertainty associated with this result will be outlined here. For the 2002 BR, the baseline for a 20% improvement was the 1997 BR, which is the baseline used in this study; however, it is possible that since original construction of 1997 dwellings, further work has been done to upgrade their energy efficiency. Both groups have a similar normal distribution as shown in section 3.3, which suggests that this is minimal, but this is only an indicative result. As was stated in section 3.4, there is survey evidence that retrofitting work for newer dwellings affects just 3% of dwellings; however, this survey was done four years before the year of analysis used in this chapter. The EMEEES guideline for assessing BR in new dwelling specifies a zero level for autonomous improvement (Maas and Monne, 2009). Other potential differences between the treatment group and the control group are the impact of different incomes and any differences in occupancy. Some of these aspects are discussed in more detail in section 3.6.

3.5.2 Part II – 2002 BR compliance

According to the 2002 BR, compliance can be demonstrated with any of the compliance methods as listed in section 3.4 (DEHLG, 2002). There are implications for energy consumption according to which method is chosen. Using input data from the BER data set, the annual consumption of a fully compliant semi-detached dwelling is 11.2MWh ±11.3%, based on making a calculation according to all methods and adopting a confidence interval determined according to the range that the methods provide. For each entry in the BER data set, there is no indication what compliance method was used to demonstrate BR compliance. The minimum energy standard required to achieve BR compliance might not necessarily be a priority of the dwelling design and so it is not correct to choose the compliance value that is the most probable, since compliance can be demonstrated at the lowest minimum level. It was therefore concluded that it is appropriate to use the compliance method (*Elemental heat loss + permitted openings variation*), which gave the highest energy consumption figure per dwelling, but was still compliant with the 2002 BR. For a semi-detached dwelling constructed to the 2002 BR, the fully-compliant annual energy consumption, according to the *Elemental heat loss + permitted openings variation* method is 12.44 MWh. This is designated as the baseline value, i.e. a measure of what the dwelling energy consumption should be with full building regulation compliance.

The average energy consumption of an actual-compliance 2002 BR semi-detached dwelling, according to the DEAP calculations using mean, median and mode values for building element U-values was 14.05MWh ±1.4%. Compared to the baseline full-compliance consumption, this represents an increase in total energy consumption of 13±1.6% (see Table 3-10), which is higher than the default value of 10% as recommended in EMEEES (Maas and Monne, 2009). The purpose of the high EMEEES default value was to encourage data gathering and empirical analysis that would generate a more accurate result for BR non-compliance. As far as the author is aware, there has been no publically available work on the actual level of compliance in Ireland.

Table 3-10. Level of compliance results.

	Annual Energy Consumption
2002 BR (actual compliance)	14.05 MWh ±1.4%
2002 BR (full compliance)	12.44 MWh
Non-Compliance	1.61 MWh ±12%
Non-Compliance (%)	13 ±1.6%

Finally, the results of the sensitivity analysis are a small increase in the possible quantity of discrepancy but a large increase in the confidence interval of the result, see Table 3-11.

Table 3-11. Level of compliance, sensitivity analysis results

	Annual Energy Consumption
2002 BR (sensitivity analysis)	14.35 MWh ±6.6%
2002 BR (full compliance)	12.44 MWh
Non-Compliance	1.98 MWh ±43%
Non-Compliance (%)	15.3 ±6.6%

3.6 Discussion

The first main result of this chapter is that the empirical impact of the 2002 BR, in terms of metered consumption, has a quantified improvement in energy efficiency of new houses of 11.2±1.9% compared with a target improvement of 20%. This marks a significant shortfall in the target energy savings. While there is a degree of uncertainty in the results, it is clear that the 2002 BR in the sample analysed are significantly underperforming in terms of energy conservation. This has implications for the occupants of the dwellings built to the 2002 BR, for those responsible for the 2002 BR policy design and implementation, and for those seeking to address the energy consumption of the residential sector. It is an important result for those carrying out ex-ante modelling on the impacts of future energy use (and related emissions) of the more recent 2008 BR and 2011 BR.

An analysis of the impact of BER grading on house prices, conducted by the ESRI identified a small positive effect that was stronger for buyers than renters, and was stronger when selling conditions were worse (Hyland et al, 2012). In the context of building regulation non-compliance and the economic value of energy efficiency, many dwellings in Ireland are overvalued, since their level of energy efficiency is below what their building specification would suggest. This implies a potential requirement for investment in dwelling energy efficiency simply to achieve the targeted BR level. In Ireland there is currently a large scale retrofitting scheme in place called the Better Energy scheme, which seeks, through grant incentivization, to upgrade the energy efficiency of 1 million residential and commercial dwellings (DCENR, 2011). In the event of the 2002 BR underachieving their target savings, it will be necessary for the national retrofitting policy to expend resources merely to achieve the default level of energy efficiency performance.

The results in this chapter are limited to a non-representative sample of over 6,000 dwellings, but they are indicative of possible results in other types of gas-connected dwellings and in other areas of Ireland. The results can also be used to imply the impact of the 2002 BR in non-gas connected dwelling types; this cautious extrapolation is subject to a large number of caveats: compared to non-gas connected dwellings, gas connected households are more likely to be in urban areas (especially the two biggest cities of Dublin & Cork), centrally heated and have automatic temperature control, and be most satisfied with the quality of space-heating (Watson et al., 2003). They are also more likely to be in a higher income quintile and be occupied by employed or working persons (CSO, 2007b). It is possible that both the shortfall in metered energy consumption and the non-compliance findings could be larger and smaller in other dwelling types, fuel types and locations.

In terms of a sample of dwellings being used to quantify the wider impact of the 2002 BR, there are two key issues which can be said to be responsible for the shortfall in performance: dwelling occupant behaviour and the level of BR non-compliance. Behaviour has not been explicitly quantified in this chapter, however the analysis of non-compliance has given a quantified level of non-compliance (13±1.6%) for the sample of dwellings studied, the second main result of this chapter.

The findings on non-compliance point to significant issues with BR enforcement in Ireland. Enforcement is an issue that affects all energy efficiency policies; as was noted in the section 3.2, it is an issue repeatedly highlighted as one of the most crucial to the success of BR. Shortcomings with enforcement of the 2002 BR will impact other BR policies such as the 2008 BR and the 2011 BR, which have an even more ambitious scale of improvement than the 2002 BR: 40% and 60% respectively, relative to 2002 levels. If nothing is done to address issues leading to the shortfall recorded in earlier BR, there is a risk of a growing divergence between the actual energy performance of a dwelling and the stipulated energy performance according to the latest BR generation. These concerns have also been raised elsewhere: "… if building regulation enforcement is not effective then it is difficult to see how … new dwellings comply with these regulations, or how, at a national level, the achievement of thermal performance targets can be assured" (Thornton, 2008).

While this study of the 2002 BR has implications for the 2002 BR policy, and other BR policies, it also has implications for all forecasts of the energy consumption of the residential sector. Compared to an ex-ante prediction of the impact of the 2002 BR policy, an ex-post calculation will most likely show a substantial shortfall, which will have implications for the energy savings targets as listed in the NEEAP; other energy efficiency policies will therefore need to make up the shortfall. If these other polices are also subject to shortfalls, there are very real concerns that the policy targets will not be met.

3.7 Conclusions

There has been a 44 ±9.5% shortfall in target energy savings for the 2002 BR. As part of the reason for that shortfall, this chapter has concluded that there are real issues with BR non-compliance in Ireland. This points to an increased need for adequate BR enforcement from the Building Control Authority. While BR in Ireland are mandatory for all new buildings, in view of the poor rate of enforcement, the policy might be more accurately described as "de-facto voluntary" (Hitchin, 2008). As a minimum, the current rate of inspection for BR compliance as set by Building Control Authority needs to increase from 12-15% - a clear majority of dwellings should be inspected. For the year 2006, assuming 50,000 dwellings were built to 2002 BR with an average annual space heating consumption of 14 MWh (which includes 13% non-compliance), the consumer cost of non-compliance compared to 0% non-compliance was approximately €3.5 million. This payment was made to energy suppliers, assuming VAT at 13.5%, this is revenue of €469,000, which would have been able to pay for approximately 12 building inspectors at an average annual salary of €40,000.

As stated in section 3.1, Irish energy saving's targets are currently placing a lot of importance on residential BR. In light of BR policy underachieving, and the need for other policies to help make up lost ground, there is much scope in partnering BR policies with other policies to achieve success. Simple examples include information campaigns to aid awareness and defeat non-compliance; a more innovative example is in Germany where the landlord of a dwelling is liable if the building code is not compliant (Haney et al., 2010). In terms of enforcing BR compliance, a more enlightened approach in Australia and Denmark is a financial fine commensurate with the degree of energy wastage due to non-compliance (Hitchin, 2008). Other innovative measures addressing BR compliance include incentives for builders to build beyond the target energy codes, e.g. in Japan & USA (Haney et al., 2010).

As stated in section 3.2.1, in terms of energy efficiency policy, building regulations have negative costs; this is especially true compared to retrofitting to improve building efficiency, since changes made at the design stage are much less costly than changes made after the building has been constructed. However, the costs of guaranteed BR implementation are consistently underappreciated and underestimated. Except for high profile cases of BR non-compliance, which are mostly concerned with building safety, the impact of non-compliance is currently not very visible. This is because penalties for non-compliance are very rarely imposed in Ireland. An approach that links the cost of BR non-compliance with the penalty imposed on the builder, would raise the profile of non-compliance for the building occupant, and raise the incentive for the builder to fully comply at the construction stage.

The importance of ex-post analysis for energy efficiency policies has previously been highlighted but must be reiterated (Hull et al., 2009; Rogan et al., 2011; Cahill and Gallachóir, 2012). The key challenge in conducting an ex-post analysis is sufficient data to reach robust and useful conclusions. This study was greatly enabled by access to a metered consumption data set for all natural gas consuming households in Ireland. Appropriate surveys containing information such as how space heating is used, i.e. dwelling internal temperatures and hours of space heating would have greatly aided the analysis.

The results of this analysis have implications for other energy efficiency and renewable energy policies, especially those which have not been subject to explicit ex-post evaluation. Estimates of ex-ante energy savings must be qualified by the uncertainty relating to the implementation of these policies, which as the results of this chapter show, should be borne in mind when modelling the expected impact of an energy efficiency policy. This chapter has shown that behaviour and non-compliance can erode energy savings significantly, making the difficulty of achieving energy savings through energy efficiency policy even greater.

4 An Energy Demand And Constraint Optimized Model Of The Irish Energy System

Abstract

This chapter presents a model of energy demand and supply for Ireland with a focus on evaluating, and providing insights for, energy efficiency policies. The demand-side comprises detailed sectoral sub-models, with a bottom-up approach used for the transport and residential sectors and a top-down approach used for the industry and services sectors. The supply side uses the linear programming optimisation features of the Open Source Energy Modelling System (OSeMOSYS) applied to electricity generation to calculate the least-cost solution. This chapter presents the first national level model developed within the Long Range Alternatives Planning (LEAP) software to combine detailed end-use analysis on the demand side with a cost-minimizing optimization approach for modelling the electricity generation sector. Through three scenarios over the period 2009-2020, the model examines the aggregate impact on energy demand of a selection of current and proposed energy efficiency policies from Ireland's NEEAP. In 2020, energy demand in the energy efficiency scenario is 8.1% lower than the reference scenario and 13.7% lower in the energy efficiency+ scenario.

Keywords: energy efficiency policies; top-down modelling; bottom-up modelling; LEAP; OSeMOSYS

4.1 Introduction

Decades of rapid growth in fossil fuel consumption, widespread concerns about the impact of climate change and the resulting environmental degradation (Pachauri, 2007), and concerns about energy security and affordability have led to a renewed interest in policies which can effect energy efficiency and a transition to a low-carbon energy system. This renewed interest has been guided and informed by a suite of energy policy modelling tools, which have been used at all stages of the policy design, implementation and evaluation stage. While many facets of energy policy have been informed by recourse to analytical models, the outputs, temporal and spatial scope, assumptions, system boundaries, and theoretical frameworks of these analytical tools vary dramatically. In terms of model appropriateness, it is vital for an analysis of energy efficiency policy to be tailored to local conditions; there is no "one size fits all". In turn, the results of these analyses require a level of filtration and translation in order to appropriately inform design and implementation of government policy.

This chapter describes an energy model for one country, Ireland (Ireland LEAP model) and uses it to develop a number of future energy scenarios for the period to 2020. It adopts a different approach to that used to generate Ireland's national energy forecasts (Clancy and Scheer, 2011) in that it provides more sectoral and technical detail, which is necessary in particular for modelling energy efficiency policies, that are applied at a sectoral level (for example building regulations, retrofit programs for houses, performance based car taxation, etc.) (Hull et al., 2009). The tool used in this chapter is the Long range Energy Alternatives Planning System (LEAP). While LEAP is not new, the model described in this chapter is innovative in a number of ways, namely:

- The demand-side is constructed from sectoral sub-models (transport, residential, industry, services) with a unique modelling approach (aggregating two bottom-up, engineering sectoral models with two top-down, econometric models)
- This is the first national level model developed within LEAP to combine detailed end-use analysis on the demand side with a cost-minimizing

optimization approach for modelling the electric generation sector using the Open Source Energy Modelling System (OSeMOSYS) (Howells et al., 2011)

Through a detailed scenario analysis, the chapter analyses (1) the aggregate impact of a number of energy efficiency policies and (2) the potential impact of improvements in energy efficiency beyond current policy projections. As such, its primary contribution is to assessing energy policy in Ireland; however, this research has also made a valuable contribution in terms of helping to test and debug the new OSeMOSYS optimization capabilities in LEAP. The purpose of the chapter is two-fold: (i) present a new energy model for Ireland and scenario results to inform policy choices and (ii) through the detailed methodology provided, guide others who wish to develop a detailed sectoral LEAP model for another region.

The chapter is laid out as follows: section 4.2 discusses energy systems modelling and where the model used here fits within the broad suite of available options for energy modelling tools. Section 4.3 outlines the methodology employed, highlighting the different approaches for the individual sectors and how OSeMOSYS is incorporated to optimize electricity generation. Section 4.4 presents the results for Ireland for the different energy efficiency scenarios, in terms of energy savings. Section 4.5 contains a discussion and section 4.6 concludes.

4.2 Energy systems modelling

4.2.1 Modelling approach

There are many approaches to energy modelling and scenario analysis – a recent review paper lists 364 unique examples (Suganthi, 2011) - and the different methodologies, data-requirements, types of problem to be solved range from the simple to the exceedingly complex (Nakata, 2004). Comprehensive categorization in terms of what is modelled (energy demand, energy supply and the energy system) and the modelling approach used (econometric, techno-economic, partial and general equilibrium, simulation, optimization and end-use accounting) (Edenhofer, 2006) leads to a complex taxonomy of models; in lieu of this complex categorization, a simple distinction is often made between a bottom-up approach, which is more data intensive and more appropriate for detailed analysis of individual energy policies and a top-down approach, which has a more econometric approach and uses less technology explicit data (van Beeck, 1999; Barker et al., 2007).

Despite the distinction, the two categories of bottom-up and top-down aren't mutually exclusive, there also exists a "hybrid" class where the two approaches are combined; one of the main contributions of the hybrid approach is the detection of missing information and dynamics that simple top-down or bottom-up models cannot detect on their own (Hourcade et al., 2006). While it is possible to build an energy systems model entirely from first principles using energy flow equations, energy end-use consumption rates and activity rates, there are a number of off-the-shelf computer packages that provide a framework for building a model, running scenarios and generating results for analysis. In this chapter a hybrid combination of both bottom-up and top-down approaches is taken and the LEAP software is used.

4.2.2 Bottom-up modelling

One of the main uses of the Ireland LEAP model in this chapter is modelling the explicit impact of individual energy efficiency policies. Because many of the policies are technical in nature (e.g. changes to MJ/km or kWh/m^2) and they target a particular sector (e.g. low mileage passenger cars or low energy-rated dwellings), a bottom-up approach is adopted for two sectors (residential & transport) that have sufficient high-quality data available. In most cases the data used is publically available and is specific to the local conditions in Ireland; otherwise, data-proxies or data from other countries are used. The projections for energy demand in each bottom-up sector are based on existing and future technical characteristics of the individual energy consuming units and in all cases, these projections are linked to macro-economic activity metrics such as GDP, GNP or house numbers that were the output generated by a separate macro-economic model (Bergin et al., 2010).

4.2.3 Top-down modelling

For the two top-down sectors (services & industry) in the Ireland LEAP model, energy demand is derived from an elasticity with Gross Added Value (GVA) as an activity variable: for services, GVA is associated with the sector in-aggregate and for industry, GVA is linked with each sub-sector. This econometric-type approach is better suited to sectors which are more closely linked to economic activity such as industry (van Beeck, 1999). In the Ireland LEAP model, the same exogenously derived macro-economic activity variables that were used in the bottom-up sectors are used in the top-down sectors and in this way the two separate approaches are consistent. While top-down modelling based on regression analysis of historical trends can be used to generate a general trend of energy efficiency, the baseline will still incorporate many distorting factors, such as the impact of past investment in energy efficiency technologies and this must be borne in mind when comparing an energy efficiency scenario with a baseline scenario, in order to isolate the impact of energy efficiency (van Beeck, 1999). In addition, lack of detailed sub-sectoral data point towards the use of a top-down approach. This is particularly the case for the services sector, apart from a few individual case studies (O Gallachóir et al., 2007).

4.2.4 LEAP & OSeMOSYS

LEAP is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute (Heaps, 2011). It is an integrated modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. LEAP can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emissions as well as local and regional air pollutants; it can also be used as a comprehensive accounting system for conducting integrated cost-benefit analyses of energy scenarios. The most recent version of LEAP[19] now functions with Open Source Energy Modelling System (OseMOSYS). While OSeMOSYS is capable of modelling the entire energy system in a stand-alone capacity, within LEAP it is applied specifically to calculate least-cost

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[19] 2012.0.0.24

capacity expansion and dispatch pathways for the electricity generation sector, based on minimizing the overall cost of providing energy services. The OSeMOSYS code has been explained in greater detail elsewhere (Howells et al., 2011; Welsch et al., 2012). A more detailed discussion of LEAP and OSeMOSYS is contained in Appendix D.

The LEAP–OSeMOSYS configuration does not currently model the spatial dynamics of the electricity system operation. In the Ireland LEAP model, transmission and distribution losses are a fixed figure of 8.3%. A software model capable of modelling the spatial dynamics of the T&D system would model this figure dynamically; however, for the relatively short time horizon (2009-2020) in this analysis, it is not expected that the losses figure would diverge much from the 8.3% figure and therefore LEAP–OSeMOSYS is considered sufficient for modelling changing electricity loads on the Irish power system. For longer modelling time horizons (e.g. to 2050) and with larger changes to the power system, e.g. with the development of the grid for more wind and more power-lines, this fixed losses figure will change more (it is a function of distance and voltage of lines) and the spatial limitations of OSeMOSYS could become an issue. In such circumstances, the results from LEAP-OSeMOSYS could be soft-linked to another power systems modelling tool. Another aspect of spatial modelling relates to the spatial distribution of wind energy, which is also not considered in this LEAP-OSeMOSYS model.

The capability of LEAP–OSeMOSYS for modelling the temporal dynamics of a predominantly synchronous electricity power system is generally considered sufficient, in terms of the temporal resolution of the model; however, for a power system with a certain proportion of variable and asynchronous power, the capability of LEAP–OSeMOSYS is quite limited. This is relevant to the Irish power system as follows: as the amount of wind generated electricity on the power system increases, the necessity of the power system to respond to larger variations of asynchronous power supply (i.e. intermittency) becomes more acute. These dynamic variations are only captured when the power system is examined at a high temporal resolution, i.e. hourly or greater. Currently LEAP is sufficiently robust to model a power system at an hourly resolution; however, LEAP-OSeMOSYS is limited to time-slices of 48-hour durations. The implications of these limitations are discussed in more detail in the discussion section.

LEAP has been adopted by hundreds of organizations in more than 190 countries, and its users include government agencies, universities, non-governmental organizations, consulting companies, and energy utilities. LEAP has been applied at many different scales ranging from cities and states to national, regional and global applications. While LEAP is less sophisticated than other energy modelling tools such as MARKAL (Loulou et al., 2004), TIMES (Loulou and Labriet, 2007) or MESSAGE (IIASA, 2012), its contribution primarily lies in its flexibility, transparency and ease-of use and its emphasis on data management and reporting as much as on its modelling algorithms (Nakata, 2004). LEAP has been used in over 70 peer-reviewed journal papers (Connolly et al., 2010) for a variety of modelling problems (Shin et al., 2005; Dagher and Ruble, 2011; Huang et al., 2011; Takase and Suzuki, 2011) and it has also been used to inform policies for achieving an 80% cut in GHG emissions in Massachusetts (Breslow and Affairs, 2011). LEAP has been variously described as a bottom-up model (Suganthi, 2011), an accounting model (Mundaca et al., 2010) and a top-down model (Connolly et al., 2010); however, different approaches can be mixed and matched within a single model and this chapter demonstrates a combination of a bottom-up approach and a top-down approach.

4.2.5 Scenario analysis of Irish energy policy

Through its facilitation of scenario analysis, LEAP enables the evaluation of energy efficiency policies by comparing their energy requirements, their social costs, benefits and their environmental impacts to a baseline or reference scenario. Individual policy measures can be generated into individual scenarios, which can in turn be combined (in different combinations and permutations) into alternative aggregated scenarios. This approach allows an assessment of the marginal impact of an individual policy as well as the interactions that occur when multiple policies and measures are combined. The base year for the Ireland LEAP model is 2008 and the scenario modelling period is 2009-2020, which is the same modelling period as Ireland's National Energy Efficiency Action Plan (NEEAP) (DCENR, 2009).

Although this modelling time horizon covers some past years for which historical data exists (2009-2011), this is not seen as a deficiency, but as an opportunity to validate the model against actual data. The scenarios developed in this model have a quantitative basis although some of the choices for the integrated scenarios are qualitative or expert-based. There are three aggregated scenarios: a reference scenario, an energy efficiency scenario and an energy efficiency+ scenario.

- *Reference scenario:* Expected energy consumption in the business-as-usual scenario, which excludes the impact of any future government targets or energy efficiency policies provides a baseline, which enables quantification of the impact of the energy efficiency scenario and energy efficiency+ scenario.
- *Energy Efficiency scenario:* Expected cumulative impact of all the sector-specific scenarios on energy consumption for a selection of current or proposed energy efficiency policies at probable implementation rates. Many of the energy efficiency policies in this scenario are in Ireland's NEEAP.
- *Energy Efficiency+ scenario*: Expected impact on energy consumption of a selection of energy efficiency policies beyond their assumed rate of implementation; also includes exploratory scenarios for which no polices currently exist.

For the aggregate energy efficiency and energy efficiency+ scenarios, details for individual policy measures modelled within each sector and sub-sector are shown in Table 4-1. It is important to note that with the exception of the *Electric Vehicle*$_{average}$ (EV), *retrofit*$_{average}$ and *building regs*$_{average}$ policies, all policy measures from the energy efficiency scenario are also modelled in the energy efficiency+ scenario.

Table 4-1 – Aggregate scenarios by sector, sub-sector, policy and description

Aggregate Scenario	**Sector**	**Sub-Sector**	**Policy**	**Description**
Reference	All	All	-	*business-as-usual*
Energy Efficiency	Transport	Private Cars	$EV_{average}$	*10% EV penetration by 2020, EVs replace cars with average mileage*
		Private Cars	*mileage reduction*	*Mobility management causes mileage reduction of private cars*
		Private Cars, Taxis & Hackney, Buses	*efficient driving*	*Improved vehicle efficiency for all road vehicles due to better driving*
	Residential	New Dwellings	*building regs* $2011_{average}$	*Rollout of 2011 building regulations with historic levels of non-compliance*
		New Dwellings	*building regs* $2013_{average}$	*Rollout of 2013 building regulations with historic levels of non-compliance*
		All Dwellings	*CFL lighting*	*Full penetration of more energy efficient CFL bulbs*
		Existing Dwellings	$retrofit_{average}$	*Annual retrofit of 100,000 dwellings, average retrofit depth*
Energy Efficiency+	Transport	Private Cars	*high efficiency vehicles*	*New cars are efficient so average emissions by 2020 are 95g* CO_2*/km*
		Private Cars	EV_{best}	*10% EV penetration by 2020, EVs replace cars with high mileage*
		Private Cars, Trains, Buses	*modal shift*	*Passenger KMs shift from private cars to public transport (train & bus)*
		Private Cars	*private car occupancy*	*Increase in private car occupancy from 1.93 to 2.5*
	Residential	Existing Dwellings	$retrofit_{best}$	*Annual retrofit of 100,000 dwellings, deep retrofit*
		New Dwellings	*building regs* 2011_{best}	*Rollout of 2011 building regulations with full compliance*
		New Dwellings	*building regs* 2013_{best}	*Rollout of 2013 building regulations with full compliance*
	Industry	All NACE categories	*GVA change*	*20% GVA increase in one sub-sector & 25% GVA decrease in other sub-sector*
		All NACE categories	*efficiency change*	*Energy efficiency of all industry sub-sectors decreases by 10%*

4.3 Methodology

The section presents the methodology behind the Ireland LEAP model. Following the organization of the model, it describes each sector and sub-sector in turn. The section is divided into (i) energy demand, which is divided sectorally into industry, services, residential and transport and (ii) energy supply, which is comprised of energy resources, electricity generation, and transmission and distribution. A distinction is made between model generation and model data entry: the energy demand part of the model started as a *tabula rasa* where the first step was to design a structure and then within each of these sectors, owing to varying data availability and different scenario analysis requirements, a unique modelling approach and design was required. For the electricity generation sector, the model structure was in place at the outset and so the work required to complete a fully functioning model was appropriate data characterisation of the electricity generating units and assumptions about the expansion of the electricity system's generation capacity over time.

4.3.1 Energy demand

The high-level tree structure used in the energy demand analysis is shown in Appendix Figure 1 – LEAP Tree Structure and is described according to each sector and sub-sector below.

Transport sector

Energy demand in Irish transport has not decoupled from economic growth as it has in other sectors. It has grown by 181% in the period 1990–2007 and increased its share of total demand from 28% to 43% in the same period (Howley, Dennehy, and Gallachoir, 2009b). The transport sector was subdivided into passenger cars, public passenger transport, aviation and freight.

Passenger car: External to LEAP, a private car stock model was developed (Daly and Gallachóir, 2011b), building on earlier analysis on historic private car transport energy trends (Daly and Gallachóir, 2011a); this was incorporated into the Ireland LEAP model using the Transport Analysis demand mode and was extended to include taxis and hackneys. The LEAP passenger car sector disaggregates the Irish car stock into a demographic and technological model, explicitly incorporating the vehicle efficiency and mileage profile of cars across engine types (according to cylinder capacity, cc) and vintages. The overall annual mileage of the car stock (in vehicle kilometers, vkm) and annual car sales was modelled based on a top-down econometric model shown in Equation 4-1, where Vkm^T is vehicle kilometers in year T; ΔGNP and ΔP are the explanatory variables, the year-on-year percentage change in national income (Bergin et al., 2009) and fuel price (Capros et al., 2008) respectively; δI_{Sales}, δI_{Vkm}, δP_{Sales} and

δP_{Vkm} are the income and price elasticities with respect to sales and activity, taken from a study of car energy demand (Johansson and Schipper, 1997).

$$Vkm^{T} = Vkm^{T-1} \times (1 + \Delta GNP^{T} \times \delta I_{Vkm}) \times (1 + \Delta P^{T} \times \delta P_{Vkm})$$
$$Sales^{T} = Sales^{T-1} \times (1 + \Delta GNP^{T} \times \delta I_{Sales}) \times (1 + \Delta P^{T} \times \delta P_{Sales})$$

Equation 4-1

Details and sources for vehicle retirement rates, mileage profile, specific fuel consumption are described elsewhere (Daly and Gallachóir, 2011b). Energy demand for each year is calculated as the product of stock, distance travelled and specific energy consumption in each technology and age category. The bottom-up, technology rich methodology for passenger cars is enabled by the availability of good data for car registrations, activity and efficiency and it readily allows scenario analysis that measures improvements due to technological efficiency, overall travel reduction, modal shift, switch to biofuels and efficient driving.

Public passenger transport: Passenger rail was divided according to five main services: DART and LUAS (both urban light rail systems), Dublin suburban, mainline services, and international travel (between Dublin and Belfast). Based on the average annual growth for overall passenger rail travel (in passenger kilometres, pkm) between 2000 and 2008 (CSO, 2009a), a annual growth rate of 6% was chosen for the model time horizon (2009-2010). Final energy intensity of 1.06 MJ/pkm was calculated as the quotient of overall energy demand (SEAI, 2011) and overall rail travel in pkm, and was kept constant over the model time horizon. Bus travel was disaggregated into Dublin suburban, Ireland intercity, school buses, touring coaches and other scheduled services (mostly town and city routes). Energy demand data for each of these modes was available from fuel excise duty relief receipts; vehicle kilometre data was available for buses operated by Dublin Bus and Bus Éireann (CSO, 2009a) and these were used to calculate fuel intensity values of 10.8 MJ/vkm for inter-urban routes and 19.9 MJ/vkm for urban routes. A 6% annual average growth rate was applied for overall bus travel, reflecting the rise between 2000 and 2008, and energy intensity values were kept constant.

Aviation: A forecast for domestic and international aviation energy demand was taken from another study (Dineen, 2009) which generated a projection for international aviation passenger numbers based on an econometric origin-destination model of tourism destination choice and forecast domestic aviation activity based on current regional travel and population projections. In our model, energy demand was calculated using the weighted average fuel demand per passenger and weighted average flight distance to each region.

Freight: Freight transport demand was divided into road freight and rail freight. Road freight was further divided into light goods vehicles (LGV) and heavy goods vehicles (HGV). HGV energy demand forecasts were based on a study (Whyte, 2010), which took a commodity-based approach to projecting tonne-kilometer (tkm) demand based on projections for sectors of the economy (Bergin et al., 2009). Specific energy consumption in MJ/tkm for each vehicle class, based on unladen weight, was based on a Finnish study (Mäkelä & Auvinen, 2007). Poor data exists for LGV in Ireland, so a simple top-down activity-based model was implemented. National GDP forecasts were used as the explanatory variable driving LGV activity (in vehicle kilometers, vkm) with an elasticity of 1. An average efficiency for LGV in 2008 of 3.03 MJ/vkm was calculated based on 2008 activity data and total LGV energy demand from the Energy Balance (SEAI, 2011). Rail freight energy demand was modelled similarly to LGV demand, except tonne-kilometres were assumed to remain at 2008 levels (CSO, 2009a); an energy intensity value of 0.7 MJ/tkm based on a UK Climate Change Working Group report was used (McKinnon, 2007).

Residential sector

Over the period 1990 to 2008, the residential sector in Ireland recorded a 38.2% increase in primary energy requirement. In 2008, it had a 25.2% share of Total Primary Energy Requirement (TPER) and a 23.8% share of (Total Final Consumption) TFC. Adequate data for a bottom-up model for the examination of the impact of technical energy efficiency policies was available for two energy end-use sub-sectors: space & water heating and lighting & appliances. For the energy consumption of space and water heating, an engineering archetype modelling approach (Swan and Ugursal,

2009) was used which via a number of dwelling archetypes, represented all the dwelling types in the dwelling stock. For each of these dwelling archetypes, the space & water heating energy consumption was calculated using an engineering heat flow model. For the purposes of scenario modelling, a distinction was made between existing dwellings and new dwellings. The existing dwellings category consisted of the entire permanently dwelling stock in 2008 and the new dwellings category were those dwellings which became occupied between 2009 and 2020, and which included dwellings that were constructed before 2009 but only became occupied after 2009. Dwelling numbers for the 35 existing dwelling archetypes are shown in Table 4-2.

Table 4-2 – Residential sector number of base year existing dwellings by archetype

Dwelling Type	One Storey Detached	Two Storey Detached	Two Storey Semi-Detached	Terrace	Apartment
Energy Rating					
A	16	487	565	216	110
B	1,844	17,884	25,186	31,916	55,504
C	20,397	51,284	103,779	81,352	101,400
D	36,008	41,658	131,514	91,388	101,692
E	26,443	23,137	84,479	85,058	76,669
F	16,075	11,977	42,572	50,342	31,994
G	32,053	20,926	42,775	72,288	39,016

The requisite data was data-mined from a database of Building Energy Ratings (BER), which at the time of the analysis contained 130,000 BER certificates[20] and associated data for dwellings assessed between 2007 and 2010. This approach facilitated modelling the retrofitting of dwellings to improve their energy efficiency as a shift in BER bands. New dwellings were modelled using 25 dwelling archetypes: the same five dwelling types as for existing dwellings, four Building Regulations (BR) categories (2005, 2008, 2011, 2013) and a final category to account for dwellings which were constructed prior to 2008, but which would only become occupied between 2009 and 2020. This last category was necessary due to the property bubble, which Ireland experienced between 2002 and 2007 leading to a large surplus

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[20] Approximately 7% of the total residential dwelling stock

of vacant dwellings in 2008 which is expected to reduce the demand for new dwelling construction between 2009 and 2020. The details of the dwelling energy consumption for the BR archetypes were calculated based on improvements to the Building Regulations (BR) (Dineen and Gallachóir, 2011); in the energy efficiency scenario, 13% non-compliance was assumed and in the energy efficiency+ scenario 0% non-compliance was assumed.

The number of existing dwellings was reduced annually to account for obsolescence (destruction and abandonment of dwellings) using a Department of the Environment, Heritage and Local Government figure of 0.73% of the total housing stock per annum (DECLG, 2012). New dwelling numbers were taken from projections on the total stock of dwellings made by the Economic and Social Research Institute (ESRI). The annual number of new dwellings reflected the overall increase in the total number of dwellings in the stock plus the number of new dwellings needed to replace obsolete dwellings.

The sub-sectoral structure for lighting, cooking and appliances is shown in Table 4-3. In each case the energy consumption was modelled as the product of an activity level by an energy intensity. Activity level was modelled based on historical penetration rates and projected based on assumed saturation levels; data on activity level specific to Ireland (O Leary et al., 2008) and UK data from the ODYSSEE database (ODYSSEE, 2012) were used. The energy intensity of each appliance was projected using specific consumption data from the UK ODYSSEE database. A number of additional policy scenarios were developed for the introduction of the 2011 and 2013 building regulations for new dwellings and the phase-out of incandescent light bulbs.

Table 4-3 – Lighting, cooking and appliances energy-end-use types

Sub-sector	Energy-end-use types
Lighting	Incandescent
	CFL
Cooking	Electrical
	Natural Gas
	LPG
White Appliances	Refrigerators
	Freezers
	Clothes-washers
	Clothes-dryers
	Dishwashers
Electrical Appliances	Miscellaneous[21]

Industry sector

Final energy consumption of the industry sector of the Irish economy grew by 45% over the period 1990 to 2008 (Howley, Dennehy, and Gallachoir, 2009a). There was a significant amount of structural change in the sector with different sub-sectors undergoing significant change in relative size over the period. Due to an absence of reliable energy-consuming-technology data in industry (such as electric motors, process heat, refrigeration, etc.), a top-down modelling approach was adopted. Final energy demand in the industry sector was modelled using a combination of historical energy consumption and economic output trends to generate forecasts for 13 separate sub-sectors. For each sub-sector a trend of historical energy intensity was derived by dividing energy use statistics (Barriscale, 2009) by the sub-sector's historical gross value added (GVA) at constant prices. This clearly captures energy intensity rather than energy efficiency, which would require further analysis on dematerialisation (Cahill and Gallachóir, 2012). Using a regression 'best fit' curve, the energy intensity trend was derived and then extrapolated to 2020. GVA growth forecasts (Bergin et al., 2010) were available for three industrial branches (High-tech manufacturing, traditional manufacturing & food) and were thus used for the appropriate sub-sector. In a number of cases, an appropriate sub-sectoral GVA forecast was

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[21] An aggregate figure to cover all appliances not covered in the previous appliance category, e.g. televisions, entertainment systems, home computers, etc.

derived using a weighted average (CSO, 2009b)[22] of the forecasts for two GVA branches.

Many of the large users of energy in Irish industry participate in the EU Emissions Trading System (ETS). Using data compiled by the Environmental Protection Agency (EPA) and made available to Sustainable Energy Authority of Ireland (SEAI), it was possible to estimate the share of total fuel in each sub-sector consumed by the ETS sites. The ETS share figures have been applied equally to all ten fuel types in each sub-sector. In the reference scenario it is assumed that the ETS shares remain unchanged up to the end-year of the model. For the sector as a whole, or for each sub-sector separately, the modelling structure enabled explorations of a change in energy efficiency (intensity); GVA (growth or decline); ETS and non-ETS share of energy consumption and individual fuel share targets, e.g. renewables share.

The impact of the recession is captured, to a limited extent, via the macro-economic indicators of GDP, GNP and GVA that declines between 2008 and 2010; the extent it limited because the recession has been more severe than these original macro-economic predictions anticipate. The structural changes assumed stem from the macro-economic forecasts provided by the ESRI for three industrial branches (High-tech manufacturing, traditional manufacturing & food). In summary, NACE categories of Food (15), Paper Printing (21-22), Chemicals (24), Machinery & Equipment (29), Electrical Optical (30-33) and Transport Equipment (34-35) increase in energy demand share whereas NACE categories of Non-energy mining (13-14), Textiles (17-18), Wood (20), Rubber Plastics (25), Non-metallic minerals (26), Basic metals (27-28) and Other (16, 19, 23, 36 & 37) decreased in energy demand share.

Services sector

For the period 1990-2008, final energy consumption for the services sector grew by 80%, reflecting the increasing size of the sector, as measured in part by numbers employed (Howley, Dennehy, and Gallachoir, 2009a). In terms of data availability, the services sector is the least understood and in this chapter was modelled with a simple top-down calculation derived from the national energy

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[22] The weights based on the GVA split of the two parts of the sub-sector

forecasts (Clancy et al., 2010). Energy intensity values for electricity and heat were calculated from national energy forecasts and an appropriate activity value was used to calculate the energy demand according to the national energy forecasts.

4.3.2 Energy supply

This section describes the structure and data requirements for the Ireland LEAP model's energy supply: the energy resources and the electricity generation sector, which includes the transmission and distribution system.

Energy resources

There is only a small supply of indigenous energy in Ireland (wind, hydro, peat & natural gas); in 2008, Ireland imported 89.5% of its energy demand (Howley, Gallachoir, et al., 2009). In categories of primary and secondary fuel (corresponding to unprocessed and refined fuels respectively), the fuel types required for meeting the energy demand from 2008-2020 were included in the model. Fuel costs are taken from the IEA's World Energy Outlook 2009 (IEA, 2009) and adjusted for transport costs to Ireland (see Table 4-4).

Table 4-4 - Fuel prices (source: IEA, Smyth (2008) & Browne (2011))

Fuels (€/GJ)	**2008**	**2010**	**2015**	**2020**
MSW	0.56	0.40	0.20	0.20
Peat	1.01	1.02	1.04	1.06
Coal	2.10	2.17	2.65	2.75
Natural Gas	4.08	4.00	4.15	4.35
Biogas	4.26	4.10	3.70	3.70
Diesel Oil	10.23	10.13	11.25	11.84

Electricity generation

In 2008, electricity comprised a 17.1% share of TFC (Howley, Dennehy, and Gallachoir, 2009a). There were 17 conventional dispatchable power plants and approximately 84 wind farms (EirGrid, 2008); in our model this 7.02 GW power portfolio of 101 different power plants was aggregated to 11 processes, see Table 4-5.

Table 4-5 – Base year parameters for electricity generation sector

Plant	Capacity (GW)	Efficiency (%)	Availability (%)	Capital Costs (€Million/MW)	Fixed O&M (€1000/MW)	Variable O&M (€1000/MWh)
MSW CHP	0	25%	85%	0.8	80	0.2
Biogas	0	33.5%	85%	0.8	20	0.2
Turbine Gas-Condensing Steam	0.4	40%	85%	0.9	20	0.2
Hydro	0.22	100%	50%	1	0	0.2
Lignite (Peat)	0.35	41.5%	90%	1.42	40	0.2
Gas Turbine Distillate Oil (OCGT)	0.5	38%	85%	0.4	30	0.2
Steam Turbine Oil	1.15	32%	85%	0.44	22.5	0.2
Hard Coal	0.84	39.5%	85%	1.4	40	0.2
CCGT Gas (older units)	1.42	47.5%	85%	0.8	10	0.2
CCGT Gas (newer units)	1.14	55%	85%	0.7	10	0.2
Wind	1.01	100%	32%[23]	1.3	25	0.2

For the modelling time horizon, maximum availability and maximum capacity for each electricity unit was set according to base year values and any shortfall in electricity demand was imported. Over the modelling time horizon, the model calculated the capacity expansion required to meet the changing electricity demand and it also calculated the electricity dispatch for each time slice; following a series of tests with different time slices (hourly, daily, weekly) the model was run with weekday/weekend time slices (104 time slices per annum) for electricity demand curves and wind availability curves. For electricity demand for each of the aggregated scenarios (reference, energy efficiency, energy efficiency+), the model calculated the capacity expansion and electricity dispatch in three different ways:

1. *LEAP running costs:* The capacity expansion was built according to explicitly stated exogenous capacity values for each unit according to the EirGrid (transmission system operator) projections for 2020 (EirGridSONI, 2011a); dispatch is done in merit-order according to the lowest sum cost of fuel and O&M costs, i.e. running costs.

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[23] Average figure: data entered in model in weekly/weekend time slice format

2. *OSeMOSYS optimized:* Using linear programming optimization, OSeMOSYS makes capacity expansion calculations to generate "an energy system with the lowest total net present value of the social costs of the system over the entire period of calculation" (Heaps, 2011); in this context, additional data on interest rates (used to amortize capital costs of process) for the modelling time horizon were also entered into the model. OSeMOSYS does not have a specific dispatch rule, but in optimizing the overall energy system it dispatches optimally according to the specified constraints, which in this run were electricity generation availability and some maximum capacity values.
3. *OSeMOSYS optimized and CO_2 constrained:* This run was the same as Dispatch No. 2 with an additional constraint on CO_2 emission limits.

4.3.3 Transmission and distribution system

For each scenario, the transmission & distribution system was modelled over the full time horizon with an unchanging 8.3% loss (EirGridSONI, 2011b). The model was set up such that any shortfall in electricity generation was imported and any surplus was exported.

4.4 Results

This section first presents results for TFC for the entire energy system for the three aggregated scenarios for the period 2009-2020. The results are also given for the individual scenarios in the residential, transport and industry sectors. Finally, results for the electricity generation sector using different capacity expansion and dispatch runs are also presented. In the Ireland LEAP model, all sectors and sub-sectors have reference scenario data for the base year (2008) and for the modelling time horizon (2009-2020). However only some sectors and sub-sectors have data for the energy efficiency scenario and energy efficiency+ scenario (see Table 4-1). A number of caveats come with these results:

1. The inherent uncertainties in all input assumptions; this applies directly to fuel prices projections (IEA) and macro-economic projections of GDP, GNP & GVA (Bergin et al., 2010).

2. The results vary depending on the model assumptions; the modelling in this chapter uses macro-economic projections that underpinned the 2010 national energy forecasts (Clancy et al., 2010) which have changed as Ireland's economic situation has worsened.
3. Due to methodological differences, which were mostly due to data availability, some sectors are modelled in more detail and robustness than other sectors. This leads to results for certain sub-sectors having more uncertainty than other sub-sectors.
4. For energy efficiency policies that are examined, the implementation rate of the policies is inherently uncertain and has a direct result on the overall level of energy savings achieved. Studies of building regulations in Ireland have found discrepancy between target savings and actual energy savings, see Chapter 3.
5. Like most energy systems modelling, the modelling here is based on fixed rates of energy consumption that fail to account well for the behavioural aspect of energy consumers. This is a common problem for all energy models (Laitner et al., 2002).

4.4.1 Overall TFC

The results for overall TFC in 2020 for all sectors and for the transport and residential sub-sectors for each scenario are shown in Table 4-6. The overall TFC in 2020 for the reference scenario is 16.9% higher than in 2008. The policies modelled in the energy efficiency scenario lead to an increase of TFC of 7.4% and the impact of the energy efficiency+ scenario is an increase of 1.1%. The impact of each individual energy efficiency policy and exploration for each sub-sector is discussed in more detail below.

Table 4-6 – TFC for all sectors and sub-sectors for base year and all scenarios (units: ktoe)

Sector	Sub-Sector	Base Year (2008)	Reference (2020)	Energy Efficiency (2020)	Energy Efficiency+ (2020)
Transport	Fuel Tourism	421	295	295	295
	Freight	929	951	951	951
	Road Private Car	1,921	2,106	1,327	1,218
	Taxis & Hackneys	53	71	67	65
	Passenger Rail	50	100	102	101
	Buses	113	230	217	223
	Passenger Aviation	486	996	996	996
	Subtotal	3,975	4,750	3,954	3,848
Residential	Space Heating	2,006	2,127	1,871	1,535
	Water Heating	704	756	737	677
	Lighting	91	62	36	36
	Cooking	110	138	138	138
	Appliances	389	619	619	619
	Subtotal	3,300	3,702	3,297	3,005
Industry	All NACE Categories	2,517	3,256	3,256	3,025
Services	All Sub-Sectors	1,782	1,822	1,822	1,822
	Total	11,573	13,530	12,433	11,701

4.4.2 Reference scenario

For the reference scenario, all input data for the base year of 2008 is historical data and the energy demand is 9% of the recorded energy balance by SEAI for 2008 (Howley, Dennehy, and Gallachoir, 2009a); for 2009 and 2010, the model's results are within 7.1% and 6.1% respectively (Howley et al., 2010). In the period 2009-2010, the impact of the recession (as recorded by a fall in GDP) causes the modelled energy demand to fall off immediately but by 2013, energy demand has returned to 2008 levels and by 2020 the energy demand has increased by 16.3%, see Figure 4-1.

Transport sector

Overall TFC in the reference scenario for the transport sector grows by 20% and by 2020 its share of overall TFC has grown from 34% to 35%. In the reference scenario, the total car stock rises from 1.91 million cars in 2008 to 2.02 million cars in 2020 (a function of growth in car sales tied to an assumed recovery of the economy) and fleet activity rises from 29.6 billion vehicle kilometers (bvkm) to 33.2 bvkm in 2020. The forecast energy growth is due to the rising car stock and consequent vehicle activity. Increased vehicle efficiency and the decreasing per-car annual mileage slow down the growth, while a dip in 2018 energy is due to the model's 19-year vintage limit and the large number of 2000-registered vehicles in the stock that are retired that year. Both the freight sub-sector and the passenger aviation sub-sector have an energy demand profile that corresponds to the level of activity in the economy whereas the sub-sectors of taxis & hackneys, passenger rail, and buses have a relatively fixed growth rate.

Residential sector

For the residential sector reference scenario, the addition of new dwellings (the rate of which is higher than the natural obsolescence rate of the existing dwelling stock) leads to an overall 12.2% increase in TFC. Newer dwellings are more energy efficient than existing dwellings, reflecting the impact of the 2005 and 2008 building regulations. By 2020, space and water heating TFC have decreased in share of total residential TFC from 82% to 78%, whereas lighting, cooking and appliances have increased in TFC from 18% to 22%.

Industry sector

As outlined in Section 4.3.1, TFC in the industry sector is closely tied to the economic forecasts and in the reference scenario increases by 29.4% overall. By using an extrapolation of historical energy intensity trends to predict future intensity, the reference scenario represents a business-as-usual scenario where the influence of policies, measures and technical change follows a historical trend. Therefore, the scenario includes the influence of future measures and technological improvements that will be as effective as existing and past ones.

Services sector

Between 2008 and 2020 the TFC of the services sector is modelled to rise by 2.3%. This is a function of GVA growth and gradually declining energy intensity of the thermal and electricity energy-end use demands.

4.4.3 Energy efficiency scenario

As described in Section 4.3.1, the energy efficiency scenario is an amalgamation of all the energy efficiency policy scenarios for each sector, or sub-sector, that represent energy efficiency policies that are currently in place, or for which there is a commitment. Many of these policies can be found in Ireland's NEEAP (DCENR, 2009). The overall results show an 8.1% fall in energy consumption relative to the reference scenario. This reduction in energy consumption is due to three policies in the transport sector (electric vehicles, reduced private car demand & more efficient vehicles) and three policies in the residential sector (retrofitting scheme, building regulations & CFL lighting), see Figure 4-1.

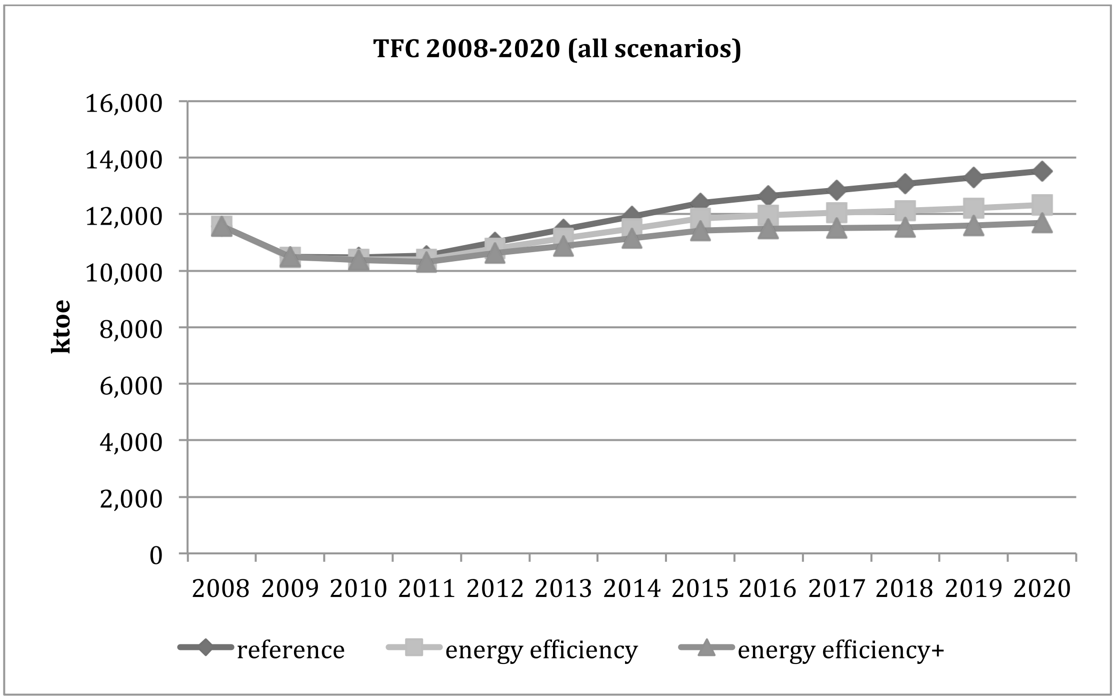

Figure 4-1 – TFC for each aggregate scenario for base year (2008) and modelling time horizon (2009-2020)

Transport sector

In the transport sector, there are no policies for the freight and passenger aviation sub-sectors. The most significant policy is a target to have 10% of all private cars electric by 2020 (DCENR, 2009). Assuming that this target will be met, the *electric vehicle*$_{average}$ policy scenario models new electric vehicles (EVs) (0.72 MJ/km) displacing average internal combustion engine sales and mileage (efficiency 2.25 MJ/km and 16,032 kms/year). The two other policies are *efficient driving*, where the mileages of all terrestrial vehicles (private cars, taxis & hackneys & buses) reduce due to better driving campaigns and *passenger car mileage*, where passenger car mileage declines as a result of mobility management campaigns (e.g., e-working, land use management).

The combined impact of these policies is a 16.7% reduction in energy consumption compared to the reference scenario.

Residential sector

For existing dwellings in the reference scenario, there is an assumption of no retrofitting work between 2009 and 2020. The *retrofit*$_{average}$ scenario models the potential impact of the Better Energy Homes scheme (Clancy and Scheer, 2011). In the energy efficiency scenario, an annual retrofit rate of 100,000 is assumed, which results in 800,000 residential dwellings being retrofitted between 2009 and 2020. Dwellings undergoing retrofit are limited to D to G bands, the retrofit depth reflects current trends to date, and the take-up rate reflects the share of overall dwellings in the total dwelling stock (Dineen et al., 2011). Other policies in the residential sector are *building regulations 2011*$_{average}$ and *building regulations 2013*$_{average}$, which in-line with the findings from the previous chapter are assumed to have 13% non-compliance. *CFL lighting*, the policy to upgrade all dwellings to CFL lighting by 2012 rather than just a gradual phase out to a residual level of incandescent penetration of 5% by 2025. The combined impact of these policies is a reduction in TFC of 8.1% compared to the reference scenario.

4.4.4 Energy efficiency+ scenario

The energy efficiency+ scenario includes the impact of all policy scenarios from the energy efficiency scenario; it also includes the impact of certain energy efficiency policies beyond their current rate of implementation (transport & residential sectors) and explores the impact, in the absence of any government policies, of changes in the structure and intensity of current energy demand (transport & industry sectors). The results for this scenario are a 13.7% reduction in TFC compared to the reference scenario.

Transport sector

There are three exploratory scenarios in the transport sector for which no policy currently exists: *efficient vehicles*, whereby the stock of new cars bought by 2015 complies with EU Regulation 443/2009, requiring the average new car sold in the EU to achieve maximum new-car emissions of

95g CO_2/km by 2020, this scenario assumes that technology improves at a faster rate (2%/annum) than historically; while this target is included in the NEEAP and is also included in national energy forecasts reference scenario (Clancy and Scheer, 2011), there is no policy in place. *Private car occupancy*, examines the impact of a linear increase in private car occupancy from 1.93 in 2008 to 2.5 in 2020 and *modal shift* shifts passenger kilometers from private cars to public transport (passenger trains and buses). As a result, buses become more efficient, although activity increases too. Finally, EV_{best} examines the impact of the proportion of EVs sales rising to 30%, reaching 10% of the 2.2 million cars in the fleet by 2020. The net effect on TFC for these all policies and measures is a reduction of 19%.

Residential sector

The energy efficiency+ scenario explores the impact of a retrofitting scenario beyond its current rate of implementation: $retrofit_{best}$ is realized by retrofitting dwellings to a full retrofit. The scenario assumes full compliance with *building regulations* 2011_{best} and *building regulations* 2013_{best}. For space and water heating, this results in 15.9% savings compared to the energy efficiency scenario and 24.4% savings compared to the reference scenario.

Industry sector

Two exploratory scenarios were run in the industry sector: *GVA change,* examined the impact of growth in GVA of 20% for NACE 21_22 (pulp, paper, publishing and printing) and a simultaneous sub-sector specific decline in GVA of 25% for NACE 26 (non-metallic mineral products); *efficiency change* examined a decrease in energy intensity of 10% for all sub-sectors by 2020. The combined impact of these two exploratory scenarios on TFC is a 7.1% reduction compared to the reference scenario.

4.4.5 Electricity generation sector

Three separate sets of results for electricity generation dispatch and capacity expansion were compiled for each of the aggregated scenarios (reference, energy efficiency & energy efficiency+). The three separate sets of results are based on three distinct dispatch runs for electricity generation: the first run used the running costs dispatch rule in LEAP, the second run used OSeMOSYS (without a CO_2 emissions constraint) and the third run used OSeMOSYS (with a CO_2 emissions constraint). The results for electricity generation in 2020 for the energy efficiency scenario are in Table 4-7 and are described below in detail; the results for all runs and all scenarios are in Appendix C.

Table 4-7 - Electricity generation in 2020 results for energy efficiency scenario for three electricity dispatches runs (units: TWh)

Plant	Running Costs (fuel and O&M costs)	Optimized (no constraint)	Optimized (CO_2 constraint)
MSW CHP	0.15	0.89	0.89
Biogas	0.04	0.00	0.01
Turbine Gas-Condensing	0.37	0.06	0.05
Hydro	1.02	1.00	1.00
Lignite (Peat)	2.63	2.60	2.60
Gas Turbine Diesel (OCGT)	0.88	0.05	0.05
Steam Turbine Oil	0.00	0.00	0.00
Hard Coal	5.43	5.32	1.78
CCGT Gas (older units)	2.98	1.42	1.42
CCGT Gas (newer units)	6.33	10.18	13.72
Wind	11.91	11.94	11.94

Running costs run (LEAP)

For the electricity generation sector, the base year was modelled within 6.3% of the actual electricity production and within 18.3% of CO_2 emissions. The electricity generation capacity was set according to Eirgrid[24] projections for 2020 and for each year, was dispatched in merit order of running costs where running costs was a sum of fuel costs and operation & maintenance costs.

Optimized run (OSeMOSYS)

Using the optimization functions of LEAP based on the linear programming code of OSeMOSYS, the dispatch decision for electricity generation sector was optimized according to least cost of the total generation sector. Maximum capacity constraints based on upper resource limits were imposed for Municipal Solid Waste (MSW) CHP (Browne et al., 2011), biogas (Smyth, 2011) and wind. It is interesting to note that the optimized run, which unlike the running cost run isn't constrained to have 4GW installed wind capacity, has just 1.01 GW of installed wind capacity and relies largely on gas generated electricity.

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[24] The Irish transmission system operator

Optimized run with CO_2 constraint (OSeMOSYS)

Ireland's 2020 ETS target requires a 20% cut in CO_2 emissions compared to 2005 levels and the optimized CO_2 constrained run investigates how the electricity system will meet this target. The result is a reduction in coal generation and an increase in wind generation partnered with gas. The impact of the three different runs on the CO_2 intensity of the electricity generated in the reference scenario is shown in Figure 4-2.

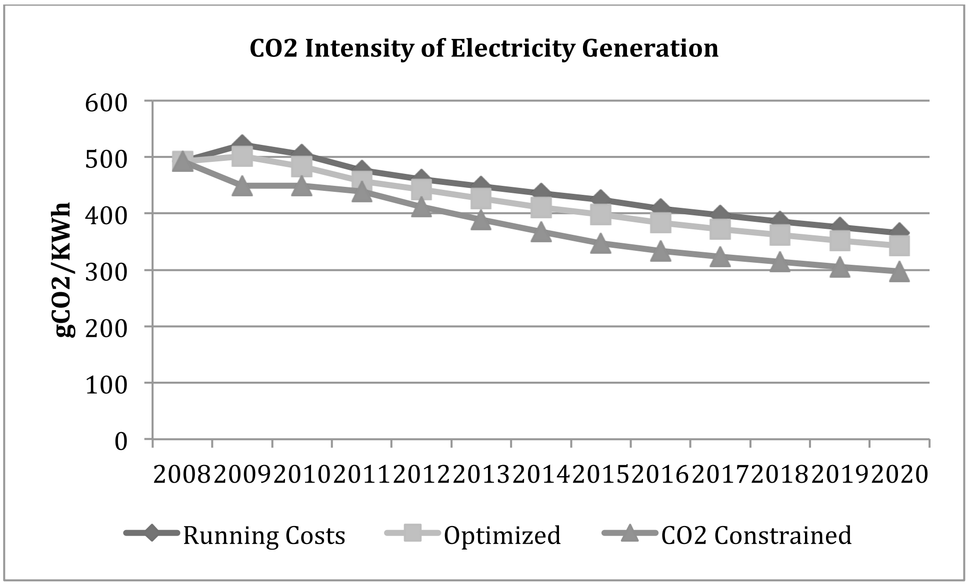

Figure 4-2 – CO_2 intensity of electricity generation for three electricity dispatch runs

4.5 Discussion

Using a LEAP energy model built for Ireland, this chapter has focused in detail on two sectors (residential and transport) and has used bottom-up modelling to help quantify the impact of energy efficiency policies in these sectors. Combined with two other sectors of the economy (industry and services), this chapter has presented three aggregated energy demand scenarios: a reference scenario, an energy efficiency scenario and an energy efficiency+ scenario.

4.5.1 Modelling the uncertainty of energy efficiency policies

While the bottom-up approach adopted for two sectors permits quantification of the impact of an individual policies, the combined effect of all policies is not simply the sum of all their individual impacts. In reality, energy efficiency savings in one area will reduce energy savings in another area and a failure to account for this leads to double-counting, which has been defined by EMEEES as "the combined effect of overlapping measures may be smaller or larger than the sum of the separate effects" (EMEEES, 2009). For example, the combined effect of a policy that increases private car fuel efficiency and a policy that increases vehicle occupancy will be less than the sum of their separately modelled effect. The discrepancy between the sum of all individual policies and their combined effect when modelled simultaneously, i.e. the double-counting potential, is shown in Figure 4-3. To calculate the double counting potential, two values were compared: firstly, twelve separate scenarios for each of the twelve energy efficiency measures in Figure 4-3 were run and the energy savings (compared to the reference scenario) for each of these individual scenarios were summed to 33.4 GWh; secondly, the energy efficiency + scenario, i.e. one integrated scenario with the twelve energy efficiency measures from Figure 4-3 was run and the energy savings (compared to the reference scenario) from this one run was calculated to be 21.6 GWh. The difference between these two values, 11.8 GWh, is the double counting potential.

It is suggested by the author, that further work could render this double counting potential as a confidence interval for expected energy savings during energy modelling exercises. In view of the fact that both approaches are useful, it is recommended that when individual policies are modelled, a confidence interval derived from the double-counting potential range, be applied to account for the uncertainty in its potential impact. The double counting potential points to some of the aleatory uncertainty in this modeling. Because the energy savings will depend a great deal on what happens in the interaction of various dynamics, it is not possible to quantify the savings especially when using a static baseline.

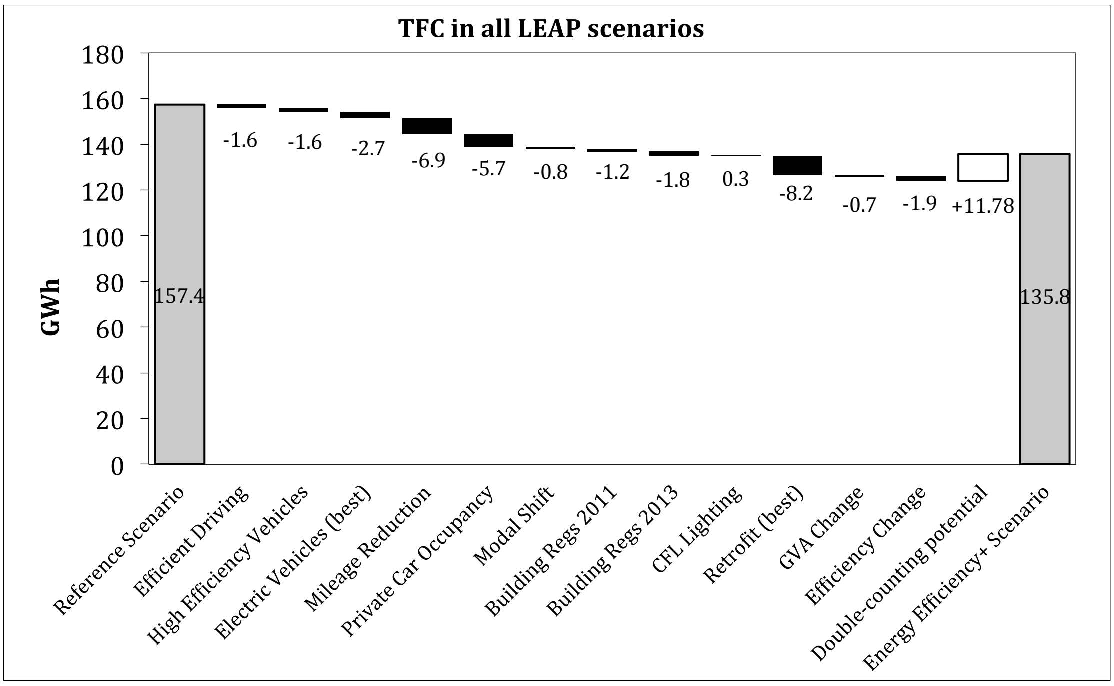

Figure 4-3 – TFC for reference scenario and all policy measures in energy efficiency+ scenario in year 2020 (units: GWh)

In energy system's modeling, structural uncertainty refers to uncertainty stemming from an incorrect or mis-application of a particular energy modeling technique. "The importance of structural uncertainty analysis is in knowing when and where a model may be applied to produce reasonable results and, perhaps more importantly, where the model will fail". While difficult to address, a suggested approach is to consider "through simulation, the consequences of changes in the model" (Smith, 2002). This is essentially the approach adopted here, though it is only applied at the micro, and not the macro, level: three difference policies (*building regulations, electrical vehicles, residential retrofitting*) have been given varying implementation rates; see Figure 4.4. A substantial part of the uncertainty is epistemic, i.e. with more data it would be possible to improve the certainty of the results.

4.5.2 Comparison with NEEAP targets

As noted in Section 3, many of the policies modelled in this chapter are also in the NEEAP. Due to the data available, and the model structure employed, this analysis has been able to examine a number of policies in depth, mostly technical policies as stipulated by regulation. However, there are a number of policy types in NEEAP that have not been examined in depth. In the residential sector, these policies are typically more niche in focus (e.g. houses of tomorrow scheme for developers, warmer homes scheme for fuel poor households, greener homes scheme for home installation of micro-renewables); they account for 4.5% of residential sector energy savings. The smart meter installation policy was not included since at the time of model construction relevant data on smart meter trials was not available. Policies in the industry and services sector were not modelled due to an absence of sufficiently disaggregated data.

This chapter is not an attempt to comprehensively model all policies in NEEAP, and for many of the policies that are modelled, different assumptions are taken. With this caveat, a comparison is made between some NEEAP and LEAP policy measures and the results are shown in Table 4-8. Note that the NEEAP savings are in units of Primary Energy Equivalent (DCENR, 2009) and that the LEAP savings in this table have been converted into equivalent units. All the units in this chapter, except for Table 4-8, are TFC. The following chapter has a more in-depth analysis of TPER, as part of an analysis of residential fuel switching and CO_2 emissions.

Table 4-8 – Comparison of NEEAP and LEAP energy savings in 2016 (units: GWh)

Sector	Policy Measure	NEEAP	LEAP
Residential	$\text{Retrofit}_{\text{average}}$	600	2436
	BRegs 2011	1100	711
	BRegs 2013	395	832
	CFL Lighting	1200	1175
Transport	$\text{Electric Vehicles}_{\text{average}}$	955	660
	Private Car Demand	1090	3390
	Efficient Driving	655	1060

4.5.3 LEAP/OSeMOSYS time resolution

The work in this chapter has involved extensive testing of the capabilities of the LEAP/OSeMOSYS partnership. The addition of OSeMOSYS code brings significant added value to LEAP for modelling an energy system in greater resolution and accuracy approximating real world conditions. In the current version of LEAP[25], it is possible to model the dispatch of the electricity generating units for an hourly time resolution; however, dispatch modelling at an hourly time resolution within LEAP/OSeMOSYS is not currently possible due to excessive demands on

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[25] 2012.0.0.24

the RAM[26] of the computer performing the operation. The weekly/weekend time slices was the maximum resolution that the model could solve.

While optimization models can have as little as six annual time slices (Kannan, 2011) or as many as six daily time slices (Howells et al., 2005), it has been noted that the decision about which time slice resolution to use can affect what investment decision is made (Deane et al., 2012). In this respect, it is crucial for the modelling software to be appropriate to the problem solved. Ireland is expected to have high penetration of intermittent wind energy (Clancy and Scheer, 2011), so the power model needed to definitively model the inter-temporal dynamics of the electricity systems will need to have high time resolution.

Although models capable of modelling all the dynamics of a power system (reliability, flexibility and unit commitment & dispatch) are specialized power systems models, there is scope for energy optimization models being able to solve high resolution problems. For OSeMOSYS as a feature of LEAP, the limitation to model the dispatch of the power system at a high (i.e. hourly or sub-hourly) resolution stems in part from the ability of the solver, and in part from the trade-off between an intuitively simple code and a code with an ability to model highly complex and large problems; the ethos of OSeMOSYS currently favours the former approach (Howells et al., 2011). Future developments of OSeMOSYS code are expected to include an improved ability to model intermittent renewables together with less flexible base load generation for long term energy systems expansion (Welsch et al., 2012).

4.6 Conclusions

4.6.1 Assessing energy policy - an integrated approach

Despite the range of energy models have been developed to help guide and inform all aspects of energy policy (Connolly et al., 2010) it has also been argued that, “such models provide biased estimates that tend to reinforce the status quo, inadequately inform policy-makers about new market potential, and serve to constrain the development of innovative policies” (Laitner, 2006). In this context, it is vital that energy models are able to bridge the “disconnect between the

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[26] 12GB RAM, Intel Xeon 3.0 GHz processor, Microsoft Windows 7, 64 bit

questions policy makers want answered and the results provided by modelling exercises" (Munson, 2004).

In terms of a coherent monitoring of energy policy that combines ex-ante and ex-post analysis, LEAP offers an excellent framework and tool for improved communication between modelling experts and policy makers. It is possible to model in detail the expected energy performance of a policy and to track annually its actual performance. For an ex-post analysis, LEAP is also suitable asking hypothetical questions – what would the energy performance have been if a certain parameter was different? For example, the impact on energy consumption of variable implementation rates for the electric vehicle policy and the residential retrofit scheme is shown in Figure 4-4. Similarly, the difference between building regulations assuming full compliance or non-compliance, as analysed in Chapter 3, could also be shown. This analysis has also shown how LEAP can be employed to demonstrate the double counting potential of individual ex-ante analyses – when energy efficiency policies are modelled together, their impact can be less than the sum of their separately modelled and summed energy savings. LEAP can also evaluate primary energy and the impact of CO_2 emissions.

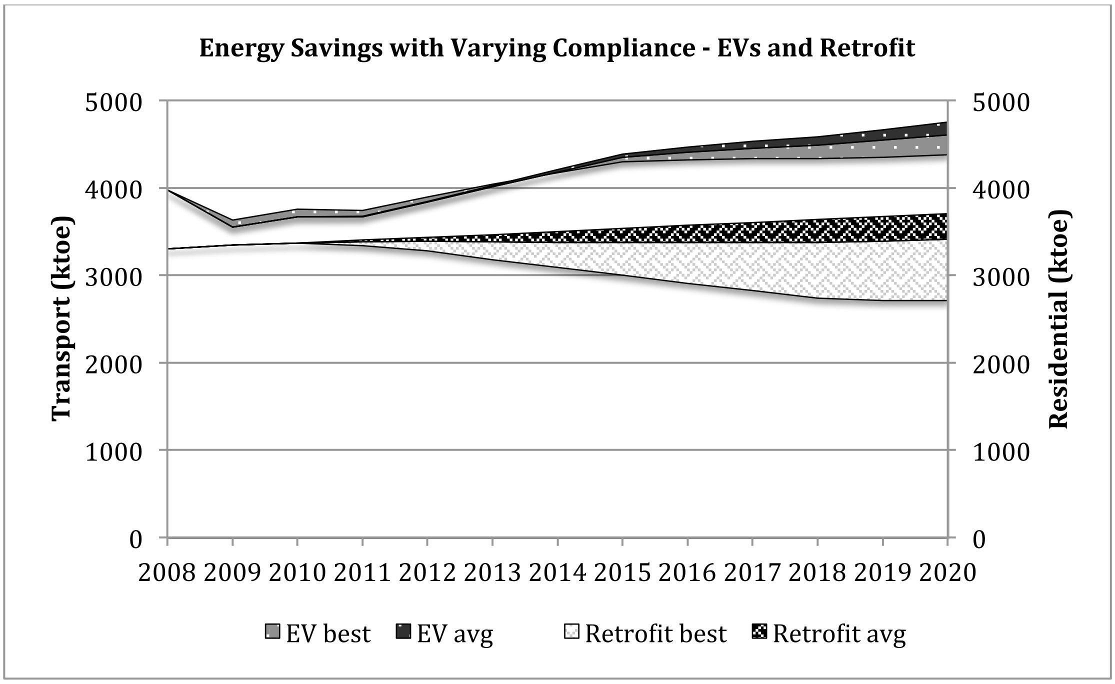

Figure 4-4 – TFC according to varying implementation rates for EV and retrofit policy measures (units: ktoe)

This chapter has demonstrated a model for Ireland, which at the sector specific level enables detailed analysis of the impact of individual energy efficiency policies, which in turn can be combined into aggregated scenarios, representing portfolios of policies. The potential role in Ireland for LEAP as an energy planning tool for has been acknowledged in Ireland's national energy forecasts: "The long-term vision is to use LEAP-Ireland as a planning tool for assessing the future impacts of possible energy efficiency policies and measures, complementing and providing an alternative perspective to ongoing macro-economic modelling" (Clancy et al., 2010).

4.6.2 Soft-linking

Energy optimization models can be adapted to capture all power system dynamics, for example in order to capture the impact of variable wind power (Pina et al., 2011) assessed the impact of going down to an hourly resolution with three day types per season; their findings confirmed the importance of a higher resolution to better depict renewable resource availability, but also electricity demand dynamics. However, a different approach that begins with the acknowledgement that not all energy questions can be answered by one energy model is the soft-linking methodology that has been successfully used and demonstrated to enhance the robustness of different software packages with different strengths (Deane et al., 2012). PLEXOS, a power systems modelling software was used to sense-check the results of TIMES, a long term energy optimization model. The sense-checking in turn was used to inform new constraints and bounds for the TIMES model. By modelling individual sectors and policies in detail, the LEAP model in this chapter can be used to inform inputs to the TIMES model. Soft-linking can also be employed to help calibrate the electricity generation sector dispatch and capacity expansion aspect of the LEAP/OSeMOSYS modelling partnership.

The prime advantage of OSeMOSYS over Plexos is that the former is integrated with LEAP, which enables simultaneous and integrated demand-side and supply side energy system modelling, while the later only models the electricity sector with an exogenously input electricity demand. In LEAP-OSeMOSYS, it is possible to run and compare integrated scenarios of varying electricity demand and for these scenarios, to compare energy demand, emissions and cost for the entire energy system. Plexos models the electricity power system in more advanced detail, which makes it more useful for certain situations, but not for all analyses.

5 Natural Gas as a Transition Fuel – A Decomposition Analysis of CO_2 Constrained Pathways

Abstract

This chapter uses a TIMES model of the Irish energy system to analyse the role for natural gas in Ireland's future energy system. The chapter describes a scenario analysis of low carbon pathways for Ireland for the period 2005-2050 and analyses the varying natural gas demand in these three scenarios: reference, 80% cut in CO_2 emissions and 95% cut in CO_2 emissions. A key technology for natural gas is carbon, capture and sequestration (CCS). A decomposition analysis of the two CO_2 constrained scenarios in terms of emission reduction attributable to energy efficiency, fossil fuel switching and renewable energy is also presented. In the 80% cut in CO_2 emissions scenario, fuel switching of fossil fuels (primarily natural gas) contributes 15% to emissions reduction but in the 95% scenario, it contributes just 1%.

Keywords: natural gas; transition fuel; decomposition analysis; TIMES model; gas CCS

5.1 Introduction

The energy sector has been identified as the single biggest emitter of greenhouse gas emissions, and in the context of reducing emissions to mitigate the worst impacts of anthropogenic climate change, there have been calls for large-scale resources to be invested in technology that can help decarbonise the energy system (IEA, 2012a). Due to the long lead times and enormous capital costs in the energy sector, this decarbonization process will take many decades. A low carbon energy system would look very different to today's energy system, which (excluding nuclear) derives 81.1% of its primary energy supply from fossil fuels (IEA, 2012b).

Natural gas has the lowest emissions of all fossil fuels and in the context of reducing emissions via fuel switching from coal and oil, it has been called a transition fuel (Economides and Wood, 2009) and a bridging fuel (Vinois, 2010) to a low carbon energy system. This view is not without controversy: on the one hand, while modelling exercises have explicitly cited natural gas as playing a crucial role in transition to zero carbon energy system (Stephenson et al., 2012), concerns have been raised about the environmental credentials of natural gas production (Gormley, 2010) and its role in promulgating fossil fuel extraction.

Emissions from the power sector in Europe are currently covered by the Emissions Trading Scheme (ETS). As of 2012, there is no mandatory long term EU target for CO_2 emissions reductions, though some countries such as the UK have introduced legislation to make such a reduction obligatory (Kannan et al., 2009). The analysis described in this chapter is based on analysis originally done to inform the Climate Change Response Bill in Ireland which proposed an 80% cut in GHG emissions relative to 1990 (Gormley, 2010).

This chapter uses an energy optimization model (Irish TIMES) for the Irish energy system to analyse the role of natural gas in different scenarios of emissions reduction for the time period 2005-2050. The Irish TIMES model was built in UCC as part of the EPA Climate Change Research Programme (2007-2013)(Ó Gallachóir et al., 2012). This chapter is laid out as follows: section 5.2 has a brief description of the Irish TIMES model including the three scenarios, section 5.3 describes the results for the three scenarios with a focus on natural gas demand and also includes a decomposition analysis of the reduction in emissions. Section 5.4 concludes.

5.2 Irish TIMES

The TIMES (The Integrated MARKAL-EFOM System) model was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), an international community which uses long term energy scenarios to conduct in-depth energy and environmental analyses[27]. TIMES is a technology rich, bottom-up model, which uses linear-programming to produce a least-cost energy system optimized according to a number of user constraints. The Irish TIMES project has focused on the Irish energy system and the potential for Ireland to make large cuts in CO_2 emissions by 2050. The Irish TIMES model was originally extracted from the Pan European TIMES (PET) model and then updated with improved data based on much extensive local knowledge (Ó Gallachóir et al., 2012). A detailed description of the TIMES energy system model is contained in Appendix F; a brief description of the inputs and outputs of the Irish TIMES model is below.

For inputs to the Irish TIMES model, there are approximately 1600 technology options for all sectors of the economy. Each of these technologies has associated costs (e.g. capital costs, O&M costs, discount rates), efficiencies (e.g. heat rates, learning curves) and detailed technical parameters (e.g. technology lifetime, emission factors, process capacity, availability). Fuel price projections are taken from IEA world energy outlook 2009 (IEA, 2009) and energy service demand for each sector (e.g. residential, transport) and end-use (e.g. home heating demand, passenger km) are calculated exogenously and added to the model: this energy service demand is the energy that the TIMES model must calculate an energy system to serve. Constraints of capacity, activity, emissions and resource availability are also added to the model (Chiodi et al., 2012).

The TIMES model output is an energy system, which services the end-use energy demands for all time slices at lowest cost. The model optimizes this energy systems using linear-programming, i.e. it calculates a solution to meet the energy service demand, but there is no feedback to the model's macro-economic

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[27] http://www.iea-etsap.org/web/index.asp

inputs such as GDP. It produces energy pathways over multiple time slices for a long-term time horizon and the solution in the model is in terms of technology choice; it doesn't provide any input to what policy instruments are necessary to implement the technical solutions and it models behaviour in a simplified way (Ó Gallachóir et al., 2012). There model currently allows technology change to achieve emissions reductions but does not allow any reduction in energy service demands in response to increased costs, i.e. there is no demand response; however, work is on-going in UCC to address this by introducing elastic demand.

5.2.1 Scenarios

This section describes the three scenarios that were run to 2050. These three scenarios are shown in Figure 5-1, which shows the actual CO_2eq emissions for the reference scenario (*REF)* and the constrained emission pathways for the 80% cut in CO_2 emissions scenario (*CO2-80*) and the 95% cut in CO_2 emissions scenario *(CO2-95)*. The constrained emission time path for each emission reduction scenario is shown in Table 5.1.

Table 5-1 – CO_2 emission reduction pathways for *CO2-80* and *CO2-95* scenarios

Year	2020	2030	2040	2050
CO2-80	25%	40%	60%	80%
CO2-95	25%	50%	70%	95%

The 2030 interim target and 2050 final target are in line with the European Low Carbon road map: "In order to be in line with the 80 to 95% overall GHG reduction objective by 2050, the Roadmap indicates that a cost effective and gradual transition would require a 40% domestic reduction of greenhouse gas emissions compared to 1990 as a milestone for 2030, and 80% for 2050". Although the results aren't shown here, the Irish TIMES model was run with a single emissions constraint of 80% for 2050 and without the interim targets. In this scenario the results were extremely unrealistic: for most of the modelling time horizon there was negligible change in the energy system, then in the final time slice there was large scale switching to an energy system that would meet the targets.

REF: The reference scenario is a non-CO_2 constrained scenario but it is bound by the objective function to produce a least-cost energy system. It is an economically optimum scenario, which differs from reference scenarios, which are projections of time-series historic trends or a simulation of energy demand in the absence of energy policies such as were described in Chapter 4.

CO2-80: This scenario imposes an 80% cut in CO_2 emissions by 2050 compared to 1990. Emissions in 1990 were 30.2 Mt CO_2, and the reduction target is 6.04 Mt CO_2. This reduction is an 80% reduction in CO_2 for the energy sector only.

CO2-95: This scenario imposes a 95% cut in CO_2 emissions by 2050 compared to 1990. The absolute CO_2 emissions target for this scenario is 1.51 Mt CO_2. The rationale for this scenario stems from the higher than average contribution to CO_2eq emissions that the Irish agriculture sector makes. In 2005, the average EU-27 share for CO_2eq emissions from agriculture was 11%, in Ireland agriculture had a 28.5% share (McGettigan et al., 2010). If the agriculture sector in Ireland can achieve a 50% reduction in $CO_{2\text{-}eq}$ emissions by 2050 (relative to 1990), then the Irish energy system will need to make a 95% reduction in order for the entire economy to make a net 80% reduction in total CO_2eq emissions.

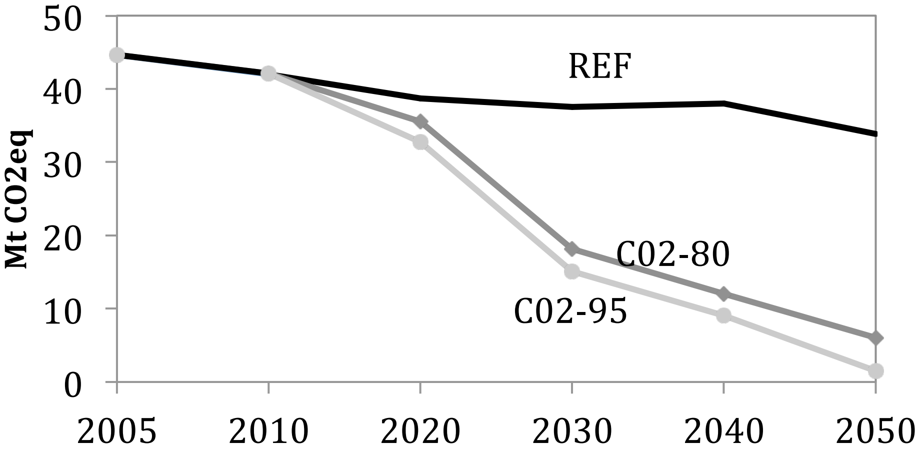

Figure 5-1 – Reference and CO_2 constrained scenario pathways

5.2.2 Decomposition analysis

Decomposition analysis has been widely and successfully used to analyse the driving forces behind changes in CO_2 emissions and energy consumption. It is typically used to analyse empirical data, i.e. historic changes in various sectors of the economy. In an Irish context decomposition has been used to examine energy consumption in industry (Cahill and Gallachóir, 2012) and the residential sector (see Chapter 2). Decomposition analysis techniques have been used to analyse aspects of the results of a TIMES model (Kesicki and Anandarajah, 2011), although these are much less common.

A more detailed description of the properties of decomposition analysis and some of the different methodologies is in Chapter 2. This analysis uses the same decomposition methodology as that chapter, Log Mean Divisia Index I (LMDI I) methodology (Ang and Liu, 2001) and to decompose the change in CO_2 emissions from the Irish TIMES model, it uses a simple decomposition identity (Capros et al., 2012). For the *CO2-80* scenario and *CO2-95* scenario, this analysis decomposes the change in emissions relative to the reference scenario. The general form of the decomposition formula used is shown in Equation 5-1.

$$\Delta CO_2 = \Delta CO_{2activity} + \Delta CO_{2energyefficiency} + \Delta CO_{2fuelswitching} + \Delta CO_{2renewable}$$

Equation 5-1

The four terms in Equation 5-1 are changes in emissions in terms of:

- *Activity*: the change in emissions due to changes in GDP (€). Because there is no demand response in the Irish TIMES energy system model, GDP remains the same in the reference scenario, CO2-80 scenario and CO2-95 scenario, therefore this effect is zero.
- *Energy efficiency:* the change in emissions due to the changing efficiency of energy required to achieve the same level of economic activity (GDP). In this analysis energy efficiency is defined as: total energy/GDP, i.e. it is the inverse of energy intensity.
- *Fossil fuel switching:* the change in emissions due to fuel switching of fossil fuels of different CO_2 intensity, e.g. a switch from coal to gas. It is defined in this analysis as CO_2/fossil fuel energy.
- *Renewable energy:* the change in emission due to the increasing share of carbon free energy in the fuel mix. It is defined in this analysis as fossil fuel energy/total energy.

The particular form of the decomposition equation is:

$$\Delta CO_2 = \sum_n \frac{(CO_2^{CO2-80} - CO_2^{REF})}{(\ln CO_2^{CO2-80} - \ln CO_2^{REF})} \times \left\{ \ln\left(\frac{GDP^{CO2-80}}{GDP^{REF}}\right) + \ln\left(\frac{Int^{CO2-80}}{Int^{REF}}\right) + \ln\left(\frac{RE^{CO2-80}}{RE^{REF}}\right) \ln\left(\frac{CO_2Int^{CO2-80}}{CO_2Int^{REF}}\right) \right\}$$

Equation 5-2

5.3 Results

The high-level decomposition analysis presented in this chapter gives an insight to the relative contribution to emission mitigation from the three effects discussed: renewable energy, fossil fuel switching and energy efficiency. In standard figures of energy consumption, the contribution from renewable energy is a clear and quantified amount; however, energy efficiency and fossil fuel switching are not visible in such standards figures since their impact is only apparent when compared to a counterfactual baseline. Therefore, to disentangle the relative contribution of each of these three emission reduction strategies and to combine them into a single graph, a decomposition analysis was required. For each of the three scenarios, the results are presented first in terms of total and sectoral energy consumption with a particular focus on the contribution from natural gas in each sector. The decomposition analysis are shown for the *CO2-80* scenario and *CO2-95* scenario with the changes in CO_2 emissions decomposed into three effects: (1) fuel switching between fossil fuels, (2) changes in energy efficiency, and (3) increased use of renewable energy. The overall consumption results for each sector for the base year (2005) and the three scenarios in 2050 are shown in Table 5-1.

While sectoral disaggregation and decomposition of the Irish TIMES scenario results are readily doable, it is not currently possible to aggregate such decompositions into a single result as shown in Figure 5-2. This is because there is no common indicator such as GDP or GVA that is valid for both sectors and the energy system as a whole. With respect to the focus in this analysis being on natural gas across the entire energy system, it is only with an aggregated decomposition analysis that relevant trends can be analysed.

Table 5-2 – Gas consumption by sector for base year and all scenarios (units: mtoe)

	BASE	REF	CO2-80	CO2-95
Agriculture	0.34	0.43	0.43	0.43
Commercial	1.67	2.06	1.74	1.69
Industry	2.62	2.38	2.38	2.39
Residential	2.94	3.13	2.69	2.38
Transport	4.23	5.76	3.71	3.70
Total	11.80	13.77	10.95	10.59

5.3.1 REF

In the *REF* scenario, energy demand for 2050 is not constrained according to any CO_2 emissions target and the solution is an energy system of increased consumption in most sectors. It is important to emphasize that this switch is made for economic reasons where there is no price or constraint on CO_2 emissions.

In the *REF* scenario and for the modelling period of 2005-2050, the overall energy consumption of the entire energy system increases by 16.7% while the associated CO_2 emissions fall by 24.7%. This is due to cost-optimal fuel switching from higher CO_2 emitting fuels such as oil to lower CO_2 emitting fuels such as natural gas and renewables. This trend of increased energy consumption but lower CO_2 emissions holds for all sectors (including electricity generation) with the exception of industry where energy consumption decreases by 9.2% and transport where emissions rise by 20.2%

In terms of natural gas in the *REF* scenario, the absolute consumption and share of overall consumption relative to the base year increases in every sector in the *REF* scenario with the exception of electricity sector, see Table 5-2. The sectors with the largest growth are the residential, commercial and transport sectors. Growth in the commercial and residential sectors is in line with historic trends; however, the transport sector grows from zero natural gas in 2005 to a small amount of freight demand in 2050. Gas generated electricity decreases its share from 42.9% to 34% and becomes the largest generator of electricity, with the second largest being wind. The main difference between the *REF* scenario and 2005 for the electricity sector is the reduced share of coal generation from 34.2% to 7.3% and the increased share of wind generation from 4.3% to 48.4%.

Table 5-3 Share of natural gas of energy consumption by sector for base year and all scenarios

	BASE	REF	CO2-80	CO2-95
Agriculture	0.0%	10.0%	10.0%	0.3%
Commercial	18.1%	39.7%	17.7%	0.0%
Industry	20.7%	24.8%	4.0%	3.7%
Residential	20.4%	30.3%	34.9%	7.6%
Transport	0.0%	21.9%	0.0%	0.0%
Electricity	40.3%	49.7%	36.7%	0.0%

5.3.2 CO2-80

The results for the *CO2-80* scenario are very different to the *REF* scenario. The imposed pathway of CO_2 emissions (40% reduction in 2030, 60% in 2040 and 80% in 2050 – see Figure 5-1) produces an energy system in 2050 with 20% more investment compared to the *REF* scenario (Chiodi et al., 2012). Energy consumption in the *CO2-80* scenario is 7.2% lower than the base year and 20.5 % lower than the energy consumption in the *REF* scenario.

The transport, commercial and residential sectors reduce their energy consumption significantly (-35.7%, -15.5%, -14.3% respectively), whereas the agriculture and industry sectors change by 0% and -0.01% respectively. Moving to a more stringent CO_2 reduction target, increases the demand for electricity, which increases by 31.7% compared to the *REF* scenario. The increased electricity requirements are met by renewable electricity (mostly onshore and offshore wind) and gas CCS, which have a 66.7% and 18.3% share respectively. Unlike the *REF* scenario, no gas is used in freight, which has its energy demand mostly served by biodiesel.

In terms of how the CO_2 emissions reduction is achieved in the *CO2-80* scenario, the decomposition analysis gives some insight to the relative contribution of each mitigation mode, the results for which are shown in Figure 5-2. The impact of fuel switching of fossil fuels is attributable to the increased share of natural gas compared with the dominance of oil in the *REF* scenario. It is the smallest effect of the three but its impact is not insignificant. Towards the end of the analysis period it grows as energy efficiency shrinks. The impact of energy efficiency is stripped of any hidden structural effects because for both scenarios, GDP is the same. The enlarged share of renewable energy has the most significant impact on CO_2 emissions, contributing 65% of the reduction in emissions over the entire period (2005-2050).

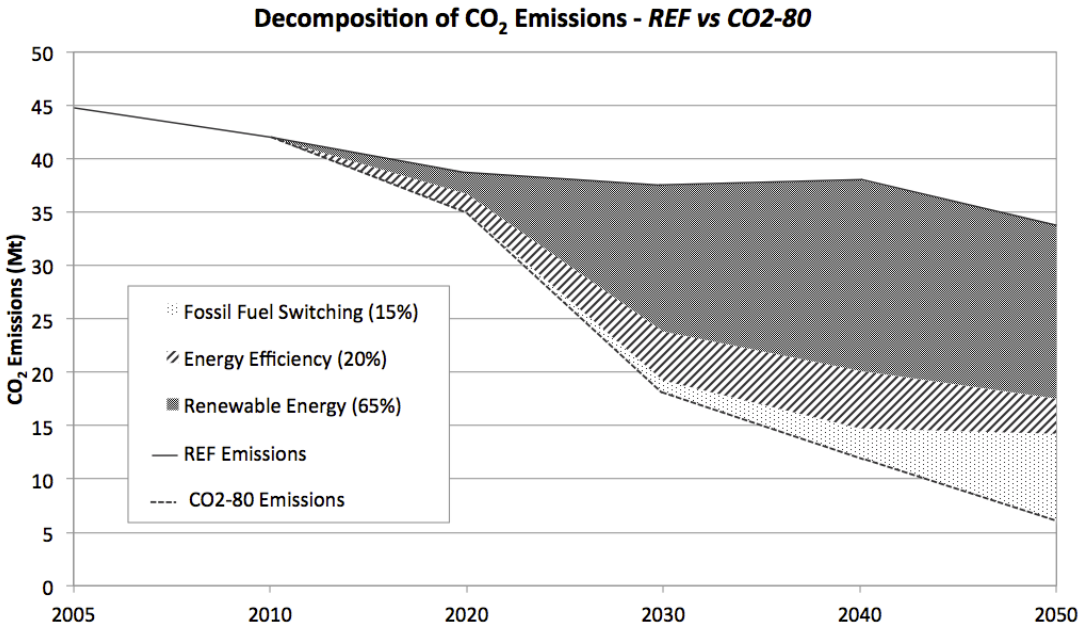

Figure 5-2 – Decomposition of change in C0₂ emissions – *REF* vs. *CO2-80*

5.3.3 CO2-95

The structure of energy demand continues to change considerably in the *CO2-95* scenario and there is a continued shift to electricity used to service energy demand. This trend is consistent across all scenarios for varying rates of emission reduction with a very approximate 2.5% rise in electricity GWh for every percentage point increase in the emissions constraint. Overall energy consumption in the *CO2-95* scenario is 23.1% lower than the *REF* scenario. The stringency of the CO_2 emissions target means that electricity generation is dominated by renewables (97.1%) made up mostly of wind energy (67%) and biomass (28.2%). In the electricity generation sector there is no gas used for standard generation or for CCS. In the residential sector, gas is only used for a fraction of residential heating load and its main end-use is cooking. There is no gas transport and very small shares in the industry and commercial sectors.

In terms of CO_2 emissions reduction, in the *CO2-95* scenario, the contribution of fuel switching of fossil fuels shrinks as technical limits are reached; by 2050, all fossil fuel switching options have been exhausted and because of a minimum amount of oil consumption in the transport sector, CO_2 emissions due to fuel switching of fossil fuels actually marginally increase (7%)

in 2050 (not shown in Figure 5-3). The energy efficiency contribution to CO_2 emissions reduction is relatively stable, within 5% of the contribution in the 80% scenario. The bulk of the CO_2 emissions reduction comes from renewable energy, which provides 83% of the CO_2 emissions reduction in the 95% scenario. The results are shown in Figure 5-3.

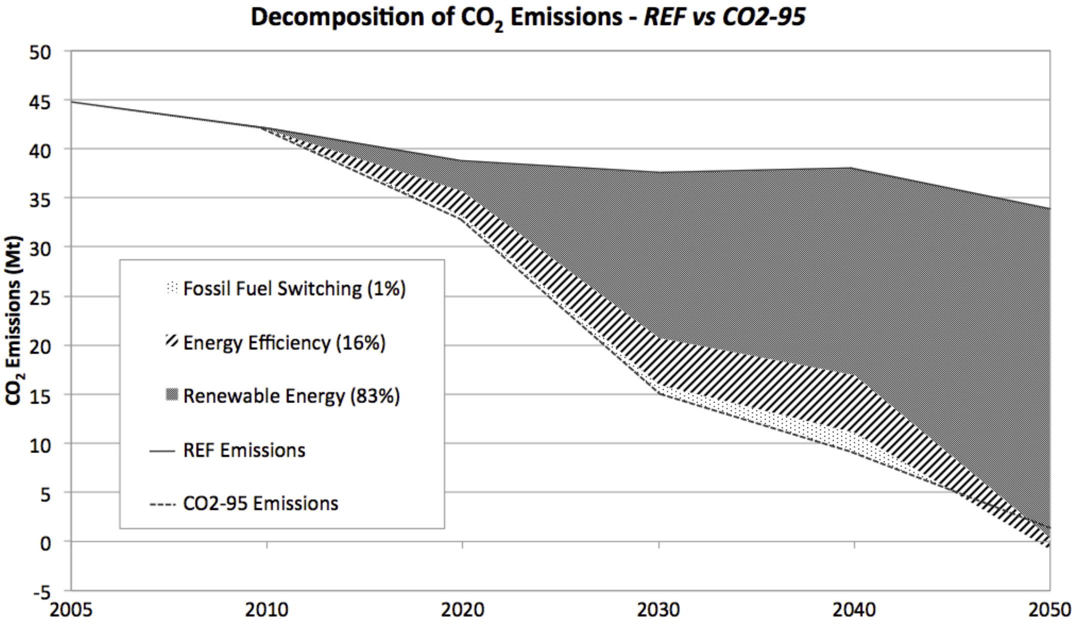

Figure 5-3 - Decomposition of change in CO_2 emissions – *REF* vs. *CO2-95*

5.4 Conclusions

In the *REF* scenario for the year 2050, Irish TIMES produces an energy system that is economically optimal but is in CO_2 terms, unconstrained. This differs from the current energy system, which is not economically optimal and has constraints on CO_2 (i.e. the ETS and carbon tax of €20/t). This frames the results analysis, particularly in terms of technologies present in the *REF* scenario, but absent in reality, the most interesting result in this respect is the presence of freight gas in the *REF* scenario. In Ireland, there is an active interest in gas as a transport fuel, with BGN currently trialling CNG buses in Cork (McGrath, 2012). However in the *CO2-80* scenario, gas freight is replaced by a renewable alternative, imported biodiesel.

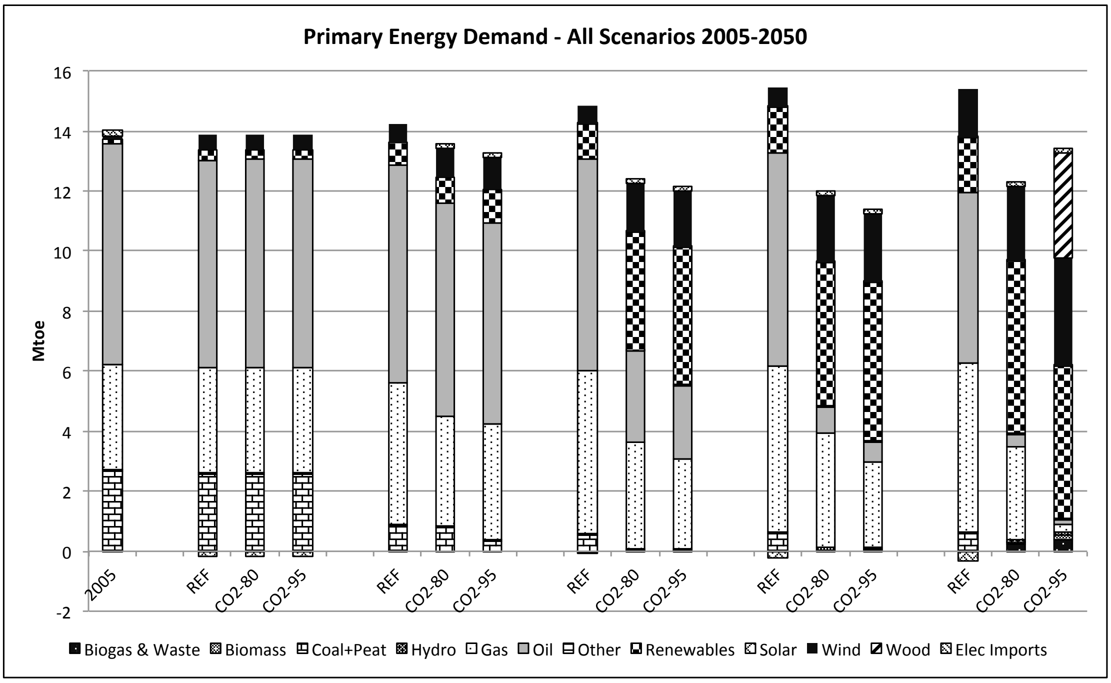

Figure 5-4 – Primary energy demand – all scenarios 2005-2050

In the *REF* scenario, the share of gas increases in all sectors; in primary energy terms, gas has a 37.2% share. Compared to the *REF* scenario, natural gas primary energy demand is 44.3% lower in the *CO2-80* scenario but it still has an overall share of primary energy (25.4%), which is higher than the base year share (24.9%). This illustrates well the potential for natural gas to be as a bridging fuel to a low-carbon energy system. Compared to the base year, absolute natural gas demand in the *REF* scenario is 61% higher whereas in the *CO2-80* scenario it is only 10% lower than the base year. In the *CO2-80* scenario, natural gas increases its share in the residential sector, holds its share in the commercial and agriculture sector, almost disappears in the industry sector and completely disappears from the transport sector. It retains a presence in the electricity sector primarily due to the role of gas CCS. As a low carbon technology, CCS still has substantial uncertainty surrounding its development and rollout as a successful mitigation option. The next chapter will examine in detail the potential role of CCS in the *CO2-80* scenario and in Ireland.

Regarding the potential for fuel switching, most of the emissions reduction is made by switching to gas, and most of the changes are made in the *CO2-80* scenario. In the *CO2-95* scenario the share of gas declines to 2% and the impact of fossil fuel switching declines to 1% overall as technical limits are reached. Emissions reduction is achieved almost entirely by renewable energy. The *CO2-95* scenario represents a low carbon energy system in which gas does not have a share. In this chapter, the term transition period is defined as the time period between various states of energy system decarbonization, where decarbonization is achieved by imposed emission reduction constraints of between 25% and 95%, see Table 5.1. It is expected that a decarbonized energy system would in reality be progressively achieved and that the interim transition periods can be approximated by the incrementally more stringent emission reduction limits. While the transition from an 80% reduction to a 95% reduction is not modeled in a single scenario, the state of the energy system is revealed in the incrementally more stringent emission reduction limits. Figure 5.2 shows the contribution of fossil fuel switching (predominantly to natural gas CCS) particularly between 60% and 80% emissions reduction, when the transition is increased to 95% (in Figure 5.3), there is a limit to how much fossil fuel switching can achieve, at the 95% level, all of the emissions reduction is from renewable energy. The technology that makes natural gas a key transition fuel in the 80% emission scenario is CCS. A key reason gas CCS is chosen over coal CCS are the lower residual emissions for gas CCS (6.7 kt/MWh) compared to coal CCS (11.9 kt/MWh. Further differences between coal and gas CCS are discussed in more detail in the next chapter.

In conclusion natural gas has a key role in Ireland as a transition fuel to a low carbon future energy system. Its relatively low cost and low emission technology help to keep to the marginal cost of carbon down to €273/tonne CO_2 in the *CO2-80* scenario, but in the *CO2-95* scenario the marginal cost of carbon rises to €1308/tonne CO_2 (Chiodi et al., 2012). Marginal CO_2 costs indicate severe convexity with respect to the carbon target.

This chapter has used decomposition analysis, which is more typically used for analysing historic emissions; however, it has been proven to be useful at providing insight to the results of energy models, particularly detailed and complex models such as TIMES. Decomposition analysis of energy systems models is therefore considered an underutilized analytic methodology.

6 The Potential for Carbon Capture and Storage in Ireland

Abstract

This chapter presents an analysis of the potential for mitigation of CO_2 emissions from electricity generation using carbon, capture and storage (CCS) in Ireland. Using the Irish TIMES energy systems model with technology pathways to 2050 for deep climate mitigation scenarios, CCS is found to have an important role alongside other low carbon generation options. A comparison of coal CCS and gas CCS under different input assumptions and CO_2 mitigation targets shows that gas CCS is the chosen technology in most scenarios, but that it has some key disadvantages in comparison to coal CCS. A sensitivity analysis of fuel price finds both the absolute and relative price of coal and gas affect which technology is most competitive. An analysis of the potential sites for CCS in Ireland is presented with five different combinations of capture and storage locations investigated for their cost and impact on energy security of supply. The lowest cost CCS option in the 80% CO2 emissions reduction scenario is found to be a gas CCS plant located in Cork with sequestration in depleted gas fields off the south coast of Ireland.

Keywords: coal CCS; gas CCS; TIMES scenario analysis; CO_2 emissions mitigation; cost of CO_2 avoided

6.1 Introduction

In 2010, global CO_2 emissions for the energy sector were 30.3 Gt (IEA, 2012a). In order to reduce point $C0_2$ emissions to help mitigate anthropogenic climate change (IEA, 2010), there have been growing calls for decarbonisation investment in order "to avoid lock-in of high-emissions technology" (Brockett, 2010) and as part of this proposed energy transition, there has been much discussion and research into the potential for carbon, capture and storage (CCS) technology (IEA, 2011b) (CSA et al., 2008; Azar et al., 2010) (Metz et al., 2005; DCMNR, 2007; Edenhofer et al., 2010). CCS is most often associated with capturing CO_2 emissions from coal (Kaarstad et al., 2011)) and to a lesser extent from natural gas (Rubin and Zhai, 2012) and biomass, which is capable of achieving negative emissions; CCS is also being explored for CO_2 sequestration in industry, particularly in cement and steel manufacture (IEA, 2010). While each stage (capture, transport and storage) of CCS is a proven technology, fully operational and commercial-scale CCS projects are rare, with only eight plants currently in existence globally (Global CCS Institute, 2012).

Despite being an uncertain technology, the expectations for CSS are high: in the IEA-ETP energy scenarios consistent with a two degree rise in global temperature, CCS contributes 22% to the global emissions reductions required in 2050 (IEA, 2012). According to an EU Energy Roadmap, "CCS [...] will have to contribute significantly in most scenarios with a particularly strong role of up to 32% in power generation in the case of constrained nuclear production and shares between 19 to 24% in other scenarios with the exception of the High [renewable energy] scenario" (EC, 2011). Research to reduce the cost and improve the efficiency of capturing CO_2 emissions is ongoing (Rubin, 2005); however, the pace of construction of new CCS plants has slowed in recent years with many CCS plants encountering difficulties not foreseen at the design stage (Global CCS Institute, 2011; van Renssen, 2012). This reduced number of large-scale demonstration projects in only a few locations is insufficient for adequate lessons and conclusions to be learned such that CCS, which faces both general obstacles and locally presented ones, can be deployed in sufficient locations for it to be effective (Kaarstad et al., 2011).

In addition to the global IEA-ETP study already cited, many country and regional analyses have concluded a role for CCS, though the results vary according to local conditions and constraints. In the UK for a 60% emission reduction scenario, coal CCS provided 45% of the energy demand; gas CCS was an option but it was not chosen, perhaps due to the availability of nuclear (R. Kannan, 2009). Two separate studies of Spain and Portugal produced different CCS portfolios in terms of an optimum energy mix: Spain installed coal CCS (Cabal et al., 2012) while Portugal installed gas CCS (Seixas et al., 2012) because for the latter, it was more economic to import electricity at prices that made coal CCS economic for the former. In China (Karlsson et al., 2011) conducted a study of long term energy futures for China and found that coal CCS was key technology in an emission constrained scenario.

The Irish TIMES project (Ó Gallachóir et al., 2012) has focused on modelling the technology pathway for the Irish energy system to achieve deep cuts in CO_2 emissions in line with the reductions necessary to preserve atmospheric concentrations at 450ppm and in accord with "the scientific view that the increase in global temperature should be below two degrees Celsius" (UNFCC, 2009). A model (as described in the previous chapter) developed for the year 2050 used scenario analysis to investigate the energy system that can achieve an 80% cut in CO_2 emissions and a 95% cut in CO_2 emissions in Ireland and the results for some of these scenarios included CCS (Chiodi et al., 2012).

This chapter investigates the role for CCS in more detail and seeks to include local constraints and conditions which are crucial to any modelling exercises (Strachan et al., 2011). Through a number of different scenarios, an analysis of CCS based on the following research questions is presented:

- What are the key differences which determine whether coal or gas CCS is chosen for CO_2 mitigation?
- What are the full costs of CCS when local constraints and site location are included?
- In a security of supply scenario, what are the increase in costs?

The chapter is laid out as follows: Section 6.2 reviews CCS in Ireland in terms of existing policy and local characteristics that will affect the costs, performance and rollout of the technology. Section 6.3 describes the methodology used to investigate these issues and answer the research questions. Section 6.4 describes the results, section 6.5 is a discussion and section 6.6 concludes.

6.2 CCS in Ireland

In 2010, electricity generation in Ireland emitted 13.3 Mt of $C0_2$, approximately 22% of Ireland's total CO_2 emissions and approximately 0.04% of global CO_2 emissions associated with electricity generation. Ireland is a small but globalized economy and as such, is generally a technology "taker" that is highly influenced by developments at an international and EU level. While much of the precedent for CCS comes from abroad, many of the characteristics that determine which CCS technology will be most appropriate and where to site a CCS electricity generation plant are local conditions that must be studied and investigated. This section reviews both the international and EU context as well as the various stages and aspects of CCS technology that must be adapted to Irish conditions in order for it to be optimally utilized. This includes an assessment of Ireland's storage's capacity and other factors, which will impact the rollout of CCS in Ireland such as the impact on energy security of supply.

6.2.1 Policy context

International: Many reports have posited the current decade (2010-2020) and the near future to be of critical importance to the development of CCS (CSA et al., 2008; IEA, 2010) (Lipponen et al., 2011; McAuley and Polaski, 2011). In 2010, the IEA published a CCS roadmap, which laid out many of the challenges and steps necessary for CCS to become a reality and a target to have 100 CCS plants in operation by 2020 and 3000 by 2050. It found that if CCS technologies are not used, it will increase the cost of achieving CO_2 stabilisation by 70% (IEA, 2010). In a review of the roadmap one year later, it was noted that progress has been made, in the number of demonstration projects in operation; however, challenges related to "joint planning of CO_2 transportation infrastructure", "data on CO_2 storage" and "public awareness of CCS technologies" remain (Markusson and Haszeldine, 2010; Lipponen et al., 2011).

In the wake of decelerating progress in 2012, the Global Status of CCS report called for renewed funding for CCS demonstration projects (Global CCS Institute, 2012).

EU: Much of Ireland's legislation and targets in the energy arena are EU sourced. In 2011, the EC published a roadmap document which explored the energy pathways to an energy system with 80% lower GHG emissions by 2050; the report noted that CCS "has to play a pivotal role in system transformation" contributing up to 32% of the electricity needs in certain scenarios (EC, 2011). The report also noted the importance of CCS in keeping gas as a large contributor to power generation and in biomass terms, by generating negative emissions. While the EU have through their analyses highlighted the importance of CCS as a bridging technology, they have also emphasised the challenges of safe storage of CO_2 and from the perspective of storage capacity have advised mutual consideration of security of fuel supply and CCS (CSA et al., 2008; EC, 2009b). Current EU targets are for 2020 and no firm targets or policies exist for longer term time horizons such as 2050.

Ireland: From 1990 to 2011, the carbon intensity of electricity in Ireland declined by 45% largely through fuel switching to gas and renewable energy: in 2011, Ireland's fuel mix in electricity generation was 56% gas, 20% coal, 11% peat & 8% wind (Howley et al., 2012). Peat is currently maintained by subsidies, for security of supply and political reasons (Tuohy et al., 2009) and its use is expected to decline over time as more biomass co-firing takes its place (Clancy and Scheer, 2011). Ireland has ambitious targets for 40% penetration of renewable electricity by 2020 as part of the 20/20/20 EU Climate Package and is currently formulating a longer-term decarbonization pathway at a national level (O'Donnell et al., 2012) and EU level (EC, 2011), towards the target of an 80% cut in CO_2 emissions by 2050.

The Irish government have made clear they have no objection to CCS (Hanna, 2010) and noted in a 2006 White Paper that, "Subject to developments, the Government would envisage the commercial operation of a new clean coal power generation plant before 2020" (DCMNR, 2007). In addition to that statement, there has been analysis on the future technology options for low carbon electricity (Pöyry, 2010), an initial assessment of the geological storage capacity (CSA et al., 2008), a number of conferences focused on CCS (Convery, 2008) (Lewis, 2010) and a number of cost and feasibility assessments of CCS in Ireland (SEI, 2005; Monaghan et al., 2006; CSA et al., 2008). In nearly all instances, the prevailing view is that CCS in collaboration with coal generation will provide a solution (DCMNR, 2007) (CSA et al., 2008) (McAuley and Polaski, 2011), despite there being no assessment of the potential for gas CCS. There is currently no legislation regarding CCS and its planned role in Ireland's energy future is currently unclear.

Ireland has considerable renewables potential in wind and ocean, however these are all asynchronous and intermittent sources. There is consensus that for an electricity system with a large amount of renewables, some conventional thermal plant will be required to provide: back-up for reasons of security; load-balancing for intermittent renewable generation; and inertia balancing to asynchronous power generation. The marginal costs of renewables technologies are also very high once large reductions (>60%) in emissions are required; in these high emissions reduction scenarios, CCS is competitive with, and in some instances, cheaper than, renewable energy sources.

6.2.2 Technology context

The emphasis in this chapter is on CCS technology focused on point sources and associated with power generation as it is the most developed of all the CCS technologies. CCS of CO_2 emissions from manufacturing of cement, iron & steel, chemicals and pulp & paper has been proposed (IEA, 2010), but it is significantly more theoretical than the power system. Sequestration of distributed CO_2 emissions (transport, residential sector) has also been proposed, although at the moment this technology remains too expensive to be considered a mitigation option (CSA et al., 2008; House et al., 2011). The sequestered rate for power generation CCS varies according to the fuel and except in the case of biofuels (which is not considered here)[28], there is still a residual level of emissions,

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[28] There are plans in place to include bio CCS in an updated Irish TIMES model. When the Irish TIMES model was originally extracted from the Pan European Times model in 2008, there was such uncertainty about bio CCS that it wasn't included as a technology option; according to the IEA, there is still significant uncertainty with the technology (IEA, 2010). There are no pilot or demonstration plants in existence, in contrast to coal and natural gas CCS. In addition to the

typically 10-14% of the non-CCS emissions rate. In this regard, CCS can be considered a bridge technology to a low carbon energy system.

The three key stages of CCS are (i) capture of emissions, (ii) transport of emissions and (iii) storage of emissions. Since the particular nature of each of these stages will be affected by the local characteristics, a discussion of each stage in the Ireland context is made below.

Capture

For the capture stage, there are three key types of technologies (Farrelly et al., 2010; IEA, 2010; Global CCS Institute, 2011), post-combustion, pre-combustion and oxy-firing. The differences between them are critical in terms of answering the question which CCS option Ireland should opt for. While it has been noted that Ireland does not at present need to select a technology type, owing to their status of being in-development (CSA et al., 2008), the choice of technology will in part determine what fuel will be used (peat, coal or gas). Ireland's main coal power generation plant (Moneypoint) has no plans to close imminently, although there has been research out what should replace it post-2025 (Tol et al., 2010). Other dynamics likely to affect future Irish power system is the cessation of subsidies for peat generation. While fully developed CCS technology is not imminently available yet, the UK have managed the uncertainty about whether or not to invest by mandating that all new coal plants which are built be upgraded to capture-ready, such that they can be readily converted to CCS status (Markusson and Haszeldine, 2010).

A very brief description of the three capture technologies is as follows:

Post-combustion: The basic approach for post-combustion capture is to use solvent absorption to separate CO_2. Typical projects involve the use of chemical amine-based solvents to selectively remove CO_2, which upon heating, releases a high-purity CO_2 off gas stream suitable for storage without any further treatment. Absorption processes are currently the most advanced of the post-

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uncertainty of the technology, there is uncertainty with regard to the life-cycle reduction of emissions when proper accounting of land-use emissions are taken into account (Vuuren et al, 2013; Kriegler et al, 2013) and this is also something which will be developed in an updated version of Irish TIMES.

combustion technologies and can be applied to newly designed fossil fuel power plants, or retrofitted to existing plants. While mature and commercially available, the technology has yet to be fully demonstrated at commercial-scale power plants.

Pre-combustion: Pre-combustion is for Integrated Gasification Combined Cycle (IGCC) coal plants; under high pressure the feedstock fuel is gasified and the resultant gas mixture is treated to produce CO_2 and a hydrogen rich synthetic gas. The CO_2 is removed using an acid gas removal process and the syngas is supplied to a gas turbine power block to produce electricity.

Oxy-firing: This technology works by combusting the feedstock fuel with oxygen, instead of air; this eliminates the nitrogen contained in combustion air, which leads to the production steam and CO_2; the latter is cleaned, dried and compressed and is thus ready for storage.

Transport

Since it is not expected that any capture site will be located immediately alongside the sequestration site, it is inevitable that transportation of the sequestered CO_2 between the capture and storage stages will be required. Transport is a critical stage in cost terms since the distance between capture and storage will have a direct impact on the overall stage costs, with excess costs rendering the entire project unfeasible. While shipping of compressed CO_2 in the manner of LNG is only economic for great distances (estimated at 1000km (CSA et al., 2008)), it is not considered here. Pipelines are the primary technology, they are mature and proven (CSA-GroupTPA-Solutions, 2007; IEA, 2010) but the application and scale is unique and the challenges are great. As an island, Ireland has much potential for offshore storage, but this will significantly increase the transport capital and operating costs; the unit costs of offshore pipeline are roughly double those of onshore pipelines (Zep, 2011). The cost of transport will affect choice of site and consideration should also be given to using pre-existing pipelines.

Storage

In the main, technology for storage of CO_2 emissions are not man-made but rather, geological, with depleted oil & gas fields, used aquifers and empty saline caverns being the main contenders. This minimizes costs; although the costs of getting good data can be high, they are unavoidable since good data about local geology and the type and extent of its potential for storage of CO_2 is crucial to a decision on CCS. Countries with good knowledge of their storage resources tend to have advanced oil and gas industry; in many case experience with enhanced-oil-recovery (EOR) has contributed expertise that can be applied to CCS (Hanna, 2010; Kaarstad et al., 2011). The EU has called for increased resources for storage assessment (EC, 2009b; EirGrid et al., 2010); this was highlighted in Ireland (Monaghan et al., 2006; Howley et al., 2011) and has been taken up to some extent by national studies (CSA et al., 2008) (Farrelly et al., 2010).

There have been a number of estimates and studies of CCS storage capacity in Ireland, see Table 6-1. In 2008 SEAI and the EPA commissioned a major study of all the storage capacity in Ireland for potential use as sequestration for CO_2 emissions (CSA et al., 2008). This study noted significant uncertainty with much of the information currently unavailable and noted the need for more extensive modelling and information gathering of the resources. It noted a practical capacity of 1505 Mt, enough to last for 117 years storage of all Irish point CO_2 emissions[29].

Table 6-1 – Estimates of CO_2 storage capacity in Ireland

	(CSA et al, 2008)	**(Kjärstad et al, 2009)**	**(Joule II Project)[30]**
CO_2 Mt	1,505	455	160

The EPA conducted a more in-depth study of geological potential of the Clare basin (Farrelly et al., 2010). The study examined in detail the seal, aquifer depth, trap, reservoir quality/injection rate, storage capacity and the presence of faults. Due to the storage sites having “extremely low permeability”, the report concluded that, “the onshore portion of the Clare Basin is unsuitable for CO_2

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[29] 12.86Mt CO_2 emissions in 2008 (McGettigan et al. 2010)

[30] (IEA 2008)

storage in saline aquifers". This study and a number of others have pointed to the depleted Kinsale gas field as the best option for CCS sequestration (CSA et al., 2008).

Irish storage is mostly offshore, which from a public acceptance perspective scores higher because it is not proximal to any population centres. It is also favourable for most current Irish electricity generation, which is located in coastal areas and therefore has minimal on-land pipeline distance to travel. The exception is peat, which is located alongside the source of the indigenous fuel, in the midlands of Ireland. This puts peat at a significant cost disadvantage.

The finite capacity of storage also emphasizes the role of CCS as a bridge technology, sequestration cannot continue indefinitely. The potential for CCS storage to congregate in hubs or clusters to save money has been well made (Global CCS Institute, 2011; O'Brien, 2012) and in an Irish context would be feasible in the Irish sea if shared with the UK, since this site has already been identified by other studies as having storage potential (Kirk, 2007; Alliance, 2012).

Costs

One of main factors inhibiting and delaying CCS demonstration projects to date has been the high cost of the technology (IEA, 2010; Rubin, 2012). While this is true for the technology's technical performance parameters, there has been little research on the potential for local conditions to affect the costs of the technology. Apart from a small number of mostly demonstration plants (Global CCS Institute, 2011)), the justifications for CCS have been to date being highly specific to local circumstances. The only current economic sequestration of CO_2 in CCS is for EOR: in Northern USA, the CO_2 emissions from a coal-based synthetic fuels power plant are captured and piped to Canada where the CO_2 is used for EOR and storage (IEA, 2010). Sleipner in Norway capture the CO_2 because of carbon tax of $40 per tonne. A carbon price is a necessary part of the justification for CCS (Bozzuto, 2008), however analyses of the necessary CO_2 price have posited varying results, see Table 6-2.

Table 6-2 – Review of CO_2 prices to make CCS economically viable

	Sleipner	Vattenfall	McKinsey
€/CO_2/t	€36[31]	€27	€50

6.2.3 Energy security

Ireland has one of the highest fuel import rates in the EU, and although much of the imported energy is currently sourced from other EU & OECD countries (Dennehy et al., 2011), the share of non-OECD supply countries has been growing in recent times (IEA, 2012). The impact on the Irish economy of a gas supply interruption would be enormous and in the vicinity of billions of euro (Leahy et al., 2012). Fuel diversification has been the traditional way for Ireland to manage its energy security risk with coal being the key fuel in the Irish energy mix; however, this is somewhat superficial. Most of Ireland's imported fuel comes from the UK or Norway, OPEC members, and as such, Ireland receives a higher security of supply rating; however, in recent years, much of the UK's fuel comes from non-OECD countries, something which isn't captured in Ireland's rating. Work to improve Ireland's visibility to these security of supply metrics is currently on-going in UCC (Glynn and Gallachoir, 2013).

Being a contributor to security of supply is one of the reasons the technology has been considered by the Irish government (Hanna, 2010). Ireland also uses gas storage to minimize the exposure risks for large scale import of fossil fuels although at the end of 2005, Ireland only had 11 days of natural gas storage; whereas the EU15 average was 52 days (CSA-GroupTPA-Solutions, 2007).

There is a potential conflict with CCS because the depleted gas fields that are currently used for gas storage, have been identified as the best option for CCS sequestration in Ireland. If the Southwest Kinsale gas field is used for CO_2 sequestration, this would remove Ireland's current gas storage capacity. However, there is a much larger Kinsale Head gas field, which could provide 1½ - 2 years of gas storage, based on 2008 consumption levels. The key question therefore is the extent to which gas storage limits the capacity available for CO_2 sequestration. It is not just depleted oil and gas fields that could be subject to

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[31] Based on conversion rates of €1 = $1.12 and £0.80

competition: salt aquifers are also being investigated for use as a short term load balancer for gas OCGTs to provide short term balancing of wind generated electricity on the power system (O'Brien, 2012).

6.3 Methodology

This section outlines the energy systems model used to project energy demand and the main energy scenarios. The section outlines the CCS technologies within the model and a number of CCS site scenarios developed to incorporate local constraints, infrastructure costs and security of supply limitations. The parameters for a sensitivity analysis are also described.

6.3.1 CCS technologies

This paper uses an energy systems optimization model, Irish TIMES, to generate future energy system pathways for Ireland under different scenarios. It was described in the previous Chapter. The Irish TIMES model was used to generate energy system projections for the year 2050 for a reference scenario (*REF*) and for a number of CO_2 emission constraints: an 80% cut in CO_2 emissions relative to 1990 (*CO2-80*) and a 95% cut in CO_2 emissions relative to 1990 (*CO2-95*).

There are four CCS technology options for electricity generation in the Irish TIMES model. These are distinguished by fuel type (coal, gas or peat) and power generation type (Pulverized Coal (PC), Integrated Gasification Combined Cycle (IGCC) or Combined Cycle Gas Turbine (CCGT)). These CCS technologies and their associated reference technologies are shown in Table 6-3. The efficiency and capital costs have associated learning curves that improve over time whereas O&M costs, plant availability and sequestration rates remain the same. There are no retrofitted CCS plant in the TIMES model.

Table 6-3 – CCS technologies in Irish TIMES model

Technology	Fuel	CAPEX (€M/GW)	CO_2 emissions (kt/PJ)	Thermal efficiency (%)[32]
PC_REF	Coal	850	99	44%
PC_CCS	Coal	1415	11.8	46%
IGCC_REF	Coal	1100	99	53%
IGCC_CCS	Coal	1370	11.8	45%
IGCC_REF	Peat	1100	108	53%
IGCC_CCS	Peat	1370	12.14	47%
CCGT_REF	Gas	385	56.1	63%
CCGT_CCS	Gas	925	6.73	48%

6.3.2 CCS sites

Five CCS sites were compiled which included transport and storage costs for a number of feasible CCS locations in Ireland. While the Irish government have indicated a favourable attitude towards coal CCS (DCMNR, 2007), which would favour a capture site near the current location of a large coal plant (Moneypoint), there has been no commitment to this particular site. Informed by the issues outlined in section 6.2, this analysis estimates costs for five combinations of two CCS capture technologies, three capture sites and three storage sites as shown in Table 6-4. The purpose of these fully costed CCS sites is to investigate whether CCS is still feasible in Ireland with local constraints and which site is most appropriate. Under the headings of capture, storage and transport, the rationale for each of the five sites is explained.

Table 6-4 –Candidate sites for location of CCS in Ireland

Site	Location	Capture	Transport	Storage Type	Location
1	Moneypoint, Co Clare	PC (Coal)	236 km	Gas field	Kinsale
2	Moneypoint, Co Clare	PC (Coal)	218 km	Gas field	Spanish Point
3	Whitegate, Co. Cork	CCGT (Gas)	90 km	Gas field	Kinsale
4	Whitegate, Co. Cork	CCGT (Gas)	431 km	Gas field	Spanish Point
5	Dublin Bay, Co. Dublin	CCGT (Gas)	90 km	Oil & Gas field	East Irish

Capture: All the CCS technologies in the model are new builds but it is assumed that new capture-ready CCS power plants will be built close to, or on the site of, a

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[32] The thermal efficiencies take account of the parasitic losses due to capture of CO_2 are therefore net.

pre-existing and equivalent non-CCS power plant. The basis of this assumption is that CCS generation will take advantage of pre-existing infrastructure such as high voltage power lines, dock or pipeline for delivery of fuel, or storage capacity for stockpiled fuel. PC and gas CCGT are the two CCS technologies investigated, since they are the two CCS types chosen in the Irish TIMES model. Peat IGCC has the additional disadvantages of having the highest residual emissions (12.14 kt/PJ) of all other CCS types and the fact that since it would be located close to the source of the fuel used (in the centre of Ireland), which puts it at an excessively large distance from all potential CCS storage, which for Ireland is all located offshore. The three capture sites are Moneypoint (Co. Clare), current site of a 847 MW coal plant; Whitegate (Co. Cork), current site of two 430 MW CCGTs; and Dublin Bay (Co. Dublin), current site of one 463 MW CCGT.

Storage: For each of the three capture sites, a potential storage site located as near as possible was taken from a report on the potential for geological storage of CO_2 in Ireland. This report included three different storage types: gas field, oil field, aquifer and reviewed data for twenty three different sites around Ireland all of which were offshore (CSA et al., 2008). The sites chosen in this analysis were classified as either effective capacity or practical, though this included a large variation in the level of uncertainty in the data. The depleted Kinsale gas fields are considered the most favourable option due to their large capacity (335 Mt), location (near a number of existing power plants), quality of seal and the potential cost savings from being able to use the pre-existing pipeline. Offshore (but still untapped) gas fields off the Clare and Dublin coast are the other two identified possible sites for CO_2 storage. In addition to the one 'near' storage site per capture site, one additional storage option was chosen for two of the capture sites (Moneypoint and Whitegate) to investigate the additional transport costs that would be incurred.

Transport: Pipelines distances from the capture site to the assigned storage site or sites were estimated based on an approximate straight line plus 15%. Pipelines costs were then estimated based on literature review data. Shipping of compressed CO_2 is extremely expensive and was not investigated in this study.

Full details of all CCS costs for each site by technology stage (capture, transportation & storage) and technology type (CAPEX & OPEX) are contained in Appendix G. The literature review noted significant variation in unit prices for each stage, in part this is due to differences in technology, i.e. transport, pipeline costs vary depending on material through which the pipeline is constructed and storage costs vary depending on storage type, i.e. a depleted gas field will have lower costs than an as yet untapped gas field. The model solves in five-year time slices; it is reasonable to assume that any infrastructure required for a particular energy technology will be built within five years. Further work on the additional costs to the electricity transmission and distribution for the infrastructure required to service the expanded power system have found minimal impact in terms of influencing the technology portfolio.

6.3.3 Security of supply

Two aspects of security of supply are investigated: type of capture technology and choice of storage site. The first aspect is a cost comparison of coal CCS and gas CCS where the former is a more abundant and therefore more secure fuel. The second aspect investigates a situation when Ireland's premier site for CO_2 sequestration (the depleted gas fields at Kinsale) is reserved for gas storage. This security of supply scenario excludes the option of Kinsale gas fields for CO_2 storage and uses the same capture location (Whitegate) with alternative sequestration (Spanish Point). Security of supply is assessed in terms of the difference in capital cost, operating cost, cost of electricity and avoided cost of CO_2 compared to an unconstrained security of supply scenario.

6.3.4 Sensitivity analysis

A number of sensitivity analyses were done on two key input parameters, capital costs and fuel prices, based on a literature review as described in the following section.

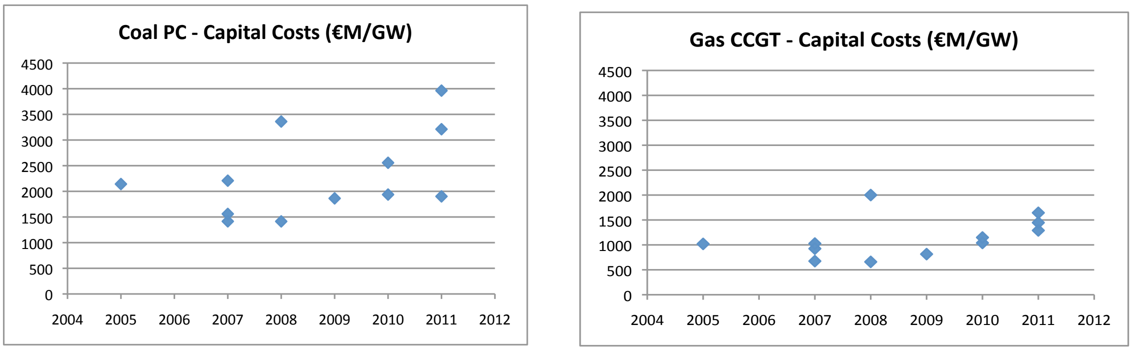

Figure 6-1 – Literature review of capital costs for coal PC and gas CCGT CCS

Capital costs: The initial costs in the Irish TIMES model were Pan European TIMES (PET) model costs in constant prices (€). A literature review of CCS capital costs found a large variance in current cost estimates implying significant uncertainty in all estimates. Problems with CCS cost data include limited number of original estimates, variation how the same metrics are compiled making comparisons difficult, no estimate of cost uncertainty (Markusson and Chalmers, 2012; Rubin, 2012). Mindful of these caveats, prices were all converted to 2000 € real to enable comparisons. While there is much research on reducing the cost, based on the date of publication of the cost estimate, there is an unscientific time trend that shows cost estimates converging towards higher estimates, see Figure 6-1.

Fuel prices: The initial fuel prices in the model were 2008 IEA fuel price projections (IEA, 2009). Variations were made based on fixed percentages (±10%, ±20%, ±50%, ±100%) and 2010 IEA WEO fuel prices (IEA, 2011c).

6.4 Results

The results examine the role of both coal CCS and gas CCS in terms of installed capacity, power output, contribution to emissions reduction, cost of CO_2 abated, cost of CO_2 avoided, levelized cost of electricity (LCOE) and overall technology cost. The first sub-section presents results for the CO_2 constrained scenarios for the entire energy system in 2050 for the *REF*, *CO2-80* and *CO2-95* scenarios. The second sub-section contains results for the five site specific scenario analysis of CCS, which includes the impact of transport and storage costs. It also examines the optimum CCS site location in Ireland and compares an unconstrained security of supply scenario with a constrained security of supply scenario. The last sub-section presents the results for a sensitivity analysis on two key performance parameters: fuel prices and capital costs of capture.

6.4.1 CO_2 constrained scenarios

A summary of the results for electricity generation for the *REF*, *CO2-80* and *CO2-95* is given in Figure 6-2; detailed results for energy consumption in all sectors for all scenarios for the Irish TIMES model are given in (Chiodi et al, 2012). In the *CO2-80* scenario, electricity demand is 31.7% higher compared to the *REF* scenario; this is because of a shift to electrification of home heating and transport. In this electricity generation portfolio, gas CCS has an installed capacity of 0.62 GW and generates 680 ktoe of electricity. It has a 19.1% share of total electricity generation and a 81% share of all gas electricity generation; in terms of sequestered CO_2 emissions, gas CCS contributes 5.6% of the 80% CO_2 reduction. Coal CCS is not chosen in the *CO2-80* scenario. In the *CO2-95* scenario, there is no gas CCS or coal CCS used for electricity generation which is sourced from 97.8% renewable sources.

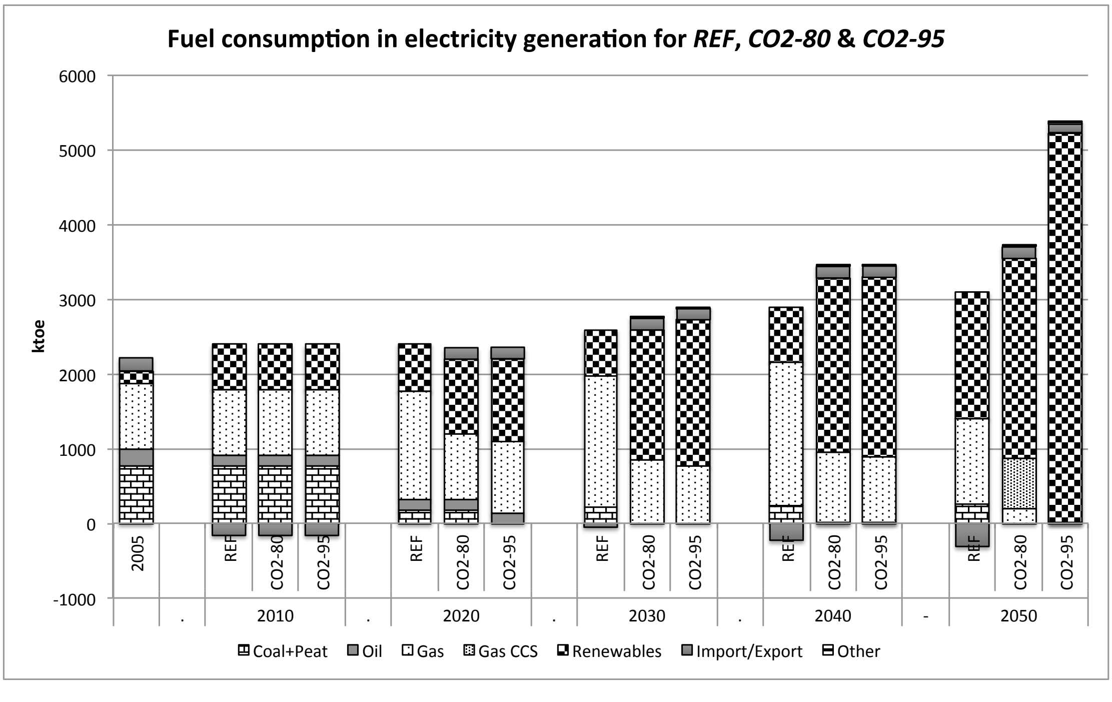

Figure 6-2 – Fuel consumption in electricity generation for *REF*, *CO2-80* & *CO2-95* scenarios (units: ktoe) (source: (Chiodi et al, 2012))

6.4.2 Cost of CO_2

The primary purpose of CCS is electricity without CO_2 emissions, and in this regard the most important metric for CCS is the mitigation cost per tonne of CO_2. Two cost of CO_2 metrics are used in this result section: the abated cost of CO_2 and the avoided cost of CO_2.

Abated cost of CO_2: Calculated in TIMES, it is in modelling terms the shadow price of CO_2. As the marginal price of CO_2, it is the price necessary to pay for the last tonne of CO_2 to be mitigated. In a broader sense, it "represents the cost of moving from one situation (such as the current mix of electricity generators, fuels and emissions in a country, region or utility system) to a different situation with lower CO_2 emissions… [and] include[s] changes in the power generation mix as well as demand reduction measures". The general form of this equation for cost of CO_2 abated (€/tCO_2) is shown in Equation 6-1 (Rubin, 2012).

$$= \frac{(NPV)_{low-c} - (NPV)_{ref}}{(tCO_2)_{ref} - (tCO2)_{low-c}}$$

Equation 6-1

Avoided cost of CO_2: This is a direct comparison of a CO_2 mitigation technology and its non-mitigating equivalent. In CCS terms, it is the CO_2 cost with and without capture. This metric is calculated from a number of input parameters in the TIMES model, but *not* as an output of the model. In CCS terms, it is a cost comparison between a reference power generation plant without CCS and a power plant with CCS. The general form of the equation for cost of CO_2 avoided (€/tCO_2) is shown in Equation 6-2 (Metz et al., 2005):

$$= \frac{(COE)_{ccs} - (COE)_{ref}}{(tCO_2 / MWh)_{ref} - (tCO_2 / MWh)_{ccs}}$$

Equation 6-2

Abated cost and avoided cost are both in units of €/t CO_2, but they are quite different and should not be used interchangeably. They are both useful in different circumstances for evaluating separate aspects of the mitigation potency of CO_2 reduction scenarios or CO_2 reduction technologies.

The abated cost of CO_2 for gas CCS in the *CO2-80* scenario was calculated as a direct output of Irish TIMES: €274, see Table 6-5. This abated cost is for the entire *CO2-80* scenario and includes all technologies necessary to achieve the 80% reduction in CO_2 emissions. Because gas CCS has a role in this scenario, part of this abated cost can be attributed to it, but because coal CCS has no role in the *CO2-80*, it has no abated cost of CO_2.

The avoided cost of CO_2 for both gas CCS and coal CCS was calculated using input data from the TIMES model: these values were €140/t CO_2 and €38 for gas and coal respectively, see Table 6-5.

Table 6-5 – Cost of abated CO_2 and avoided CO_2 for gas CCS and coal CCS

	Abated CO_2	**Avoided CO_2**
Gas CCS	€274	€140
Coal CCS	-	€38

In this sub-section, both the abated cost of CO_2 and avoided cost of CO_2 do not include transport and storage costs. Results that include these costs are in section 6.4.4.

6.4.3 Cost of electricity

The formula[33] used to calculate LCOE includes O&M rates, fuel prices and plant thermal efficiency, the full formula is shown in Appendix G. Like the cost of CO_2 abated/avoided, the LCOE is this sub-section is capture only, it does not include transport and storage costs. The LCOE results for gas CCS and coal CCS are shown in Table 6-6. The LCOE costs for coal CCS are all within the range of LCOE calculated for a similar technology for Ireland in another study (Monaghan et al., 2006).

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[33] http://www.nrel.gov/analysis/tech_lcoe_documentation.html

Table 6-6 –CO_2 intensity and LCOE for gas & coal reference & CCS power plants

		Reference	CCS
Gas CCS	**t CO2/MWh**	0.20	0.02
	(LCOE) €/MWh	€51	€76
Coal CCS	**t CO2/MWh**	0.36	0.04
	(LCOE) €/MWh	€50	€62

6.4.4 CCS site specific scenarios

This section contains results for the five CCS sites as described in section 6.3.2. The five sites are evaluated according to three different cost parameters: infrastructure costs, cost of avoided CO_2 and LCOE. The sites are also entered into the TIMES model and the results are evaluated in terms of which technologies are chosen and the CCS technology contribution to CO_2 mitigation.

Table 6-7 – Electricity production for CO2-80, CCS Sites and Security of Supply scenarios

	CO2-80 scenario	CCS sites scenario	Security of supply scenario
Biogas and Waste	86.7	244.9	265.6
Gas	194.3	212.8	224.6
Gas CCS	680.4	730.8	713.4
Hydro	103.5	104.1	104.1
Other	15.8	38.3	38.3
TradeEn ELC	153.7	153.7	153.7
Wind	2,476.9	2,481.4	2,480.1
	3,711.3	3,965.9	3,979.7

For the 80% cut in emissions, Site 3 was chosen. As can be seen in Table 6-7, this was a 7.4% increase in CCS electricity production compared to *CO2-80*. This should seen in the context of a total 6.9% increase in electricity production for the CCS site scenario.

Infrastructure costs

For the five CCS sites in Ireland, the capital costs, O&M costs for the three stages of capture, transport and storage are shown in Table 6-8. The capital costs for the total capital investment required for the project are based on a capacity of 0.62 GW, the installed capacity built for the *CO2-80* constrained scenario. The total column is the sum of capital costs for each of the three stages.

Table 6-8 – Capital costs for capture, transport and storage CCS stages for 5 CCS sites in Ireland

Site	Capture	Transport	Storage	Total
	CAPEX (€M)	CAPEX (€M)	CAPEX (€M)	CAPEX (€M)
1	€871	€142	€28	€ 1,013
2	€871	€306	€56	€ 1,205
3	€546	€31	€15	€ 591
4	€546	€469	€30	€ 1,045
5	€546	€131	€30	€ 707

This analysis found that the summed capital costs for transport and storage have an average share of total project capital costs of 25%; in certain extreme cases (Site 4), the share can reach 48% of total CCS project capital costs. Compared to capital costs for capture, which have a 23% range around the midpoint, transport and storage capital costs have a much higher range of variation: 87.7% and 57.3% respectively. Based on total capital costs, Site 3 (gas CCS capture at Whitegate, Cork and storage at Kinsale, Cork) is the cheapest solution for two reasons: gas CCS has lower capital costs than other CCS capture types and due to a pre-existing pipeline and storage infrastructure for the depleted Kinsale gas field, the additional infrastructure costs are minimal and much smaller than for any other sites. Gas CCS located in Dublin is the second least expensive option.

Cost of CO_2

The impact of infrastructure costs for each CCS site (as shown in Table 6-4 and Table 6-8) on the cost of avoided CO_2 (see Table 6-9) was significant. Compared to a ranking according to capital costs, the order of cheapest to most expensive was reversed, with gas CCS being considerably more expensive than coal CCS. This was due to the differences in CO_2 intensity of each fuel: because coal is more CO_2 intensive (99kt/PJ) compared to gas (56.1kt/PJ), when 90% of its emissions are sequestered, it achieves a larger absolute improvement than gas, which translates into a lower unit cost of avoided CO_2. In essence, coal CCS saves more CO_2 because it more emits more CO_2. When transport and storage costs are not included (see Table 6-5), the avoided cost of CO_2 for gas CCS is 266% more expensive than coal CCS; using the costs for the five CCS sites, the difference ranges between 152% and 287%.

Cost of electricity

The results for LCOE for the CCS sites are shown in Table 6-9. The differences between the sites for LCOE are much smaller than the differences for avoided cost of CO_2. Coal has the lowest LCOE for both the reference and CCS case and gas CCS has the most expensive. Comparing the reference plants with the CCS plants, the increase in costs for coal CCS is between 25% and 29%, for gas CCS the increase is between 34% and 42%.

Table 6-9 – LCOE and cost of avoided CO_2 for five CCS sites

Site	$LCOE_{REF}$ (€/MWh)	$LCOE_{CCS}$ (€/MWh)	Int_{REF}	Int_{CCS}	Avoided Cost (€/t CO2)
1	€44.89	€63.31	0.36	0.04	€58.67
2	€50.88	€68.00	0.36	0.04	€54.54
3	€50.97	€77.27	0.20	0.02	€147.96
4	€50.97	€88.46	0.20	0.02	€210.90
5	€50.97	€79.76	0.20	0.02	€161.98

6.4.5 TIMES results

This section describes the results for the five sites which were entered into the TIMES model. It describes the technologies chosen, the abated cost of CO_2 and contribution of CCS to CO_2 mitigation.

6.4.6 Security of supply

This section highlights the results of the specific CCS sites in Ireland in terms of security of supply implications. This addresses the costs incurred when the choice of CCS fuel (coal or gas) and storage site (Kinsale, Spanish Point or Irish Sea) are impacted by security of supply priorities.

In terms of investment costs, site 3 was the least expensive option. However, if as described in section 6.2.3 the Kinsale gas field is restricted for storage of gas for security of supply reasons, then alternative storage will be needed. The price of retaining capture in Cork, but relocating storage to the Spanish Point depleted field was calculated. This would necessitate an additional pipeline transport of 190 km onshore and 151 km offshore which would add €63 to the avoided cost of CO_2. This would make an alternative scenario of a gas CCS plant in Dublin with storage in the East Irish Sea more economic, due to the latter having an increased avoided cost of CO_2 of only €16. From Table 6-10, it is clear that gas CCS is economic in Cork only if storage is co-located, otherwise Dublin is cheaper.

Table 6-10 – Capital costs, LCOE and cost of avoided CO_2 for security of supply scenario

	Capture	Transport	Storage	€/MWh	€/MWh	€ t/CO2
Kinsale	€546	€31	€15	€50.97	€77.27	€147.96
Clare	€546	€469	€30	€50.97	€88.46	€210.90
Dublin	€546	€87	€30	€50.97	€78.71	€156.05

As described in Section 6.4.2, the cost of avoided CO_2 is not the same as the cost of abated CO_2, therefore the values in Table 6.10 are only broadly indicative of the cost of CO_2 abated. The electricity production results for the three Irish TIMES CCS scenarios are shown in Figure 6.3.

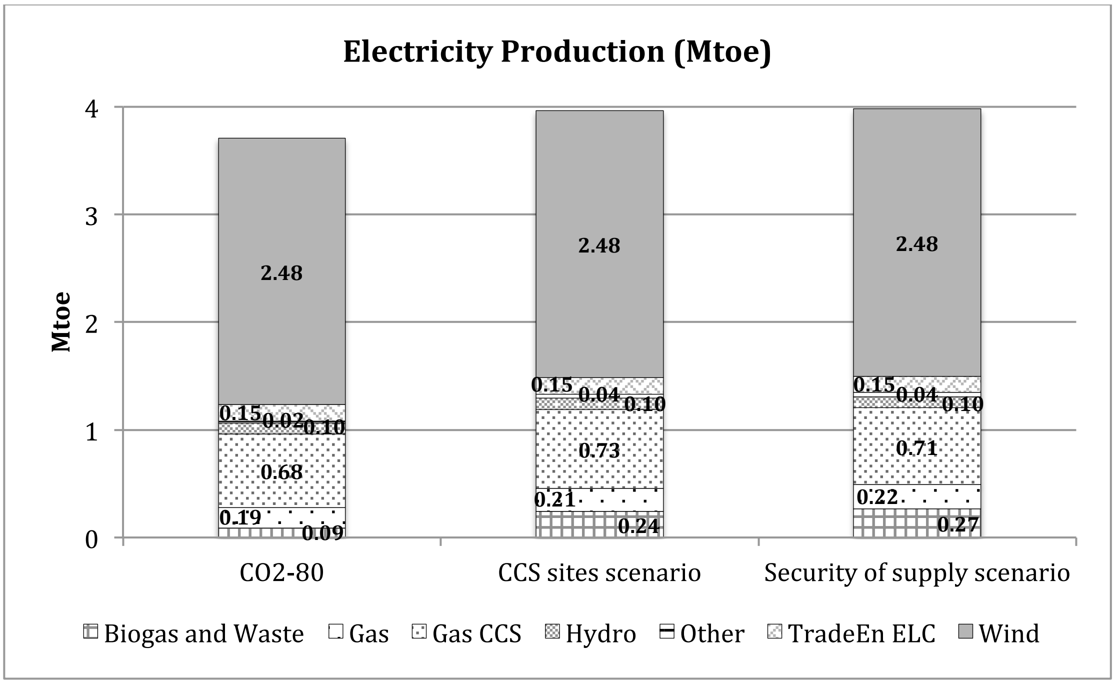

Figure 6-3 – Electricity Production for three Irish TIMES CCS Scenarios

6.4.7 Sensitivity analysis

The sensitivity analysis results on the impact of capital costs are presented in terms of the impact on cost of avoided CO_2 and LCOE for both coal CCS and gas CCS. The sensitivity analysis results for fuel costs are presented in terms of impact on cost of avoided CO_2, LCOE and impact on technology choice within the Irish TIMES model for scenarios with a range of CO_2 emissions constraints.

Capital costs

For the generation & capture stage of CCS, the literature review found considerable variation in capital costs for all CCS types and as noted in Section 6.3.4, the estimates tended to increase over time and converge towards higher costs. For each CCS type, the sensitivity analysis took capital cost values from the lowest, 1st quartile, 2nd quartile, 3rd quartile and highest estimates. In this comparison, coal CCS was more sensitive with the cost of electricity varying by 1.5 times compared to 1.2 times for gas CCS; for cost of avoided CO_2 coal CCS varied by 3.7 times compared to 1.8 times for gas CCS, see Figure 6-4.

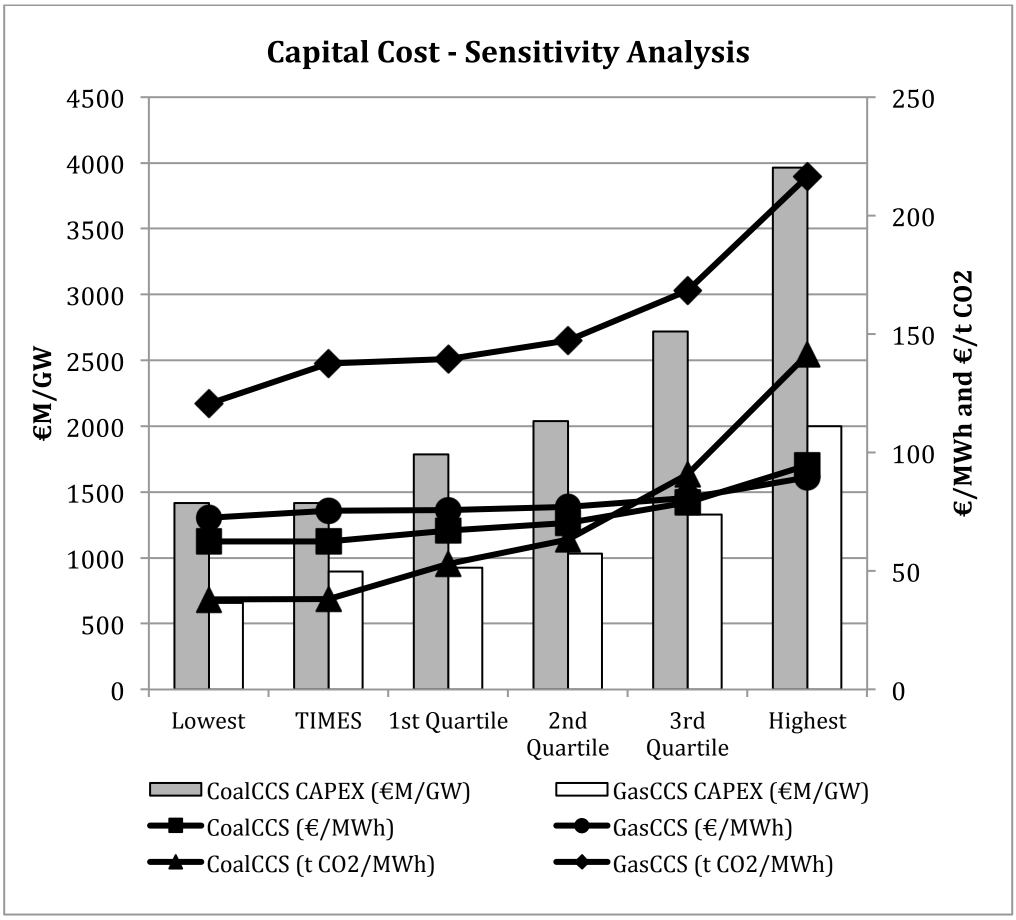

Figure 6-4 – CAPEX, LCOE and avoided cost of CO_2 results for sensitivity analysis of capital costs

Fuel costs

The sensitivity analysis examined the impact of percentage increments in fuel price (-50%, -20%, -10%, +10%, +20% +50%) and the impact of 2011 IEA prices, which were all lower than the 2008 IEA prices. These variations in coal and gas fuel prices had a differing impact on the cost of CO_2 avoided and LCOE for coal CCS and gas CCS. For changes of percentage increments, gas CCS is significantly more sensitive to fuel price changes than coal CCS: at increment changes of 10%, gas CCS is nearly twice as sensitive as coal CCS for both the avoided cost of CO_2 and LCOE; for the IEA projections, gas CCS is nearly 6 times more sensitive for LCOE and 4 times more sensitive for avoided cost of CO_2, see Figure 6-5.

The impact of fuel price sensitivity analysis on the installed capacity of CCS results in the Irish TIMES was also investigated. In addition to the changes in fixed increments and 2011 IEA prices, the impact of divergent prices (i.e. high gas prices coupled with low coal prices and vice-versa) was also investigated. As expected, the results indicate that for decreased gas prices (-10%, -20%) the installed capacity of gas CCS increases and for increased gas prices (2011 IEA prices, +10%, +20%) the installed capacity of gas CCS declines; however, for a gas price rise of higher than 30%, gas CCS became prohibitively expensive and is no longer installed. Coal CCS is affected by both coal price and gas price. For a 50% decrease in coal price, coal CCS is installed, but *only* if gas price is at least seven times higher than the coal price, otherwise gas CCS is installed, see Figure 6-6. Coal CCS is not installed for any rises in coal price.

For both Figure 6-5 (LCOE, CAPEX, avoided cost of CO2) and Figure 6-6 (TIMES results) gas CCS is considerably more sensitive to fuel price change than coal CCS and in Irish TIMES, this can result in either coal or gas CCS being chosen. The reason is that for coal CCS, capital costs are typically 60-90% higher than for gas CCS, therefore the 35-45% lower fuel price (of coal) has a much smaller bearing on the overall LCOE of coal CCS than the equivalent fuel price has on gas CCS.

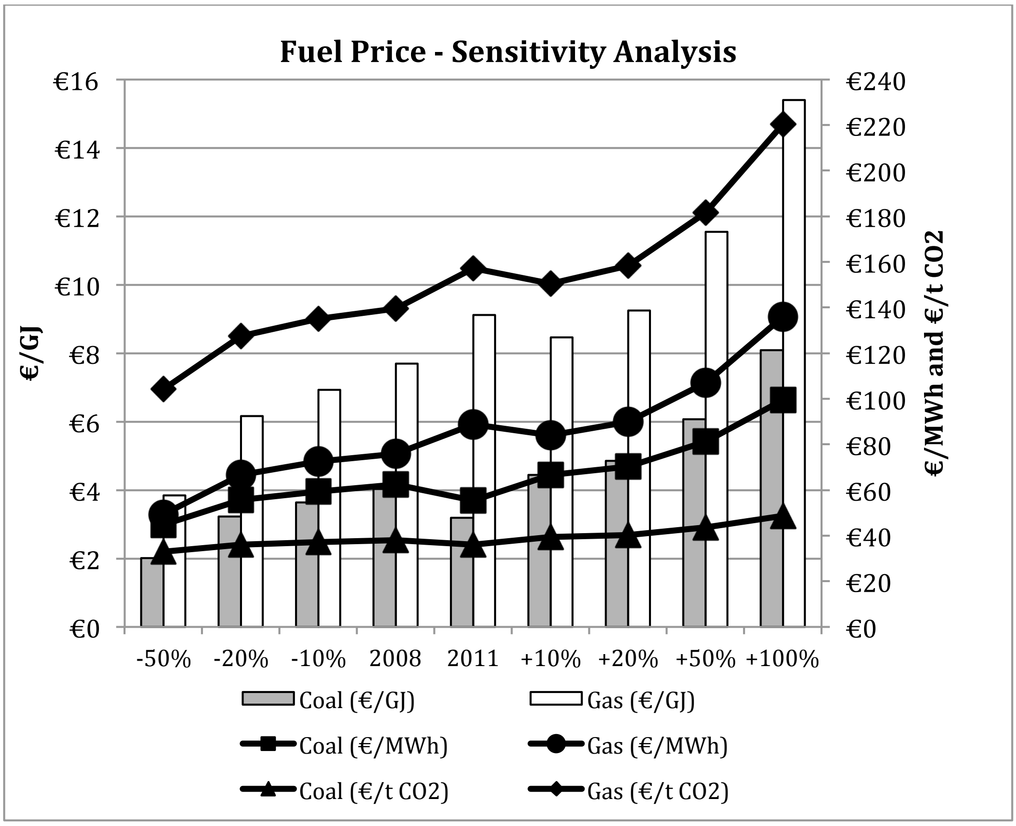

Figure 6-5 CAPEX, LCOE and avoided cost of CO_2 results for sensitivity analysis of fuel prices

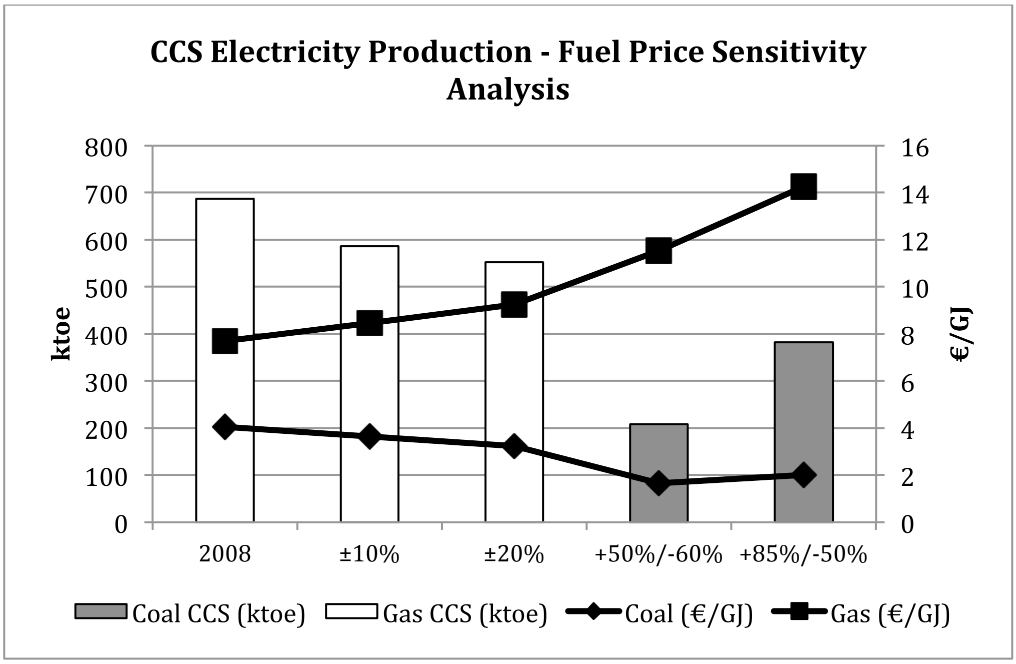

Figure 6-6 – Installed CCS capacity Irish TIMES results for sensitivity analysis of fuel price costs

6.5 Discussion

6.5.1 Coal and gas CCS

In the *CO2-80* scenario gas CCS contributes 5.6% to emissions reduction; it is chosen before coal CCS due its lower investment costs and lower residual emissions. For the *CO2-95* scenarios, there is no gas or coal CCS. In this scenario, emissions reduction is achieved by an almost total switch to renewables such as offshore wind, biomass steam turbines and biogas generators, see Figure 5-4.

Coal CCS is only economic when coal prices are 50% below 2008 prices, gas prices are at least seven times greater, and the emission target is a 80% reduction in CO_2. At lower emission reduction targets (60%, 70%), first onshore wind is installed until its capacity limit (6.9 GW) is reached and then offshore wind is installed at prices lower than coal or gas CCS. At higher CO_2 emission reduction targets (85-90%), coal CCS ceases to be a viable solution even for coal and gas prices that favour coal CCS. This is because of the residual CO_2 emissions for coal CCS (42.5t CO_2/kWh), which are nearly double the residual emissions of gas CCS (24.2t CO_2/kWh). At CO_2 emissions cuts of 85% and 90%, gas CCS is still installed, although the higher the emission reduction target, the lower the gas price necessary for gas CCS to be installed; for example gas CCS is only installed for a 90% emissions reduction if gas fuel price is 20% below 2008 levels. For emission cuts of 95%, gas CCS is not installed regardless of gas prices.

In terms of CO_2 avoided, gas CCS is 264% more expensive than coal CCS; however, in terms of LCOE, gas CCS is only 23% more expensive than coal CCS. As emission reduction targets become more stringent and more energy end-use technologies from other sectors switch to electricity (thus increasing overall electricity demand), gas CCS becomes more and more economic. For scenarios of 70% cut in emissions up to 95% cut in emissions, there is a consistent rise in electricity production. Coal CCS is also more sensitive to changes in capture capital costs, partly this is because the price of a coal CCS plant is larger than a gas CCS plant and the range of costs found in the literature review is also larger.

In summary, coal CCS is not chosen because at lower emissions cuts, there is sufficient onshore and offshore wind capacity to meet the demand for electricity and at higher emissions cuts, the residual emissions of coal CCS make it too difficult for coal CCS to contribute and gas CCS is chosen instead. This finding is in line with analyses from other countries where coal CCS was not chosen (Seixas et al., 2012). This is especially the case when coal must be imported (leading to a higher coal price) and when electricity can be imported, making import of electricity more economic at lower carbon prices. Gas CCS can compete in higher emission reduction scenarios (80-90%), but due to its residual emissions, is precluded from scenarios of 95% or higher reduction in emissions.

One other factor acting as a differentiator between coal CCS and gas CCS that hasn't been discussed is their flexibility, measured in terms of their ramp rate (MW/min). Because this is a plant performance issue, it can only be fully understood with data generated from an actually operating plant, something which is currently available. A shortage of data on CCS plant performance has led to a requirement to infer the performance based on the operation of non-CCS plants. Coal plant ramp rates (8-10 MW/min) are half the level of typical gas plant rates (20-30 MW/min). The need for flexible operation of CCS plants will be discussed in the context of the power system operation in a section below.

6.5.2 CCS sites in Ireland

The investigation of CCS sites in Ireland has three headings: project costs, CO_2 sequestration capacity and security of supply.

Project costs

Capture costs are still the largest share of overall costs (71%-84%) but it has been shown that the full capital costs of CCS can be 41.5% higher when transport and storage costs are included. When security of supply constraints are taken into account the capital cost increases can be as high as 91%. Proximity to storage makes a significant difference to overall costs; for example, the estimated increase in costs for a CCS site located in Whitegate and alternately located at Kinsale or Moneypoint is 77%. For Ireland, the results of the site specific analysis aligned with the results of the Irish TIMES model: gas CCS was the most economic option for a capture site located at Cork with sequestration off the Cork coast in one of the depleted Kinsale gas fields.

CO_2 sequestration capacity

In the Irish TIMES model, the lifetime of a CCS plant is 35 years. Based on annual sequestration rates for each fuel, the installed CCS capacity of the Irish TIMES model would require between 110 Mt and 214 Mt of storage space. Based on the theoretical storage capacity at Spanish point (120 Mt), this would inhibit this location being used for storage for a coal plant because the site would run out of storage after less than 22 years. If Kinsale gas field was used to sequester CO_2 from a co-located gas plant in Cork, it would have sufficient CO_2 storage for over 106 years, but this is contingent on all the storage being available for CO_2 and none being used for gas storage.

Security of supply

For a country that imports 88% of its primary energy (Howley et al., 2012), security of supply remains a paramount concern and in terms of CCS, security of supply has an asymmetrical impact on coal and gas. Coal is a more abundant and cheaper fuel and Ireland has the capacity to store 85 days of imported reserves (ESB, 2012). Gas is a rarer and more volatile priced commodity and in terms of storage, it currently averages only 11-12 days. Were gas storage to be higher (e.g. 50 days), there could be a potential conflict with CO_2 sequestration because the primary sites at Kinsale that have been identified for gas storage have also been identified for CO_2 sequestration. Of the two gas fields at Kinsale (5 Mt and 330 Mt), the smaller one is completely depleted and is currently used for gas storage. If the larger Kinsale Head gas field is also used for gas storage, then it cannot be used for CO_2 sequestration and an alternative must be found.

Compared to the first choice scenario of Gas CCGT located in Cork with storage in Kinsale basin, the security of supply scenario has Gas CCGT power generation and capture at the same location but instead storage is used of the west of Ireland in Spanish Point. This necessitates construction of a lengthy onshore pipeline (approx 230km) and offshore pipeline (approx 200km); compared to the base case of low capital costs due to an existing pipeline being in place, this significantly increases the costs, see Table 6-10. It can be seen from the cost comparison that a superior option in cost terms is a gas CCGT in Dublin with storage in depleted oil and gas fields in the Irish Sea.

6.5.3 Uncertainty analysis

This section outlines some uncertainties of aspects of this analysis that accompany the results. The fuel price sensitivity analyses are based on fixed percentage changes, i.e. 10% change in input parameters. Further uncertainty analysis on the probability of these parameters changing could contribute a more advanced quantification to the uncertainty of fuel price and other parameters (Rubin and Zhai, 2012).

Fuel prices

The sensitivity analysis in section 6.4.7 highlighted the differing impact of coal and gas prices on the fate of CCS; the uncertain aspect being the likely trajectory of future fuel prices. Uncertainties in fuel price will generally favour coal CCS more than gas CCS, due to the latter being more fuel price sensitive than the former, while the impact of shale gas in the United States is making gas projects more economic with reduced gas prices in the US and also making coal projects in the US and Europe more economic due to increased coal supply. While the outlook for all fuel prices is to rise, US gas price projections have fallen in recent years, whereas European gas prices projections have continued to rise (IEA, 2012b). The outlook for shale gas in Europe is uncertain, with many countries adopting a "wait-and-see" approach as various reports are prepared and published; there are currently no exploration licenses granted in Ireland and the EPA is currently conducting a shale gas review[34].

CCS plant performance

As a new technology that has yet to be successfully proliferated, CCS retains a significant degree of uncertainty regarding its operation. The assumption that CCS will become a reliable power plant is explicit in this analysis; however, it rests on assumptions about the level of plant thermal efficiency and load factor that have not yet been proven. To capture this uncertainty, modelling exercises often make a distinction between a technology that is first of a kind (FOAK) and an nth of a kind (NOAK) (Rubin and Zhai, 2012) (Parsons-Brinckerhoff, 2011) with the latter having more favourable performance parameters due to expected technology learning. Because of the time horizons involved in this analysis (30-

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[34] http://www.epa.ie/news/pr/2012/name,33317,en.html

40 years) the technology performance parameters have all assumed to be NOAK. This differs from the expected performance parameters for an actual first-time deployed CCS plant, which would be lower than that used in this analysis.

Power system operation

In addition to the uncertainty of how a CCS power plant will operate, is the uncertainty of how a CCS plant will interact with the electricity power system. It is expected, that compared to an equivalent non-CCS plant, a CCS plant will not have the same flexibility, particularly in terms of plant ramp rates. Over the past decade (2000-2010) the Irish power system has gone from a typical mix of coal, oil and gas and with no wind generated electricity to having the highest penetration rate for wind electricity for a single synchronous grid in the world (EirGrid et al., 2010). The transmission system operators (EirGrid and SONI) have faced unique challenges in managing the Irish power system's large quantities of wind, which can negatively affect the frequency of the grid and which present challenges in terms of the spinning reserve required. A crucial element in managing 30-40%+ of wind electricity are the thermal gas plants in particular the Open Cycle Gas Turbines (OCGT) with their fast start-up time and lower efficiency and Combined Cycle Gas Turbines (CCGT) with their slower start-up time and higher efficiency. In 2010 these two plant types represented 55% of the fully dispatchable capacity in Ireland (Howley et al., 2011).

It is expected that the penetration of renewables in the electricity generation sector (wind and biomass) will grow to between 30% & 40% by 2050 (Clancy and Scheer, 2011). In the Irish TIMES 2050 CO_2 constrained scenario, 52% of the electricity generation is from asynchronous wind generation. While CCS is sometimes considered a base load plant (R. Kannan, 2009), when it becomes the only thermal-type plant in the power system together with large amounts of asynchronous wind generation, CCS will need to provide some flexibility to help balance the intermittency of wind on the Irish power system. The levels of flexibility required will increase in proportion to the penetration of intermittent renewables, but it is not clear what the technical limits will be and whether CCS will impact this technical limit. At present this is an under-researched topic, in part due to a deficit of data; however, the parameter that differentiate flexible from steady-state in a CCS context have been outlined (Chalmers et al., 2009; Harland et al., 2010).

The key parameters for power plant flexibility with and without CCS are ramp up & down rates and associated costs. Although the evidence is not fully clear, there is an indication that CCS will ramp at a slower rate than a conventional plant of the same fuel class (Harland et al., 2010). In line with a standard gas plant being more flexible than a standard coal plant, it is likely that a gas CCS plant will be more flexible that a coal CCS plant. In terms of retaining both power plant flexibility of non-CCS plant and sequestration of CCS there are a number of options: if the ramp rate of CCS is slower than conventional, and there is sufficient installed capacity of CCS such that it is inhibiting the operation of the power system, there is an option to ramp the power plant in non-CCS mode and to simply vent the CO_2 emissions. The validity of this option will depend on an economic trade-off between the cost of emissions and the cost of an inhibited power system. At an aggregate level for the power system, some extra costs will be incurred by the power system – what these costs are can be calculated in PLEXOS.

6.6 Conclusions

As a CO_2 mitigation technology, CCS has a contributory role to play in Ireland's energy system; in the *CO2-80* scenario in this chapter, it contributes 5.6% to emissions reduction in 2050. In terms of levels of emission reduction, CCS has a bridging role in that it contributes to 80% CO_2 emissions reduction but not 95% CO_2 emissions reduction. CCS contributes to emission reduction only when all of Ireland's onshore wind capacity and the cheaper offshore wind capacity has been reached. The choice of coal or gas CCS depends on a number of factors such as fuel prices and level of emissions reduction, with coal CCS being favoured at 80% CO_2 emissions reduction, at coal prices 50% below 2008 prices and seven times lower than gas prices. This latter case is equivalent to a gas supply price shock which favours coal CCS. Gas CCS is favoured for gas prices up to 50% above 2008 prices and for CO_2 emission cuts up to 90%.

Taking into account all technology costs and site costs, gas CCS in Whitegate (Co. Cork) with sequestration in Kinsale gas field is the most economic option for CCS in Ireland. Other options are more expensive due to higher capture capital costs, higher transport costs to nearest storage site and higher storage costs. In a security of supply scenario where the storage of gas is based in Kinsale, the additional costs make a CCS capture site in Dublin more economic.

It has been noted that studies that exclude transport and storage cost from the avoided costs of CO_2 misrepresent the true avoided cost (Rubin, 2012) and contrary to findings in other studies, this analysis concludes that transport & storage costs can be significant and should not be disregarded. In terms of additional capital costs, they can add 91%, in terms of LCOE they can add 42.4% and in terms of cost of CO_2 avoided they can add 29.8%.

While coal CCS has been relatively widely researched and seen as the solution due to the prevalence of coal power plants and the widespread availability of coal, it isn’t necessarily the best solution for each country. Gas CCS is a viable solution for Ireland in part due to the nature of Irish emissions; where high cuts in emissions are required, gas CCS is essential and coal CCS is uneconomic, at very high cuts in emissions, only completely carbon-free (i.e. renewable energy) can provide a solution. In the security of supply scenario, coal CCS has role due to the contribution towards supply diversification.

7 Conclusions

The aim of this thesis was to analyse in-depth a number of aspects of Ireland's sustainable energy challenge with a focus on natural gas demand. This section reviews the conclusions of the thesis, organized according to the two methodologies employed: empirical analysis and bottom-up techno-economic modelling. It also includes the impacts that some of the conclusions of the thesis have had to-date. This section also contains some recommendations for policy, modelling and data as well as an outline for potential further research.

7.1 Empirical analysis

Decomposition analysis of residential gas demand

Decomposition analysis has been shown to be a powerful methodology for examining some of the underlying drivers, especially structural ones, behind changing natural gas consumption in the residential sector. The results of the analysis showed that activity effect was the most important effect in explaining changing natural gas demand over time. The weather effect was shown to have a potentially significant impact on a year-to-year basis, as well as there being a decreasing weather effect over time[35]. The decomposition analysis also showed a changing intensity trend across all dwelling types, aspects of which were explained and other aspects, which were in terms of precise quantification, outside the scope of this decomposition. The chapter also outlined the preliminary impact of the 2002 BR and in combination with the dwelling size effect, showed that the impact of BR was almost negligible. This analysis also formed part of a first step in framing a more detailed analysis of the 2002 BR, which was contained in the following chapter.

In terms of impact, this work has contributed to the annual Transmission and Development Statement report by the gas network regulator which annually makes an assessment of the capacity of the gas transmission and distribution system. Previous editions were attributing the reduction of natural gas demand in the residential sector to "increasing energy efficiency, smaller dwellings, vacant dwellings and customer response to rising gas prices" (Gaslink, 2009)

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[35] An addendum to this finding is that 2009 and 2010 were exceptionally cold winters in Ireland and this would have reversed the declining weather effect trend

whereas later editions have discounted the impact of dwelling size and vacant dwellings, "The downward trend in annual residential gas demand per customer is being attributed to enhanced building regulations[36] for new houses, increasing energy efficiency initiatives for existing houses and a response to rising gas prices" (Gaslink, 2010).

Ex-post analysis of 2002 building regulations

The ex-post analysis of the 2002 BR concluded that compared to the expected savings of 20%, there has been a substantial shortfall with energy savings of just 11.3±1.9%. In terms of the reason for this shortfall, the presence of significant non-compliance has been identified, which is causing the energy consumption of a typical semi-detached dwelling to be 13±1.6% higher than a fully compliant dwelling. Inadequate BR enforcement from the Building Control Authority was identified as one of the root causes. Results from a decomposition analysis show that a large part of the energy savings being achieved by the 2002 BR are being eroded by the increasing size of dwellings over time.

In terms of impact, the results of this work informed a submission to the Department of the Environment, Community and Local Government as part of the public consultation process regarding Building Control Legislation. This work has also contributed to the annual Transmission and Development Statement gas network analysis report, which assumed that "50% of the energy efficiency savings identified under the NEEAP document are assumed to take effect over the forecast period" (Gaslink, 2012).

7.2 Bottom-up techno-economic modelling

Ireland LEAP model

In terms of a coherent monitoring of energy policy that combines ex-ante and ex-post analysis, LEAP has been shown to offer an excellent framework and tool for improved communication between modelling experts and policy makers. The Ireland LEAP model demonstrated a detailed methodology for tracking in detail

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[36] 2008 BR, which were not included in my decomposition analysis.

the expected energy performance of a policy. The Ireland LEAP model also demonstrated a capacity for ex-ante analyses which can incorporate variable implementation rates for energy efficiency policies. At the sector specific level, the model quantified the impact of a number of individual energy efficiency policies, which were in turn combined into aggregated scenarios, representing portfolios of policies. The LEAP Ireland model also captured the double-counting potential emanating from the interaction effect of these policies, which provides an approximation for a confidence interval for the energy saving results.

Natural gas as a transition fuel

Using the Irish TIMES energy systems, the role for natural gas in a range of CO_2 constrained scenarios was examined. For an 80% reduction in emissions scenario, natural gas has in partnership with CCS, a role in the power system similar in terms of gas generated electricity to today. In higher emissions reduction scenarios (95%), natural gas demand shrinks to 2% and there is no gas CCS due to its level of residual emissions. Fuel switching to natural gas from oil can have an impact significant impact on emissions reduction, which in the 80% emissions reduction scenario, a decomposition analysis calculated at 15% of the emissions reduction. In the 95% emissions reduction scenario, technical limits are reached and the potential for fuel switching becomes negligible or else negative.

CCS potential in Ireland

CCS has a contributory role to play in Ireland's energy system; in the *CO2-80* scenario, it contributes 5.6% to emissions reduction in 2050. In terms of levels of emission reduction, CCS has a bridging role in that it contributes to the *CO2-80* scenario, but not to the *CO2-95* scenario. According to a large number of sensitivity analyses of fuel prices and emission cuts, gas CCS is a more robust mitigation option that coal CCS. This is due in part to general differences between coal and gas CCS, such as fuel prices and residual emissions, as well as local differences (unique to Ireland), which mean in lower emission reduction scenarios, coal CCS competes with onshore and offshore wind, which are chosen due to their lower cost and zero emissions. At higher emission reduction scenarios, coal CCS isn't chosen because of its higher residual emissions and gas

CCS is chosen. In scenarios of up to 90% reduction in emissions, gas CCS is chosen if gas prices are sufficiently low. At 95% emissions reduction, gas CCS is not chosen regardless of fuel price.

In terms of location for CCS in Ireland, taking into account all technology costs and site costs, gas CCS in Whitegate, Co. Cork with sequestration in Kinsale offshore depleted gas field is the most cost-optimal option. This is due to pre-existing transport and storage infrastructure that can be utilized to minimize the very high technology costs. In a security of supply scenario where the storage of gas is based in Kinsale, the additional costs make a CCS capture site in Dublin more economic.

7.3 Recommendations

7.3.1 Data

There is a direct relationship between the quality of data on energy consumption and the quality of the energy policy which can seek to influence that energy consumption. A good example (not from this thesis) has been the new CO_2 based car tax in Ireland, which was designed with detailed bottom-up data on the Irish car stock (O Gallachóir et al., 2009). This high quality data was also able to show that the progressive policy has, in terms of emissions reduction and penetration of lower emitting cars, exceeded its expected impact (Rogan et al., 2011).

This thesis has been able to quantify the impact of the 2002 Building Regulations for gas connected semi-detached dwellings in Dublin. To extend the evaluation to all dwelling types and counties would require more data than is available at present. While this ex-post analysis was facilitated by access to metered consumption data for natural gas consuming dwelling and BER data for all dwellings, the lack of a direct link between these two data-sets has prevented a more comprehensive evaluation. Measures to link BER data to metered dwelling energy consumption would bring great insights and benefits, particularly to policy-makers. Two suggestions for a methodology for linking these two data-sets are given here: use of Meter Point Reference Numbers (MPRN) unique identifiers which are present in both data-sets but currently withheld for data-protection reasons or clever use of addresses together with GIS mapping software.

In terms of additional data that would improve bottom-up modelling, this research has been greatly aided by access to the micro data for the Irish National Survey of Housing Quality conducted in 2001/2002. A follow-up survey (10 years later) would give an opportunity to evaluate much of the change that has taken place in the residential sector during this period, and through an evaluation of energy policy in place during that time, enable more nuanced energy policy design. This survey could also include other aspects of data not currently available, such as internal dwelling temperature values.

7.3.2 Modelling

Bottom-up techno-economic modelling has been shown to be most suitable for modelling the impact of technical energy policies; in simple terms, technical policies need technical modelling. The impact of structural changes in energy demand as a result of different energy technologies will be best captured with modelling designed in terms of these changes. These in particularly the case for incorporating uncertainties of policy implementation and interaction effect of different energy efficiency policies: an absence of bottom-up techno economic modelling is likely to lead to double-counting for policy energy savings. While bottom-up techno economic modelling has been incorporated into national energy forecasts, there is an acknowledged scope for more (Clancy et al., 2010).

There is a significant range of energy modelling packages available. One of the aspects that distinguishes energy modelling software is their accessibility and learning curve required and in these terms, LEAP and OSeMOSYS are excellent. LEAP is freely accessible to most users, and doesn't require large investments for becoming proficient. At the same time, the role for specialized and complex energy models (e.g. TIMES) isn't being discounted. The potential for soft linking, from one specialized form of modelling software to inform the inputs to another model, is one that is seen as having considerable potential.

7.3.3 Policy

There needs to more ex-post evaluation of energy policy. This is particularly the case for energy efficiency, which has enormous potential, but due to its nature is not as high profile as renewable energy. Energy efficiency will simply not transpire if it is not rigorously evaluated and assessed: the negajoules should not be negated.

In terms of BR, it is recommended that as a minimum, the current rate of inspection for BR compliance as set by Building Control Authority is increased from 12-15% - a clear majority of dwellings should be inspected. In terms of enforcing BR compliance, there is scope for financial fines being commensurate with the degree of energy wastage due to non-compliance. It is imperative that Building Control becomes better and identifying compliance problems before they manifest and become insolubly large.

7.4 Applicability beyond Ireland

The residential sector decomposition analysis has demonstrated a number of new effects that can be applied or adapted to residential sectors in other countries to better understand structural changes in energy demand. The analysis of building regulation compliance utilized a database of Building Energy Ratings (BER) in Ireland that was generated as a result of implementation of an EU Directive (EC, 2002); all EU countries should have a similar database and therefore the method developed here could be applied anywhere in Europe to derive a better figure for building regulation compliance. The thesis has also demonstrated the insight that can be gained from combining different types of analyses: in Chapter 3, a statistical analysis showed that the 2002 BR underachieved savings and in Chapter 2 a decomposition analysis indicated that larger dwellings are to some extent compensating for any energy savings that the 2002 BR actually are making. The combination of LEAP & OSeMOSYS presented in this thesis is the first known application of LEAP & OSeMOSYS and as explained in the chapter, can be used for tracking the performance of energy efficiency policies individually or together. Decomposition analysis of energy systems models is considered underutilized and can be applied to many energy models. The example presented here is for overall results, but there is ample scope for sectoral decomposition analysis too.

7.5 Further research

Based on the research and conclusions described so far, the following areas for potential further research are outlined:

Decomposition analysis of residential gas demand

While good decomposition analysis depends to a great extent on good data, there is much opportunity with the data that is currently available to do a regional analysis of consumption trends. Pending additional data, an analysis structured around households of different income brackets could reveal some additional information about the changing intensity trend. At a national level, should sufficient data become available, it would be possible to do a decomposition analysis to determine the differences between the national dwelling stock and the gas dwelling stock.

There is also merit in repeating this decomposition analysis in a number of years. This could investigate the impact of such factors as increased competition in the gas market: from 2011, there have been three retailers of piped gas in the residential sector, each with different contracts and pricing structures. It would also be possible to investigate the impact of a recession on natural gas consumption, particularly at a time of changing gas prices. Particular aspects of the recession likely to affect gas consumption are more gas customers in arrears, lower disposable income and higher daytime occupancy due to more people being out of work. Finally, the impact of other energy efficiency policies such as the 2008 BR, increased efficiency of boilers and the large scale retrofitting of existing dwellings could be investigated once these policies have been in place for a sufficiently long implementation period.

Ex-post analysis of 2002 building regulations

The analysis on building regulations focused exclusively on semi-detached dwellings in the Dublin area only. With sufficient data, this analysis could be extended to include other dwelling types and counties in Ireland. In terms of compliance with the 2002 BR, the result contained in this chapter is an average figure for the sample of dwellings. The BER data set should enable a more in-depth study of the range and distribution of compliance with the more recent 2008 BR. Key areas of non-compliance could also be identified (e.g. heating controls, building element u-values, renewable energy requirements). Finally, possible correlations on levels of non-compliance could be made with dwellings according to fuel types, dwelling types and locations.

At present, the two methodologies for analysing the impact of the 2002 BR and non-compliance with the 2002 BR are distinct. Further work to link consumption data with archetype modelling, would enable a comprehensive evaluation of 2002 BR. By pinpointing the non-compliance discrepancy in the 2002 BR reaching their target energy savings, it could provide an initial quantification of the behavioural impact of the dwelling occupant, which would be significant contribution to energy policy research.

Ireland LEAP model

In addition to the energy efficiency policies in the Ireland LEAP model, there is ample scope for running further scenarios on many of the policies contained in the NEEAP. In addition to extending the Ireland LEAP model and developing new scenarios, the model will also continue to be improved by exploiting a number of new data sources as they become available. Subject to the constraint of good data, the full Ireland LEAP model will in time be able to provide a fully disaggregated picture of energy demand in Ireland by all end-use types and by fuel type. The model can also be readily updated annually to include changes, e.g. in economic conditions and it could be extended to a longer time horizon, e.g. out to 2030. In terms of the role of OSeMOSYS in the power system, PLEXOS, a power systems modelling software could be used to sense-check the results of the electricity generation sector.

Natural gas as a transition fuel

In terms of the specific methodology in this chapter, there is great scope for using decomposition analysis to more fully understand the results of an energy systems models. The decomposition analysis in this chapter was based on aggregate results for all sectors. Unique decomposition identifies could be designed for each sector and more analysis could be done on the contribution of energy efficiency, renewable energy and fuel switching. Such disaggregated decomposition analysis of energy system model results hasn't been done before and would be a major contribution to understanding the results of such models.

Sector-specific decomposition formulas could also be designed: for example in the transport sector the impact of new cars (the car stock turnover rate) and technology switching could be quantified; in the residential sector, the changing structure of dwelling energy end-use (i.e. more appliances and less space-heating) could be compared with the impact of changing technology energy efficiency and the impact of direct fuel-substitution compared to the less CO_2 intensive electricity could also be investigated and quantified.

CCS potential in Ireland

An aspect of the analysis on CCS that was outlined, but wasn't completed was a soft-linking exercise to examine the impact of CCS on the functionality of the electricity sector. A model of the electricity generation sector as output by the TIMES model could be built in PLEXOS and more detailed power sector evaluations could be run of the results to check for infeasibilities or additional costs that aren't captured in the TIMES model. A more advanced and innovative version of this soft-linking would be to construct a joint gas and electricity model in PLEXOS and soft-link it to TIMES. In terms of the results of CCS sites in Ireland, more scenario analysis could be done with different emission cuts and fuel prices and the analysis of likely contenders in the Republic of Ireland could be extended to the entire island of Ireland, or even the UK. Softlinked to a gas and electricity gas model

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Appendices

Appendix A – Energy Efficiency Policies in Ireland; Decomposition Analysis Results

No.	Type	Start Year
1	Building Regulations 1991	1992
2	Building Regulations 1997	1998
3	Minimum Efficiency Standards for Boilers	1995
4	Mandatory labelling of electrical appliances	1995
5	Minimum Efficiency Standards for Appliances and Lighting	1999
6	House of Tomorrow	2001
7	Warmer Home Scheme (Low Income Housing Strategy)	2002
8	Sustainable Energy Ireland	2002
9	Energy Efficient Communities Through Spatial And Planning Policies	2002
10	Energy Conservation Standards for New Dwellings	2003
11	The Greener Homes Scheme	2006
12	Power of One - Information Campaign	2006
13	Low Carbon Homes Scheme	2006
14	Irish Response to the Energy Performance of Buildings Directive	2007
15	Best Practice Design for Social Housing	2007
16	Boiler Efficiency Campaign	2007
17	Building Regulations 2007	2008
18	Smart Metering - (Pilot Scheme)	2008
19	Condensing Boilers - Minimum Boiler Efficiency	2008

Appendix Table 1 – Energy Efficiency Policies in Ireland 1990-2008

	Dw Type	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Total Change	**Bungalow**	0.02	-0.01	0.03	-0.02	0.02	0.07	-0.05	0.06	0.03	0.07	0.02	0.02	-0.01	0.01	-0.01	0.01	0.02	0.07
	Detached	11.44	5.55	7.11	4.35	2.07	11.79	-6.30	7.91	7.73	8.57	2.49	2.78	1.22	4.13	-0.48	1.28	-4.23	12.84
	Apartment	0.58	0.11	0.32	0.58	0.08	1.05	-0.54	0.65	0.65	1.01	0.33	-0.10	0.00	0.53	-0.06	0.06	-0.30	1.20
	Semi-Det	24.01	15.69	25.40	13.04	1.82	30.27	-16.7	24.78	18.86	25.08	12.34	11.53	17.18	32.68	-0.05	-10.9	-20.5	27.20
	Terrace	7.33	2.39	3.17	3.29	3.05	7.21	-3.14	6.56	4.49	5.51	2.93	1.70	1.83	4.53	-0.57	-1.61	-2.64	7.00
Activity effect	**Bungalow**	0.03	0.01	0.01	0.03	0.04	0.02	0.00	0.02	0.03	0.03	0.00	0.02	0.00	0.01	0.03	0.00	0.12	0.03
	Detached	7.47	5.33	5.63	3.95	4.78	4.31	2.34	2.53	4.28	3.11	2.51	3.85	2.23	1.51	3.85	6.35	4.72	4.20
	Apartment	0.18	0.11	0.07	0.15	0.04	0.04	-0.03	-0.02	0.03	0.12	0.00	0.19	0.10	0.19	0.43	0.15	0.23	0.43
	Semi-Det	15.72	12.51	16.90	11.46	9.10	9.85	4.52	8.01	8.91	8.70	11.54	17.14	20.86	23.35	9.32	4.81	2.86	1.66
	Terrace	1.80	0.69	0.57	0.62	1.18	0.49	0.10	1.54	1.65	0.96	1.45	1.52	1.33	1.33	1.09	1.74	2.02	0.97
Intensity effect	**Bungalow**	-0.03	-0.02	0.02	-0.05	-0.02	0.03	-0.01	0.04	0.01	0.02	0.01	0.05	-0.05	-0.01	-0.05	0.01	-0.07	0.01
	Detached	1.02	0.95	0.39	-1.00	-2.90	3.17	-0.51	5.39	2.36	0.72	-1.14	5.99	-5.00	3.50	-2.54	-4.60	-6.53	1.62
	Apartment	0.09	0.07	0.17	0.28	-0.03	0.67	0.15	0.68	0.54	0.47	0.29	0.32	-0.38	0.46	-0.19	0.00	-0.38	0.28
	Semi-Det	1.06	5.03	5.93	-2.66	-8.25	9.62	-0.60	16.93	7.57	3.70	-3.35	13.84	-17.1	17.47	-3.00	-13.0	-158	6.04
	Terrace	4.00	2.02	2.16	2.27	2.08	4.11	1.57	4.94	2.44	1.65	1.19	4.27	-1.84	3.65	-0.72	-2.85	-3.04	2.90
2002 BR	**Bungalow**														0.01	0.01	0.00	-0.01	0.00
	Detached														-0.54	-0.13	0.17	0.08	-0.05
	Apartment														-0.05	-0.14	-0.01	-0.03	-0.06
	Semi-Det														-6.46	-1.00	-0.34	-0.24	-0.16
	Terrace														-0.18	0.15	0.12	-0.04	-0.08
Weather effect	**Bungalow**	0.02	0.00	0.01	0.01	0.00	0.02	-0.03	0.00	0.00	0.02	0.01	-0.05	0.04	0.00	-0.01	0.00	-0.02	0.03
	Detached	2.94	-0.74	1.11	1.41	0.17	4.29	-8.19	-0.11	0.80	4.61	0.92	-7.35	3.62	-0.20	-1.88	-1.00	-2.24	6.44
	Apartment	0.30	-0.07	0.08	0.17	0.07	0.33	-0.66	-0.02	0.08	0.42	0.04	-0.63	0.25	-0.05	-0.16	-0.08	-0.11	0.51
	Semi-Det	7.23	-1.91	2.64	4.24	0.94	10.73	-20.7	-0.52	1.77	12.25	3.03	-21.1	10.98	-1.03	-6.08	-2.87	-6.09	18.67
	Terrace	1.54	-0.32	0.45	0.40	-0.21	2.61	-4.81	0.08	0.40	2.90	0.28	-4.09	2.34	-0.27	-1.09	-0.62	-1.58	3.22
Size effect	**Bungalow**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Detached	0.00	0.01	-0.02	0.00	0.02	0.03	0.06	0.10	0.28	0.13	0.19	0.28	0.38	-0.13	0.21	0.35	-0.26	0.63
	Apartment	0.00	0.00	0.00	-0.02	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.03	-0.01	0.01	0.00	-0.01	0.04
	Semi-Det	0.00	0.05	-0.08	0.00	0.03	0.07	0.12	0.36	0.60	0.43	1.12	1.63	2.40	-0.65	0.70	0.48	-1.29	0.99
	Terrace	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix Table 2. Decomposition effects for permanently occupied dwellings

	Dw Type	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Total Change	**Bungalow**	0.04	0.00	0.03	0.02	-0.02	0.02	-0.01	0.01	0.02	-0.01	0.02	0.00	-0.01	-0.02	-0.01	-0.01	-0.02	0.00
	Detached	3.12	1.34	0.89	0.42	-0.41	1.09	-0.77	0.55	0.14	0.77	0.19	0.18	-0.22	0.39	-0.15	0.43	-0.01	1.78
	Apartment	0.13	-0.08	0.14	0.09	0.03	0.23	0.04	0.54	1.27	0.83	0.80	0.02	-0.08	0.43	-0.11	-0.04	-0.51	0.84
	Semi-Det	5.25	2.72	2.04	0.92	-0.07	2.92	-1.10	3.03	2.74	3.53	2.48	2.14	1.77	3.09	-0.10	-0.78	-2.75	4.50
	Terrace	1.57	0.53	0.67	0.64	0.73	1.99	0.15	1.72	1.41	1.69	1.18	0.45	0.56	1.45	0.69	-0.20	-0.51	2.27
Activity effect	**Bungalow**	0.01	0.01	-0.01	-0.01	-0.02	-0.02	0.01	-0.01	0.00	0.00	-0.01	-0.02	0.01	-0.04	0.01	-0.01	0.00	-0.01
	Detached	1.88	0.66	0.16	0.21	0.18	-0.17	0.03	-0.01	0.03	0.03	0.18	-0.26	-0.05	-0.03	0.81	0.77	0.79	0.56
	Apartment	0.02	-0.08	-0.04	-0.10	-0.08	-0.06	0.07	0.11	0.75	0.28	0.14	-0.05	0.17	0.00	0.16	0.15	0.09	0.26
	Semi-Det	2.81	0.84	0.30	0.08	0.14	0.64	0.33	0.90	1.49	1.77	1.96	1.64	2.02	1.17	0.89	0.90	0.85	0.19
	Terrace	0.48	-0.21	-0.11	-0.01	0.12	0.31	0.23	0.42	0.31	0.65	0.87	0.55	0.47	0.64	1.49	0.63	1.01	0.69
Intensity effect	**Bungalow**	0.02	-0.01	0.04	0.03	0.00	0.03	-0.01	0.02	0.02	-0.02	0.03	0.03	-0.03	0.03	-0.02	0.01	-0.01	0.00
	Detached	0.96	0.74	0.56	0.27	-0.50	0.69	0.14	0.47	-0.03	0.51	-0.19	1.03	-0.48	0.47	-0.74	-0.15	-0.59	0.60
	Apartment	0.02	0.01	0.16	0.16	0.09	0.20	0.15	0.43	0.49	0.33	0.64	0.46	-0.41	0.48	-0.16	-0.14	-0.54	0.30
	Semi-Det	1.77	2.03	1.41	0.84	-0.12	1.08	0.68	1.98	0.94	0.76	0.01	2.73	-1.42	2.29	-0.32	-1.21	-2.92	2.19
	Terrace	0.88	0.78	0.72	0.65	0.66	1.20	0.87	1.26	0.99	0.40	0.28	0.87	-0.38	0.89	-0.49	-0.62	-1.20	0.77
2002 BR	**Bungalow**														0.00	0.00	0.00	-0.01	0.01
	Detached														0.00	-0.06	-0.06	0.00	-0.01
	Apartment														-0.01	0.00	0.00	0.00	0.00
	Semi-Det														-0.16	-0.02	-0.06	-0.04	-0.01
	Terrace														-0.01	-0.02	-0.02	0.00	-0.05
Weather effect	**Bungalow**	0.01	0.00	0.00	0.00	0.00	0.01	-0.02	0.00	0.00	0.00	0.00	-0.01	0.01	0.00	0.00	0.00	0.00	0.00
	Detached	0.28	-0.07	0.17	-0.07	-0.10	0.56	-0.94	0.09	0.14	0.23	0.20	-0.60	0.30	-0.05	-0.17	-0.13	-0.19	0.62
	Apartment	0.09	-0.02	0.02	0.04	0.02	0.09	-0.18	0.00	0.03	0.22	0.03	-0.39	0.16	-0.04	-0.11	-0.06	-0.06	0.29
	Semi-Det	0.66	-0.14	0.33	0.00	-0.09	1.20	-2.11	0.14	0.30	0.99	0.48	-2.26	1.10	-0.19	-0.69	-0.42	-0.60	2.11
	Terrace	0.21	-0.04	0.06	0.00	-0.04	0.49	-0.95	0.04	0.11	0.65	0.03	-0.96	0.47	-0.07	-0.29	-0.18	-0.32	0.85
Size effect	**Bungalow**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Detached	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.00	-0.01	0.01
	Apartment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Semi-Det	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.03	0.03	0.07	-0.01	0.05	0.02	-0.05	0.02
	Terrace	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix Table 3. Decomposition effects for temporarily vacant dwellings

Appendix B – Building Simulation Inputs & Removed Values

Parameter	**Full Compliance (Elementary heat loss + permitted openings variations)**	**Actual Compliance (Mean U-values)**
Dwelling type	Semi-Detached	Semi-Detached
Total floor area (conditioned)	104.4m^2	104.4m^2
Living area	21m^2	21m^2
Number of chimneys	1	1
Number of open flues	0	0
Number of intermittent fans and passive vents	4	4
Number of flueless gas fires	0	0
No. of storeys	2	2
Structure type	Masonry	Masonry
Percent of windows & doors draught stripped (%)	100	100
No. of sides sheltered	2	2
Ventilation type	Natural ventilation	Natural ventilation
Dwelling orientation	SE/SW	SE/SW
Window area (m^2)	19.47	19.47
Window U-value (W/m^2 K)	2.56	2.49
Exposed door area (m^2)	2.48	2.48
Exposed door U-value (W/m^2 K)	2.56	2.7
Exposed floor area (m^2)	57.7	57.7
Exposed floor U-value (W/m^2 K)	0.25	0.38
Exposed wall area (m^2)	97.76	97.76
Exposed wall U-value (W/m^2 K)	0.27	0.45
Exposed roof area (m^2)	60.41	60.41
Exposed roof U-value	0.22	0.28

(W/m^2 K)		
Thermal bridging factor (W/m^2 K)	0.15	0.15
Water storage volume (l)	110	110
Insulation type	Factory insulated	Factory insulated
Insulation thickness	30	30
Proportion of low-energy light bulbs (%)	26	26
Thermal mass category	Medium	Medium
Heating system control category	2	2
Heating system responsiveness category	1	1
Central heating pump	1	1
Oil boiler – pump	0	0
Gas flue pump	1	1
Efficiency of main space heating system (%)	80	80
Fraction of heat for supplementary heating system (%)	10	10
Efficiency of supplementary space heating (%)	30	30
Main space heating type	Natural Gas	Natural Gas
Supplementary space heating type	Natural Gas	Natural Gas
Efficiency of main water heater (%)	80	80

Appendix Table 4 - Main Inputs for BER Compliance Simulation

Parameter	Number of Entries Removed
TotalFlootArea < 30m^2	2025
TotalFlootArea > 1,000m^2	13
Rating Type = Provisional	2,785
Terrace or Semi-Detached Dwelling with TotalFloorArea > 500m^2	7
DwellingType = House	35,540
HSMainSystemEfficiency = blank or < 20%	4083
HSEffAdjFactor < 0.7	56
WHMainSystemEff < 20% & > 450%	33
WHEffAdjFactor < 0.7	196
HSSupplSystemEff ≠ Null, 0 or <b19%	0
LivingAreaPercent >=90% or < 5% or = Null	321
HSSupplHeatFraction ≠ Null, 0, 0.1, 0.15, 0.2	915
DeclaredLossFactor = blank or > 20	2889
Thermal bridging factor < 0 or > 0.15	32
Negative Energy Value	167

Appendix Table 5 - Removed values from BER database prior to use in building regulation analysis

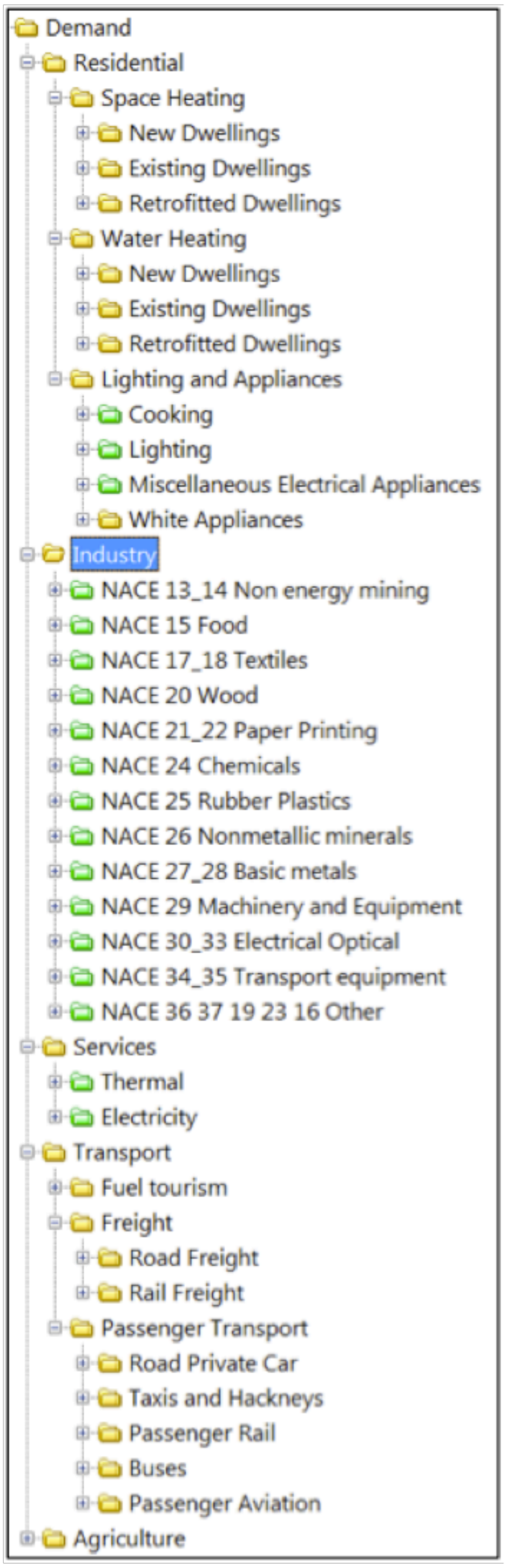
Appendix C – LEAP Electricity Generation Results & Model Tree Structure

Plant	Running Costs (fuel and O&M costs)	Optimized (no constraint)	Optimized (CO_2 constraint)
MSW CHP	0.15	0.92	0.89
Biogas	0.04	0.00	0.00
Turbine Gas-Condensing	0.37	0.32	0.24
Hydro	1.02	1.03	1.03
Lignite (Peat)	2.62	2.74	2.63
Gas Turbine Diesel (OCGT)	0.87	0.11	0.11
Steam Turbine Oil	0.00	0.00	0.01
Hard Coal	5.41	6.27	1.12
CCGT Gas (older units)	2.97	2.59	2.55
CCGT Gas (newer units)	6.25	16.46	13.32
Wind	11.91	2.82	11.34

Appendix Table 6 – Electricity generation results in 2020 for reference scenario for three electricity dispatches runs (units: TWh)

Plant	Running Costs (fuel and O&M costs)	Optimized (no constraint)	Optimized (CO_2 constraint)
MSW CHP	0.15	0.92	0.88
Biogas	0.04	0.00	0.00
Turbine Gas-Condensing	0.41	0.32	0.25
Hydro	1.03	1.03	1.03
Lignite (Peat)	2.66	2.74	2.55
Gas Turbine Diesel (OCGT)	0.94	0.11	0.13
Steam Turbine Oil	0.00	0.00	0.03
Hard Coal	5.62	6.27	0.97
CCGT Gas (older units)	2.66	2.53	2.53
CCGT Gas (newer units)	7.07	18.69	13.82
Wind	11.96	2.82	13.25

Appendix Table 7 - Electricity generation results in 2020 for energy efficiency+ scenario for three electricity dispatches runs (units: TWh)



- Demand
  - Residential
    - Space Heating
      - New Dwellings
      - Existing Dwellings
      - Retrofitted Dwellings
    - Water Heating
      - New Dwellings
      - Existing Dwellings
      - Retrofitted Dwellings
    - Lighting and Appliances
      - Cooking
      - Lighting
      - Miscellaneous Electrical Appliances
      - White Appliances
  - Industry
    - NACE 13_14 Non energy mining
    - NACE 15 Food
    - NACE 17_18 Textiles
    - NACE 20 Wood
    - NACE 21_22 Paper Printing
    - NACE 24 Chemicals
    - NACE 25 Rubber Plastics
    - NACE 26 Nonmetallic minerals
    - NACE 27_28 Basic metals
    - NACE 29 Machinery and Equipment
    - NACE 30_33 Electrical Optical
    - NACE 34_35 Transport equipment
    - NACE 36 37 19 23 16 Other
  - Services
    - Thermal
    - Electricity
  - Transport
    - Fuel tourism
    - Freight
      - Road Freight
      - Rail Freight
    - Passenger Transport
      - Road Private Car
      - Taxis and Hackneys
      - Passenger Rail
      - Buses
      - Passenger Aviation
  - Agriculture

Appendix Figure 1 – LEAP Tree Structure

Appendix D – LEAP & OSeMOSYS Software Description

LEAP

Software overview

The Long Range Energy Alternatives Planning tool (LEAP) is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute (SEI). It is an integrated modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. LEAP can be used to account for energy sector and non-energy sector GHG emissions as well as local and regional air pollutants; it can also be used as a comprehensive accounting system for conducting integrated cost-benefit analyses of energy scenarios (Heaps, 2011).

Model structure

In terms of model structure, LEAP does not have a pre-defined construction; rather it comes with a number of building blocks, from which a great variety of energy models can be built. The main mechanism by which these unique models are constructed is the tree structure folder system, which allows the user to construct a horizontally and vertically organized energy system appropriate to the country or region being analysed.

Typically, a horizontal tree-structure involves the energy flow from supply side (raw materials, refining & conversion, electricity production) to demand-side (sectoral, end-use technology). A typical vertical tree-structure for demand-side involves sectoral division (industry, residential, transport, services) at the top of the hierarchy, followed by division into sub-sectors (new dwellings, existing dwellings etc.) at each descending (more disaggregated) level. The particular tree-structure employed will usually align with the conventions of data gathering in the particular country being examined. It should also be a function of the questions the analyst seeks to answer. The inputs for each horizontal and vertical folder are described in the sections below.

Part of the tree structure used in the Ireland LEAP model is shown in Appendix Figure 1. It combines a broad horizontal structure (resources, electricity generation, transmission and development, demand) together with a vertically deep demand-side structure (industry, services, transport, residential) the detail of which is described in Chapter 4. The depth and complexity of any LEAP model enables the asking of detailed and complex research questions. In the case of the Ireland LEAP model, the sectors modelled in most detail are the transport and residential sectors and these are the sectors that are examined in most detail, i.e. in terms of variety of and number of energy policies that are examined.

Inputs

This section will describe the inputs for each folder in a typical LEAP model, with additional reference to the Ireland LEAP model.

Resources

LEAP has the facility for modelling the natural resources of a country together with the resource import requirements. In categories of primary and secondary fuel sources (corresponding to raw and refined product), the user can input: reserves, yield, imports, exports, indigenous fuel cost, import fuel cost and export fuel costs. All these fields can be entered as base year values as well as values that change over time. This folder allows a comprehensive characterisation of the entire indigenous energy resource of a country together with the import and export prices of all fuels. The data from this folder can be used in both the electricity generation demand-side sectors.

Electricity generation

For building the electricity generation sector, an entity representing each power plant in the power system is entered in the electricity generation folder. Detailed information for each electricity entity is required, this includes: capacity, efficiency, availability, capital costs, variable & fixed O&M. Asynchronous generation such as wind electricity with its associated highly variable availability profile can also be entered into the model. Default environmental information such as emissions of CO_2, CO CH_4, NOx and S_2 are associated with the fuel type for each electricity generation entity. CHP can be modelled by using the “co-fuel” input field. Electricity demand profiles can be entered in any number of time slices between hourly and seasonally.

Once this folder is built and the modelling is underway, the electricity demand profiles will be used to make a dispatch decision about what plants will service the electricity demand for each time slice. LEAP has five different dispatch rules that can be employed. These are: a simple *merit order* designation for each power plant, an *in proportion to process share* rule*,* an *in proportion to available capacity* rule, a *run to full capacity* rule or a least-cost rule based on *running cost* (O&M cost + fuel cost). If additional electricity capacity is required, there are also a number of rules that can be selected which will determine how the model decides what new capacity will be built. In LEAP, the capacity expansion decision can be modelled by the user as either explicit construction of particular power plants in particular years, or as power plants that are back-up and ready for construction only if required. There is also the option of more advanced modelling of this sector using LEAP-OSeMOSYS, which will be discussed in the following section.

Demand-side

Once a demand-side tree structure has been designed by the analyst and put in place, the user can enter *energy intensity* and *activity* equations to characterize all the energy consuming devices at the end point of each "branch" in the tree-structure. Depending on the level of detail (i.e. the number of layers in the tree-structure) that the energy intensity values are attached to, this will determine the classification of the energy model, i.e. if sectors are described with an aggregate energy intensity value, this would be classified as a top-down approach, whereas if energy intensity values are detailed at the energy device level, this would be a bottom-up approach. This flexibility of structure has led to LEAP being alternatively classified as a bottom-up model (Suganthi, 2011), an accounting model (Mundaca et al., 2010) and a top-down model (Connolly et al., 2010); all of these statements are true, different approaches can be mixed and matched within a single model.

Scenarios

Like most energy systems models, LEAP employs a reference scenario against which the alternative future scenarios are compared. The design of these scenarios is a key task by the analyst, as through these, the key research questions are explored. A useful property of LEAP is scenario inheritance whereby new scenarios can be built from existing scenarios (such as the reference scenario); in the new scenario, there is thus only the requirement to make a small adjustment in the variables under examination for the new scenario to be complete. The multiple inheritance property can also be used to package together a number of scenarios; for example, all the policies in Ireland's NEEAP could be modelled separately as individual policy measures and then together in an integrated NEEAP scenario.

Functionality

Once an energy system has been built, the time horizon for the model must be decided. The Ireland LEAP model has a base year of 2008 and the modelling time horizon is 2009-2020. It is possible to have modelling time horizon out to 2050 or 2060; the only limitation is the increasing uncertainty that occurs for longer time horizons. In terms of the precise nature of its modelling, LEAP is best classified as a simulation model because it calculates total energy demand based on the *energy intensity* and *energy activity* values and their associated growth rates over time. Applied at aggregated or disaggregated level, these growth rates can be fixed, varying, interpolated, step-changes, logarithmic changes or any other formula created by the user; LEAP is also well integrated with Microsoft Excel such that formulas can be entered as fixed values or simple references to Excel sheet ranges. LEAP models each year individually for each time slice.

While scenario analysis is the core method of LEAP, there are a number of additional different types of modelling and analysis that can be integrated with the scenario analysis. In the *useful energy analysis* a distinction is made between consumed energy and useful energy (energy service demand); in this way, the analyst can explore the implications of energy efficiency at the device level, e.g. comparing a boiler with 80% and 90% efficiency. In the *stock analysis* the analyst can explore varying levels of stock renewal, for example the replacement of light bulbs or refrigerators over time. In the *transport analysis* the analyst can add distance travelled (tonne-kilometres or person-kilometres) to the stock analysis. In the electricity sector, *capacity expansion* and *dispatch decision* can be modelled in a number of different ways as already described in the previous section.

Outputs

For each year of the modelled time horizon, LEAP calculates the total energy demand: that is, the energy consumption, primary energy and associated costs and environmental emissions. For some of the particular analysis methods described above, LEAP can also give results such as stock sales and retirements, average vehicle mileage or car-stock average efficiency; for the electricity sector results include primary energy requirements, electricity production, imports, exports, capacity added or retired, load factor, peak power requirements, average power plant efficiency, power dispatched in each time slice and the module energy balance; resources can be examined for import requirements, reserves and self-sufficiency; costs can be examined by cost type; finally, environmental factors for each emission type can be examined. In addition, users can also create their own indicators.

Strengths

While LEAP is less sophisticated than other energy modelling tools such as MARKAL (Loulou et al., 2004), TIMES (Loulou and Labriet, 2007) or MESSAGE (Messner and Strubegger, 1995) its contribution primarily lies in its flexibility, transparency and ease-of use and its emphasis on data management and reporting as much as on its modelling algorithms (Nakata, 2004). Part of the strength of the LEAP methodology is that it isn't specialist software focused on one aspect of the energy system; rather, LEAP can model all parts of the energy system from resources accounting to electricity generation to demand side. It has many built-in databases of cost, technology and environmental data from reliable sources.

LEAP is particularly appropriate for modelling the individual and aggregate impact of energy policies as it has sufficient flexibility to model particular policies in detail, as well as modelling these same policies in one group. In this context LEAP would be a very useful tool for tracking the progress of policies over time. LEAP can also be integrated with a number of other software packages, such as *Geographic Information System* (GIS) for regional analysis, Application Programming Interface (API) for adding script functionality and OSeMOSYS for optimization functionality (described below).

Limitations

Stemming from its nature as a flexible model with a moderate learning curve, LEAP has a number of limitations that are described below:

Formulas: While LEAP has a significant selection of formulas, the capacity of LEAP to create new formulas not already in the LEAP library is limited, and can easily become cumbersome. The tendency of LEAP formulas to become unwieldy when they reach a certain size functions as a limit to the complexity of the tree-structure, which by itself has no theoretical limit in size.

Simulation model: LEAP on its own is a simulation model as distinct from an optimization tool. The shortcoming of this approach is that the model is user-led, and as such cannot be used to identify solutions unknown to the user in the way that an optimization model can. This is not strictly speaking a weakness of LEAP, just a side effect of its particular approach.

Electricity sector: While the electricity system can be modelled in significant detail, there are some limitations to the level of detail LEAP can model. For example, LEAP can’t model ramp rates, minimum stable level, minimum up and down times and certain other parameters that in a fully market-led electricity system are important. In addition, LEAP can’t model very high-resolution time slices, i.e. sub 1-hour.

Electricity trading: This shortcoming stems from the same point as described above: LEAP can’t be set-up to import electricity if it is cheaper in one region that in another. For Ireland, there is electricity trading between UK and Ireland and it is difficult to model this in LEAP.

OSeMOSYS

Software description

OSeMOSYS stands for Open Source Energy Systems Modelling Software. Originally conceived at the International Atomic Energy Agency (IAEA), OSeMOSYS was developed by an international community of energy modellers and has come to have an international community together with an online forum based in the SEI[1]. On its own, OSeMOSYS is "a full-fledged systems optimization model for long-run energy planning" with the two distinct advantages that compared to most energy systems model on the market it has "a less significant learning curve and time commitment to build and operate" and that it "requires no upfront financial investment". OSeMOSYS has successfully proliferated among a target audience of "students, business analysts, government specialists, and developing country energy researchers" (Howells et al., 2011).

With the support of the United Nations Industrial Development Organization (UNIDO), a linkage between LEAP and OSeMOSYS was constructed and implemented in the launch of LEAP 2012 in July 2012 (SEI, 2012). On its own, LEAP simulates future energy demand and supply for a given energy system, rather than providing an optimized energy system that delivers future energy service demands at least cost. For example, future power plants and the order in which they shall be built have to be predefined by the analyst. These power plants are then activated, or built, when existing capacities doesn't suffice any longer to meet the peak demand plus a capacity reserve. This is the shortcoming that OseMOSYS was integrated into LEAP to solve: now the analyst can choose to run LEAP on its own, or together with OSeMOSYS.

Currently in LEAP, OSeMOSYS only provides optimization capabilities to the electricity generation sector. In this thesis, OSeMOSYS is only used as part of its back-end functionality in LEAP; as such, OSeMOSYS takes all its input from LEAP and the user has no direct access to OSeMOSYS. The discussion below therefore only discusses OSeMOSYS in the context of its partnership with LEAP.

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[1] http://osemosysmain.yolasite.com/

Functionality

Within the electricity sector in LEAP, OSeMOSYS is used to calculate the least-cost capacity expansion and dispatch for the electricity generation sector. Least-cost in this instance is defined as the lowest total discounted system cost over the modelling time horizon. Costs include all the capital costs, fuel costs, O&M costs and salvage cost parameters that can be entered for each entity in the electricity generation sector. A certain number of constraints, which OSeMOSYS must satisfy, can also be added to be problem; at present these constraints are minimum or maximum capacity and environmental emissions. Operationally, LEAP writes an input file for OSeMOSYS, runs it and imports its results back into LEAP; currently, the LEAP input file only contains the aggregated electricity demand as the main driver for the optimization within OSeMOSYS.

Outputs

The only two outputs from the joint LEAP & OSeMOSYS functionality are the capacity expansion and dispatch decision made according to OSeMOSYS's optimization calculations. All the same outputs that were already described for LEAP can be also be generated for the LEAP-OSeMOSYS pairing.

Strengths

The advantage of the LEAP-OSeMOSYS linkage is that it enables linear programming optimization without the need to learn linear programming code. The use of the LEAP interface means minimal new skills are required of the analyst. The addition of optimization means that the electricity sector can be modelled in ways more akin to the actual operation of an electricity market. A broader range of scenarios that examine least cost pathways to achieving energy efficiency can be modelled.

Limitations

Processing power: At present the optimization prowess of OSeMOSYS is limited by the ability of the solver. LEAP-OSeMOSYS is unable to optimize energy systems with a yearly time-slice of smaller than 48 hours. This is a shortcoming especially where power systems are expected to have large amounts of asynchronous or variable renewable power (e.g. wind). Specifically this is an issue with the pre-solver: a typical solver will initially create large matrices from all the input data, where there is no data for a particular parameter a zero is substituted. The pre-solve stage is where all these zeros are removed and the matrices reduced in size. This reduces the processing power required significantly. Currently OSeMOSYS does not remove these zeros for reasons of transparency (in keeping with the open source philosophy of OSeMOSYS) and ease of understanding; however, this limits the processing power. This is true at the time of writing; however, it is known that the developers of OSeMOSYS are currently seeking to address this issue together with further improvements to the code (Welsch et al., 2012).

Electricity generation system: Optimization limited to electricity sector. Unlike in TIMES when optimization can be done horizontally across all sectors, LEAP-OSeMOSYS only optimizes the electricity sector.

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Appendix E – Natural Gas Consumption & Share in Irish TIMES Scenarios

Year	**2005**	**2010**			**2020**			**2030**			**2040**			**2050**		
Sector	BASE	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95
Agriculture	0.34	0.32	0.32	0.32	0.37	0.37	0.37	0.39	0.39	0.39	0.41	0.41	0.41	0.43	0.43	0.43
Commercial	1.67	1.62	1.62	1.62	1.72	1.68	1.66	1.82	1.57	1.54	1.94	1.89	1.66	2.06	1.74	1.69
Industry	2.62	2.36	2.36	2.36	2.41	2.41	2.34	2.40	2.37	2.37	2.39	2.39	2.40	2.38	2.38	2.39
Residential	2.94	3.09	3.09	3.09	3.08	3.10	3.10	3.14	2.98	2.85	3.19	2.78	2.53	3.13	2.69	2.38
Transport	4.23	4.38	4.37	4.37	5.04	5.00	4.98	5.15	4.19	4.16	5.50	3.53	3.52	5.76	3.71	3.70
Total	11.80	11.77	11.76	11.76	12.62	12.56	12.45	12.91	11.52	11.32	13.43	11.00	10.52	13.77	10.95	10.59

Appendix Table 8 - Gas consumption by sector for all scenarios (units: mtoe)

Year	**2005**	**2010**			**2020**			**2030**			**2040**			**2050**		
Sector	BASE	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95	REF	CO2-80	CO2-95
Agriculture	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.3%	3.3%	3.3%	6.7%	6.7%	6.7%	10.0%	10.0%	0.3%
Commercial	18.1%	24.9%	24.7%	24.7%	25.2%	24.3%	25.0%	32.9%	29.8%	29.6%	36.5%	33.3%	22.2%	39.7%	17.7%	0.0%
Industry	20.7%	25.1%	25.1%	25.1%	27.3%	30.6%	34.4%	31.1%	25.3%	9.7%	25.6%	25.0%	4.7%	24.8%	4.0%	3.7%
Residential	20.4%	26.4%	26.4%	26.4%	27.2%	27.1%	27.1%	28.9%	30.4%	31.8%	29.4%	33.6%	35.6%	30.3%	34.9%	7.6%
Transport	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	0.2%	0.6%	0.4%	0.3%	0.7%	0.1%	0.0%	21.9%	0.0%	0.0%
Electricity	40.3%	37.7%	37.7%	37.7%	65.3%	46.2%	52.3%	74.5%	44.8%	39.1%	75.0%	39.6%	35.3%	49.7%	36.7%	0.0%

Appendix Table 9 - Share of natural gas of energy consumption by sector for all scenarios

Appendix F – TIMES Software Description

Irish TIMES

The Irish TIMES model is a linear optimisation model with an objective function to minimise total system cost (maximizes the total discounted surplus) subject to imposed constraints. Mathematical equations describe the relationships and interaction between the many technologies, drivers and commodities in Irish TIMES. While it is tempting to think of Irish TIMES as a simple 'merit type' model that chooses technologies simply from the least expensive to the most expensive to meet certain demands this is an oversimplification that leads to an incorrect understanding of the model value and dynamics. The richness of the Irish TIMES model is that it optimises across all sectors of the energy system for the full horizon and thus captures the interaction between sectors. The model simultaneously solves for the least cost solution subject to emission constraints, resource potentials, technology costs, technology activity and capability to meet individual energy service demands. In this way Irish TIMES allows technologies to compete both horizontally across different energy sectors and vertically through the time horizon of the model.

Software overview

The TIMES (The Integrated MARKAL-EFOM System) model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), an international community which uses long term energy scenarios to conduct in-depth energy and environmental analyses (Loulou et al., 2004). The TIMES software combines two different, but complementary, systematic approaches to modeling energy: a technical engineering approach and an economic approach (Gargiulo and Gallachoir, 2013). TIMES is a technology rich, bottom-up model, which uses linear-programming to produce a least-cost energy system, optimized according to a number of user constraints, over medium to long-term time horizons. In a nutshell, TIMES is used for, "the exploration of possible energy futures based on contrasted scenarios" (Loulou et al., 2005).

The Irish TIMES model was originally extracted from the Pan European TIMES (PET) model and then updated with improved data based on much extensive local knowledge (Ó Gallachóir et al., 2012). The Pan European Times (PET) Model is a multi-regional TIMES model of Europe comprised of 36 European regions (EU27, Iceland, Norway, Switzerland, and six Balkan countries) (Gargiulo and Gallachoir, 2013). The PET model from which the Ireland sub-model was taken was calibrated with 2005 Eurostat as a base year. The Irish TIMES project has focused on the Irish energy system and the potential for Ireland to i) increase renewable energy penetration in line with targets to 2020, ii) meet GHG emissions reduction targets in the period to 2020 and iii) transition to a low carbon economy within the longer term to 2050 (Ó Gallachóir et al., 2012).

Model structure

TIMES models encompasses all the steps from primary resources through the chain of processes that transform, transport, distribute and convert energy into the supply of energy services demanded by energy consumers (Loulou et al., 2005). On the energy supply-side, it comprises fuel mining, primary and secondary production, and exogenous import and export. The "agents" of the energy supply-side are the "producers". Through various energy carriers, energy is delivered to the demand-side, which is structured sectorally into residential, commercial, agricultural, transport and industrial sectors. The "agents" of the energy demand-side are the "consumers". The mathematical, economic and engineering relationships between these energy "producers" and "consumers" is the basis for the TIMES model.

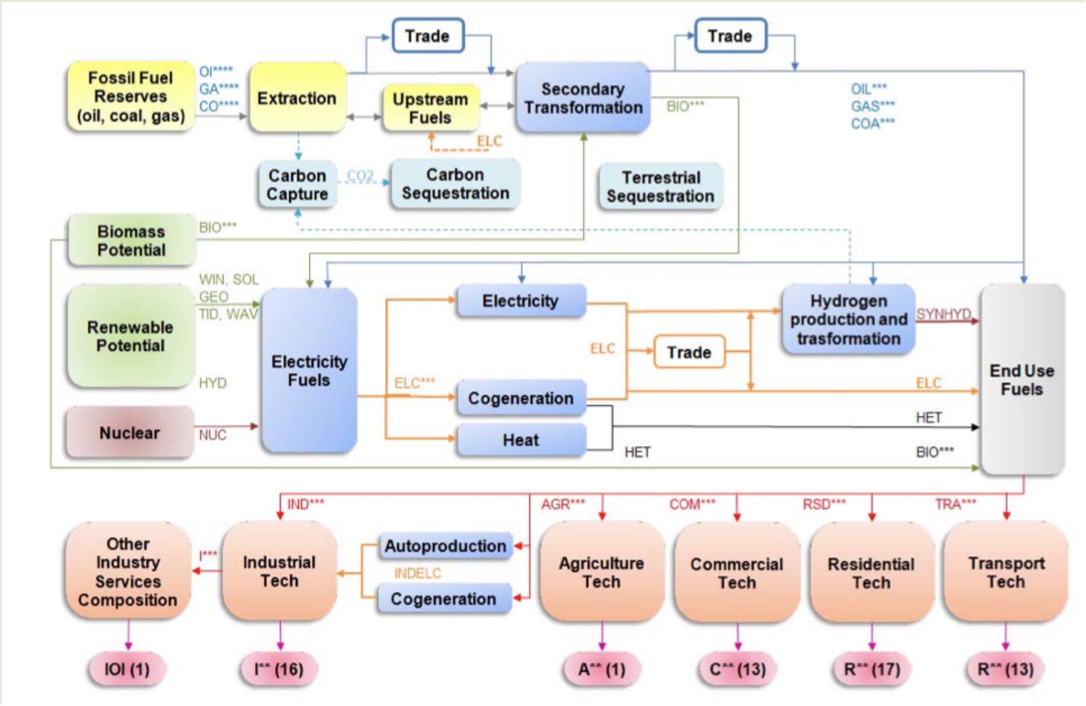
All TIMES models are constructed from three basic entities (Loulou et al., 2005):

Technologies: (also called processes) are representations of physical devices that transform commodities into other commodities. Processes may be primary sources of commodities (e.g. mining processes, import processes), or transformation activities such as conversion plants that produce electricity, energy-processing plants such as refineries, end-use demand devices such as cars and heating systems, etc.

Commodities: energy carriers, energy services, materials, monetary flows, and emissions; a commodity is either produced or consumed by some technology.

Commodity flows: the links between processes and commodities. A flow is of the same nature as a commodity but is attached to a particular process, and represents one input or one output of that process.

These three entities are used to build an energy system that characterizes the country or region in question. All TIMES models have a reference energy system, which is a basic model of the energy system before it is substantially changed either for a particular region or for a particular scenario. The Irish TIMES reference energy system, which represents the Irish energy system in 2005 and its possible long-term evolution (Ó Gallachóir et al., 2012) is shown in Appendix Figure 2. The blocks are the technologies, the writing outside the blocks (e.g. OI, GA, CO, ELC) are the commodities and the lines connecting the blocks are the commodity flows.



Appendix Figure 2 - Schematic of processes and commodities in TIMES (source: (Ó Gallachóir et al., 2012))

Inputs

There are a large number of exogenous inputs to the Irish TIMES model. Many of these are characterizations of technology or commodity entities. There are also a number of endogenous inputs that are calculated by the Irish TIMES and which are used in the final calculations for the model outputs. These inputs are described below.

Technologies

In the Irish TIMES model, there are approximately 1600 technologies for the supply-side and demand-side sectors of the economy (Ó Gallachóir et al., 2012). Each of these technologies has detailed technical parameters that can be changed and set by the user; some of these parameters include technology efficiency (e.g. heat rates, learning curves), technology lifetime, emission factors (CO_2 and non-CO_2) and availability. The data sources for most of these technologies are the IEA databases that were used to build the reference energy system. For Irish TIMES, the technologies parameters were all reviewed and revised, as appropriate, for Irish conditions. Each of these technologies also has associated costs (e.g. capital costs, O&M costs, discount rates). In most instances, these costs are input in the form of curves, i.e. as elasticities and as such, they are described as demand curves in that they can meet varying levels of energy demand at varying levels of cost (Loulou et al., 2005).

Resource potential

The resource potential applies mostly to commodities and supply curves, i.e. what is the cost of each commodity at various levels of supply. The resource potential also applies to technologies, particular renewable energy technologies and their resource. For example, there is a limit to the amount of onshore wind power that can be constructed in Ireland. The commodity supply curves and renewable resource for Irish TIMES have been carefully scrutinized and updated based on most recently available data, local knowledge, policies (e.g. taxes, targets) or known technical limits (Ó Gallachóir et al., 2012).

Fuel price

Projections for future fuel prices for key fuel commodities (e.g. coal, oil and gas) are taken from IEA world energy outlook 2009 (IEA, 2009) and updated for transport costs to Ireland (Ó Gallachóir et al., 2012). It is worth noting that some commodities such as natural gas have seasonal prices. Electricity prices are calculated endogenously in the model.

Macro-economic drivers

Key data behind the Irish TIMES model projections are the macro-economic projections of GDP, GNP, private income, population and number of households that is generated as the output of the Economic and Social Research Institute (ESRI) long-term macro-economic model (HERMES). These parameters are used to generate energy service demand parameters, which are the key quantities that the Irish TIMES model must produce an energy system to satisfy. In total, there are 60 different types of energy services for the transport, residential, agricultural, commercial, industry and non-energy sectors. Some examples include residential space heating (PJ), commercial refrigeration (PJ), industry iron & steel (Mt), transport car distance (Mp/km) and transport road freight (Mt/km). For each modeling period out to 2050, energy service demand parameters are input and the Irish TIMES model must meet these parameters at least cost.

Scenarios

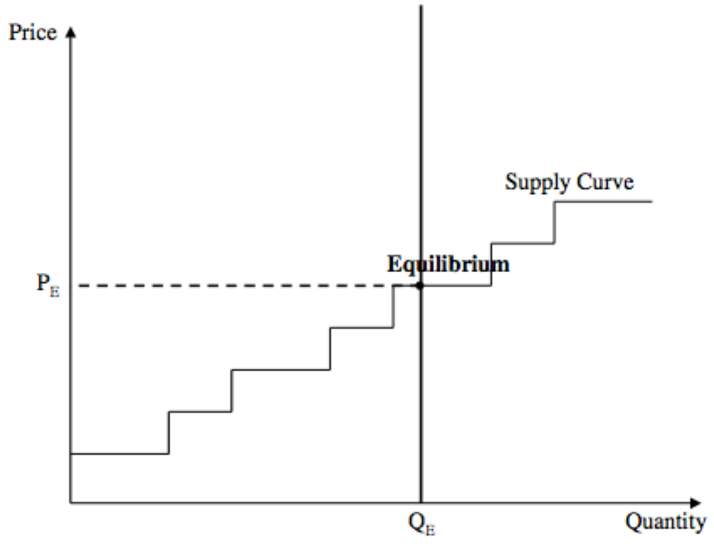
The principle insights generated from Irish TIMES are achieved through scenario analysis. The reference energy system includes a reference energy scenario, which is the scenario against which the results from other scenarios are checked. The reference scenario is generated by running the model in the absence of any policy constraints. It will not normally be completely aligned with national energy forecasts that are generated by simulating what the future energy use is anticipated to be, mainly because TIMES optimizes the energy systems providing a least cost solution. When a (single of many) policy constraint is imposed on the model (e.g. minimum share of renewable energy, maximum amount of GHG emissions or minimum level of energy security), the model generates a different least cost energy system. When the results are compared with those from the reference scenario, the different technology choices can be identified that deliver the policy constraint at least cost (Ó Gallachóir et al., 2012).

In the Irish TIMES model, there are two key modeling time-horizons: 2005-2020 and 2005-2050. The first time-horizon was run to test out known renewable energy targets for non-ETS sector for 2020, e.g. 40% renewable electricity, 12% renewable heat and 10% renewable transport. The second time horizon was to examine deep cuts in emissions, e.g. 80%-95% CO_2 by 2050.

Functionality

Once all the inputs, constraints and scenarios have been put in place, the model will attempt to solve and determine the energy system that meets the energy service demands over the entire time horizon at least cost. It does this by simultaneously making equipment investment decisions and operating, primary energy supply, and energy trade decisions, by region. Irish TIMES assumes perfect foresight, which is to say that all investment decisions are made in each period with full knowledge of future events. It optimizes horizontally (across all sectors) and vertically (across all time periods for which the limit is imposed).

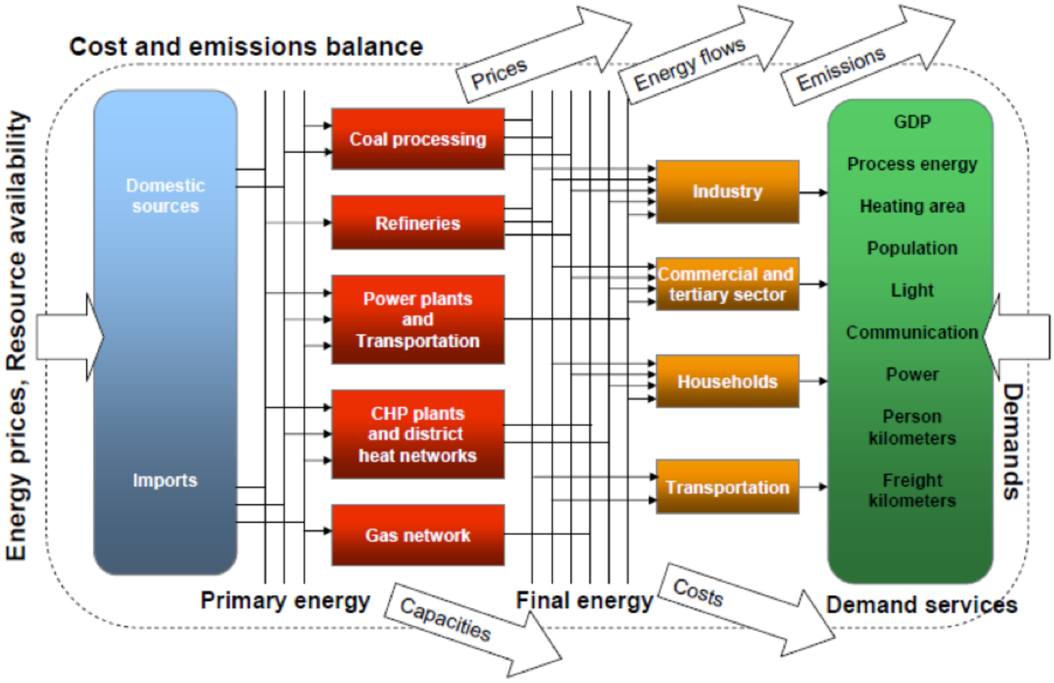
The results will be the optimal mix of technologies and fuels at each period, together with the associated emissions to meet the demand. The model configures the production and consumption of commodities (i.e. fuels, materials, and energy services) and their prices; when the model matches supply with demand, i.e. energy producers with energy consumers, it is said to be in equilibrium. Mathematically, this means that the model maximizes the producer and consumer surplus. A fully elastic TIMES model is set up such that the price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity’s price. A market is said to have reached an equilibrium at prices p and quantities q when no consumer wishes to purchase less than q and no producer wishes to produce more than q at price p. When all markets are in equilibrium the total economic surplus is maximized (i.e. the sum of producers’ and consumers’ surpluses)(Loulou et al., 2005). The version of this relationship when energy service demand is fixed (as in the version of Irish TIMES used in this thesis) is represented graphically in Appendix Figure 3.



Appendix Figure 3 - Achieving market equilibrium in Irish TIMES (source: (Loulou et al., 2005))

Outputs

The main Irish TIMES model output is an energy system, which services the end-use energy service demands at lowest cost while adhering to the various constraints (e.g 80% emissions reduction, 40% renewable electricity penetration). In the first instance, the Irish TIMES model provides an answer to the question: is the target feasible? If an energy system is possible, it can then be examined, at what cost? The model outputs are energy flows, energy commodity prices, GHG emissions, capacities of technologies, energy costs and marginal emissions abatement costs. Appendix Figure 4 has a schematic of the Irish TIMES model along with outgoing white block arrows that show the model outputs.



Appendix Figure 4 - Schematic of TIMES inputs and outputs (source: (Remne et al, 2001))

Strengths

Something of the usefulness (and strength) of TIMES can be gleaned from its popularity: it is currently in use in over 70 countries. This is also a strength of the model since it has a world-wide community engaged in maintaining and updating the model. The main "selling point" of TIMES is that it combines a detailed technology rich database with an economically optimizing solver. It is able to generate robust energy policy scenarios over long time horizons and it is able to offer strategic insight into long-term policy formation. This is especially important for the energy sector, which has such large capital investments that project lifetimes can easily exceed average generation lifetimes. The challenge of decarbonizing the energy system is an enormous and expensive one so the insight that TIMES gives is unique.

It produces energy pathways over multiple time slices for a long-term time horizon and the solution in the model is in terms of technology choice; it doesn't provide any input to what policy instruments are necessary to implement the technical solutions, it does give indicative results for the carbon price required to achieve certain reductions which can in turn be useful to inform policy design.

Limitations

Like all energy models, Irish TIMES has a number of limitations. In some instances these are simply limitations born of the structure of the model; they are inevitable based on the way the model is built. In other instances, they could be considered weaknesses and in these cases, work is on going to make improvements:

Macro-economic assumptions: This is a limitation of the model. The results of the scenarios are tied to the assumption and results of the macro-economic model, which by themselves are inherently uncertain. While scenario analysis, by its nature, tries to counteract this uncertainty by producing a range of results, this uncertainty is nevertheless present.

Limited macro-economic feedback: This is a current weakness in the Irish TIMES model: there is currently no feedback between the output of the energy system analysis and the macro-economy. Work is ongoing in UCC to develop demand response; however, full macro-economic feedback would require model soft-linking between Irish TIMES and macro-economic models.

Time resolution: For the electricity sector, there are 12 time slices (seasonal, day, night and peak); these are inadequate to capture daily supply and demand curves. For the rest of the TIMES system, there are only seasonal time slices. This is a limitation of the model. It would become computationally unwieldy if the model had to make decade long decision as well as hourly decisions. A working solution to this shortcoming is model soft-linking to more specialized power systems models, which has been pioneered by UCC (Deane et al., 2012).

Behaviour: A further limitation of the Irish TIMES model is the limited capacity to simulate behavioural aspects. This is a limitation of most energy (and indeed macro-economic) models, in that consumer behaviour is generally limited to simple price response and non-price related behaviour in generally very poorly treated.

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Appendix G – LCOE formula terms & CCS Cost Values

Levelized cost of electricity (LCOE) formula:

$$LCOE = \frac{(€_{cap} \times CRF + O\&M_{fixed})}{(8760 \times Cap_{factor})} + (€_{fuel} \times heat_{rate}) + O\&M_{\mathrm{var}}$$

Appendix Equation 1

€$_{cap}$: overnight capital cost (€/GW)

CRF: capital recovery factor, the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. See

O&M$_{fixed}$: Fixed Operation & Maintenance costs (€/kW/yr)

Cap$_{factor}$: capacity factor of the technology (%)

€$_{fuel}$: fuel cost (€/GJ)

heat rate: (KJ/kWh)

O&M$_{var}$: Variable Operation & Maintenance costs (€/kWh)

Capital Recovery Formula (CRF)

$$CRF = \frac{\left\{ i(1+i)^n \right\}}{\left\{ \left[(1+i)^n \right] - 1 \right\}}$$

Appendix Equation 2

i = discount rate

n = number of annuities

Capture	Site	Moneypoint	Moneypoint	Whitegate	Whitegate	Dublin Bay	
	Type	Coal PC	Coal PC	Gas CCGT	Gas CCGT	Gas CCGT	
	CAPEX	€1,703	€2,028	€1,002	€1,771	€1,198	€m/GW
	Fixed O&M	€42.10	€42.10	€52.50	€52.50	€52.50	€m/KW
	Var O&M	€0.49	€0.48	€0.22	€0.36	€0.22	€m/MWh
Transport	Type	Onshore pipeline	Onshore pipeline	Onshore pipeline	Onshore pipeline	Onshore pipeline	
	Distance	186	17	40	230	0	km
	CAPEX	€0.76	€0.76	€0.76	€0.76	€0.76	€m/km
	OPEX	€0.02	€0.02	€0.02	€0.02	€1.46	€/km/tCO2
	Type	Offshore pipeline	Offshore pipeline	Offshore pipeline	Offshore pipeline	Offshore pipeline	
	Distance	50	201	50	201	90	km
	CAPEX	€0.00	€1.46	€0.00	€1.46	€1.46	€m/km
	OPEX	€0.02	€0.02	€0.02	€0.02	€0.02	€/km/tCO2
Storage	Site	Kinsale	Spanish Point	Kinsale	Spanish Point	East Irish Sea	
	Type	Gas Fields	Gas Fields	Gas Fields	Gas Fields	Oil & Gas Fields	
	Capacity	335	120	335	120	1050	Mt
	CAPEX	€0.01	€0.01	€0.01	€0.01	€0.01	€m/kt
	OPEX	€1.00	€1.00	€1.00	€1.00	€1.00	€k/kt

Appendix Table 10 - CCS Cost Values