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Climate and energy scenarios for Ireland to 2050 using the Irish TIMES energy systems model

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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: 17/06/2014

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E’ sempre interessante poter mettere la parola fine ad una tesi. Se da un lato questa comporta il sollievo per la chiusura di un periodo faticoso, di poco sonno e tanta caffeina; allo stesso tempo ti richiama anche ad un piccolo bilancio di questi ultimi tre anni vissuti intensamente. In questi ultimi tre anni ritengo di aver avuto occasioni uniche, la possibilita’ ogni giorno di soddisfare nuove curiosita’, di viaggiare e di conoscere nuovi mondi e nuove persone. Per questo vorrei in primo luogo ringraziare Brian, per avermi spinto ad intraprendere tutto questo, guidato in tutto, dato responsabilita’ e alleggerito lo serate in tante occasioni. Allo stesso modo grazie a Paul, Fionn, Hannah, James, Denis D., Denis L., Declan e Ullash e tutti quelli che ho avuto la fortuna di incrociare all’ERI per tutto quanto abbiamo condiviso di lavorativo e non. Ma in generale grazie a Cork e all’Irlanda, luoghi genuini che mai ti accolgono fino in fondo, ma che sanno sempre sorprenderti e riscaldarti.

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Executive Summary

Due to growing concerns regarding the anthropogenic interference with the climate system, countries across the world are being challenged to develop effective strategies to mitigate climate change by reducing or preventing greenhouse gas (GHG) emissions. The European Union (EU) is committed to contribute to this challenge by setting a number of climate and energy targets for the years 2020, 2030 and 2050 and then agreeing effort sharing amongst Member States. This thesis focus on one Member State, Ireland, which faces specific challenges and is not on track to meet the targets agreed to date. The methodology is replicable in other Member States.

The purpose of this thesis is to increase the evidence-based underpinning policy decisions in Ireland. Before this work commenced, there were no projections of energy demand or supply for Ireland beyond 2020. This thesis uses techno-economic energy modelling instruments to address this knowledge gap. It builds and compares robust, comprehensive policy scenarios, providing a means of assessing the implications of different future energy and emissions pathways for the Irish economy, Ireland's energy mix and the environment.

A central focus of this thesis is to explore the dynamics of the energy system moving towards a low carbon economy. This thesis develops an energy systems model to assess the implications of a range of energy and climate policy targets and target years. The thesis also compares the results generated from the least cost scenarios with official projections and target pathways.

Three specific time scale perspectives are examined in this thesis, aligning with key policy target time horizons. The results indicate that Ireland's short term mandatory emissions reduction target will not be achieved without a significant reassessment of renewable energy policy and that the current dominant policy focus on wind-generated electricity is misplaced. In the medium to long term, the results suggest that energy efficiency is the first cost effective measure to deliver emissions reduction; biomass and biofuels are likely to be the most significant fuel source for Ireland in the context of a low carbon future prompting the need for a detailed assessment of possible implications for sustainability and competition with the agri-food sectors; significant changes are required in infrastructure to deliver deep emissions reductions (to enable the electrification of heat and transport, to accommodate carbon capture and storage facilities (CCS) and for biofuels); competition between energy and agriculture for land-use will become a key issue.

The thesis also extends the functionality of energy system modelling by developing and applying new methodologies to provide additional insights with a focus on particular issues that emerge from the scenario analysis carried out. Firstly, the thesis develops a methodology for soft-linking an energy systems model with a power systems model to improve the interpretation of the electricity sector results in the energy system model. The soft-linking enables higher temporal resolution and improved characterisation of power plants and power system operation Secondly, the thesis

develops a methodology for the integration of agriculture and energy systems modelling to enable coherent economy wide climate mitigation scenario analysis. This provides a very useful starting point for considering the trade-offs between the energy system and agriculture in the context of a low carbon economy and for enabling analysis of land-use competition.

Units and abbreviations

AEEI	Autonomous Energy Efficiency Improvement
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CER	Commission for Energy Regulation
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
$CO_{2,eq}$	Carbon Dioxide equivalent
COP	Conference of the Parties
DAFF	Department of Agriculture, Fisheries and Forestry
DCENR	Department of Communications Energy and Natural Resources
DECC	Department of Energy and Climate Change
DECLG	Department of Environment, Community and Local Government
EC	European Commission
EEA	European Environment Agency
EPA	Environmental Protection Agency
ESD	Energy Service Demand
ESRI	Economic and Social Research Institute
ETS	Emissions Trading Scheme
ETSAP	Energy Technology Systems Analysis Program
EU	European Union
EVs	Electric Vehicles
GDP	Gross Domestic Product
GEC	Gross Electricity Consumption
GFC	Gross Final Energy Consumption
GHG	Greenhouse Gases
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt hours
ha	Hectare
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kt	Kilo tonne
ktoe	Kilo tonne of oil equivalent

MJ	Megajoules
Mp*km	Millions of passengers kilometre
Mt	Mega tonne
Mtoe	Mega tonne of oil equivalent
MW	Megawatt
MS	Member State
N_2O	Nitrous Oxide
NEEAP	National Energy Efficiency Action Plan
CH_4	Methane
Non-ETS	Non-Emission Trading Sectors
NREAP	National Renewable Energy Action Plan
OECD	Organization for Economic Co-operation and Development
O&M	Operation & Maintenance
PET	Pan-European TIMES
PJ	Petajoules
ppm	Part per million
RES-E	Renewable Energy Source - Electricity Sector
RES-H	Renewable Energy Source - Heating Sector
RES-T	Renewable Energy Source - Transport Sector
ROI	Republic of Ireland
SEAI	Sustainable Energy Authority of Ireland
TFC	Total Final Consumption
TPER	Total Primary Energy Requirement
TWh	Terawatt hours
UNFCCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
WEO	World Energy Outlook

1. Introduction

1.1. Background

Climate scientists have observed that greenhouse gas (GHG) concentrations in the atmosphere have been increasing significantly over the past century, compared to the rather steady level of the pre-industrial era. Carbon dioxide (CO_2) levels in the atmosphere in 2012 reached 394 parts per million (ppm), about 40% higher than in the mid-1800s (IEA, 2013a). Significant increases have also occurred in levels of methane (CH_4) and nitrous oxide (N_2O).

Greenhouse gases (GHG) in the atmosphere play a fundamental role in the regulation of the Earth’s energy balance and this unprecedented increase is the key driver for climate change. The Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC, 2013) recently quantified the increase in global mean surface temperature as 0.89 degrees Celsius (°C) over the period 1901-2012 and reconfirmed that this is driven with very high confidence by increased GHG emissions from human activities. Give the potentially dangerous impacts of continuing further on these trends, global awareness of the phenomenon of climate change is increasing and political action is underway to try and tackle the underlying causes. Although without the participation of some of the largest emitting countries, in 2009 141 Governments agreed at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties in Copenhagen in 2009 (COP-15) that the average global temperature increase, compared with pre-industrial levels, must be held below 2°C (UNFCCC, 2009). In order to reach that objective IPCC showed that global GHG atmospheric concentration must be stabilized at concentrations below 450 ppm of carbon-dioxide equivalent ($CO_{2,eq}$) by 2050, equivalent to reductions of 50% below 1990 levels (IPCC, 2007b).

Even in the absence of a wider international agreement on climate policy, some countries and regions have individually established GHG strategies with specific targets in place to investigate methods to reduce emissions. Up to date most of the policy focus has been on energy-related CO_2 emissions, which is understandable as they represent by far the largest source of emissions, namely 60% of global emissions and about 75% of Annex I[1] countries emissions (IEA, 2013a). Non-energy emissions – largely from agriculture, industrial processes and waste – have received less attention

[1] The Annex I Parties to the 1992 UN Framework Convention on Climate Change are: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, the Czech Republic, Denmark, Estonia, European Economic Community, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, the Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and United States.

by policy. Clearly however, as significant cuts will be made in energy-related CO_2 emissions, the role of non-energy emissions will grow in importance. It is therefore crucial that analysis and strategies with the focus on the climate mitigation are not restricted only to the energy system

The European Union led the ambition of reducing GHG emissions introducing the so-called 20-20-20 climate and energy package (EC, 2006a, 2009c; EU, 2009a) and aiming for reductions in GHG emissions of between 80% and 95% by the year 2050 (EC, 2011c). Among EU Member States (MS) Ireland has some unique challenges to achieve these targets. Regarding 2020 obligations, to Ireland was allocated a particularly challenging reduction target for GHG emissions not covered by the emission trading system, namely transport, residential, services and agricultural sectors. The target was set at 20% below 2005 levels while the EU average is 10%. Approximately half of these emissions are emitted by agriculture (EPA, 2013), a sector that is export driven and has little scope for emissions reduction (Schulte et al., 2011). Concurrently, the mitigation policy imperatives are made more difficult by the recent Ireland's history. Driven by economic expansion, also called the *Celtic Tiger*, the GHG emissions in the last two decades (1990-2010) have grown while EU emissions have declined (EEA, 2013). If we reference emission's targets against 1990 levels rather than 2005 levels, the result is a very different scale of challenge. The current climate framework for the year 2020, hence results for Ireland in only a 1.1% reduction compared to 1990 levels, while reductions of between 80% to 95% by 2050 relative to 1990, are equivalent to 84% and 96% relative to 2005 levels respectively.

Technologies can play an integral role in the movement to a low GHG economy. The integrated use of key technologies would make it possible to reduce dependency on imported fossil fuels, decarbonise electricity and end-use sectors, realise a sustainable future based on greater efficiency and a more balanced system which contributes to the development of new domestic economies. The potential benefit is clear for Ireland's energy system, which given the absence of significant domestic resources, imports approximately 88% of its energy needs from fossil fuels (Howley et al., 2012), when domestically there is an abundant potential for growth in renewable sources and energy efficiency. To facilitate this transition Ireland has committed to achieve by 2020 a 40% share of electricity, a 10% share of transport and a 12% share of heat from renewable sources (DCENR, 2010); and to deliver 20% energy efficiency savings (DCENR, 2009). With the exception of the target in the electricity sector that was well supported by policy instruments, Ireland is not on track to meet the targets agreed. There is therefore a need for new comprehensive policy instruments able to discern between the range of technical solutions available – from the supply to the demand side – and identify and support their optimal combination. In this context becomes clear the potential role of techno-economic model-based analysis able to generate robust policy scenarios able to identify the mix of cost optimal technology solutions and its cost implications.

This thesis seeks to inform Ireland's response to the challenges outlined in this section exploring a number of possible routes towards decarbonisation. The research questions to be addressed, the methodology and a brief outline of each chapter are presented in the following sections.

1.2. Focus of research and methods

This thesis uses techno-economic energy modelling instruments to explore the implications of the key challenges and decisions facing Ireland in energy and climate policy. It applies a combination of existing methodologies and newly developed unique methodologies to implement ad-hoc modelling tools to analyse Ireland's energy and also in some extent non-energy systems (e.g. agriculture). These methodologies are used to both examine baseline projections, and to assess the implications of emerging technologies and mobilising alternative policy choices such as carbon mitigation strategies. The focus of this research is therefore twofold. Firstly is to show how techno-economic modelling techniques can be applied in practice to analyse Irish energy and climate trends and provide robust, knowledge-based information to inform policy makers. Secondly is to contribute at the development of modelling techniques through the definition of new methodologies able to address some of the current limitations.

The key objectives to be addressed in the work are:

- Assess the techno-economic impacts of key energy and climate mitigation policies for Ireland's energy system.
- Provide insights and identify gaps on current energy trends and policies with respect to arriving at a low carbon economy by 2050.
- Evaluate the implications of different mitigation pathways and policy targets on transitioning to a low carbon economy by 2050.
- Identify emerging technologies and new commodity trends in the end-use sectors.
- Quantify the role of renewable energies and energy efficiency in future energy systems.
- Analyse the consequences for energy security, sustainability and land usage of future energy systems.
- Asses the implications of high shares of intermittent electricity generation in a low carbon power generation sectors.
- Examine the role of agriculture in achieving climate mitigation targets.

A large range of energy models has been developed in the last decades by the scientific community. These models use different approaches that vary in terms of model starting point and on the type of questions they are designed to answer. Most energy models can be classified as bottom-up techno-economic models or as top-down macro-economic models (Böhringer, 1998;

Greening and Bataille, 2009; Jebaraj and Iniyan, 2006). The top-down approach represents the energy systems and technologies as aggregate economic variables; accordingly, technological change can be seen as a price-induced substitution (Carraro and Galeotti, 1997). They are often used to address the feedback between the energy sector and other economic sectors, and between the macroeconomic impacts of climate policies on the national and global scale (IPCC, 2007b).
In contrast, bottom-up models are driven by the interactions of energy and technological change. They are generally written as mathematical programming problems and generally focus on the engineering energy-gains evident at the microeconomic level and detailed analysis of the technical and economic dimensions of specific policy options (Gargiulo and Ó Gallachóir, 2013; IPCC, 2007b). The basic difference is that each approach represents technology in a fundamentally different way. The bottom-up models, also called *technology rich* models, capture technology in the engineering sense, but are generally not readily able to take account of price changes or of macroeconomic effects. In contrast, the role of technology and impacts of technology change are generally not captured directly in top-down models, but are rather represented by the shares of the purchase of a given input in intermediate consumption, in the production function, and in labour, capital, and other inputs (IPCC, 2007b). Examples of top-down models are i) macro-economic models, e.g. HERMES (Bergin et al., 2013) and NIGEM (NIGEM); and ii) computable general equilibrium models (CGE), such GEM-E3 (GEM-E3), GTAP (GTAP), GEMINI-E3 (Bernard et al., 2008; Bernard and Vielle, 2009). Examples of bottom-up model are hence i) integrated energy system simulation models[2], as The Integrated Model to Assess the Global Environment (IMAGE) and Long range Energy Alternatives Planning System (LEAP) applications (LEAP); and .ii) dynamic energy systems optimization models[3], as the Energy Technology Perspectives (ETP)(IEA, 2012a), the Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) (IIASA-ECS; Messner and Strubegger, 1995) and MARKAL-TIMES modelling applications (IEA-ETSAP, 2011). There is also a third category, the hybrid models, in which bottom-up and top-down models are combined. Examples of these models are PRIMES (NTUA, 2011) and WITCH (Bosetti et al., 2006; Bosetti et al., 2007).

This thesis chose primarily a bottom-up energy system modelling approach with a focus on the medium (from 2020) to the long term horizon (to 2050), based on the TIMES (The Integrated Markal Efom System) modelling framework. This approach was selected for its capability of assessing simultaneously implications for i) the energy mix (including fuels and technologies) and energy dependence, ii) (certain areas of) the economy (energy prices, investments in the energy

[2] They simulate how future energy demand and supply trends will evolve based on projected trends of energy drivers.
[3] They provide energy system configurations optimised for example (depending on the formulation) to least cost.

system, marginal abatement costs, etc.), and iii) the environment (greenhouse gas emissions, etc.); and moreover due to the previous absence of models of its kind in Ireland. The research work has therefore directly contributed to the development and calibration of a new energy system model, named the Irish TIMES model. Irish TIMES is a full energy system model of Ireland by University College Cork (UCC) under the Climate Change Research Programme 2007 – 2013, in collaboration with the Economic and Social Research Institute (ESRI), Teagasc, University College Dublin (UCD), E4SMA and Kanors.

TIMES is a widely applied techno-economic model generator for local, national or multi-regional energy systems, developed and supported by the ETSAP (Energy Technology Systems Analysis Programme) community, an implementing agreement of the International Energy Agency (IEA-ETSAP, 2011)[4]. TIMES combines all the advanced features of MARKAL (Market Allocation) models (Fishbone and Abilock, 1981), and to a lesser extent of EFOM (Energy Flow Model Optimization) models (van der Voort, 1984). It uses linear programming optimization to provide a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. The objective function to maximize is the overall surplus. This is equivalent to minimizing the total discounted energy system cost while respecting environmental and many technical constraints. This cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon. The full technical documentation of the TIMES model is available in Loulou et al. (2005).

The usefulness and strengths of TIMES can be gleaned from its popularity. It is currently in use in 177 institutions across 69 countries, therefore has the significant advantage that the results can be compared with other countries. A selection of applications and case studies covering the period 2005–2010 are summarized in (IEA-ETSAP, 2008, 2011). A key characteristic of this modelling tool is that it maintained, improved and updated through a collaborative research initiative co-ordinated by the IEA-ETSAP. 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 particularly important for the energy sector, which has such large capital investments with long project lifetimes. The challenge of de-carbonizing the energy system is an enormous and expensive one, so the insights that a TIMES model provides 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 also provides indicative results for the marginal carbon abatement price required to achieve certain reductions which can in turn be useful to inform policy design.

[4] See <http://www.iea-etsap.org/web/index.asp> for more details.

Like all energy models, TIMES has also 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, research should aim to make improvements. The following list presents the main limitations:

- *Time resolution*: Long term energy systems model are generally inadequate to capture daily supply and demand curves. Even though there are no limitations on the number of timeslices in TIMES models; it would become computationally unwieldy if the model had to make decade long decision as well as hourly decisions.
- *Macro-economic assumptions:* 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:* TIMES models are generally not able to take account feedbacks between the output of the energy system analysis and the macro-economy.
- *Behaviour:* TIMES models have 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.

This thesis addresses head on the challenge that single modelling tools cannot address all aspects of energy systems with great detail. It develops new methodologies which involve the use of multiple modelling tools working in conjunction, rather than trying to incorporate them all into one comprehensive model. In particular, these *soft-linking* methodologies involved the use of dedicated power system models and agricultural partial equilibrium models working in conjunction with the energy system model.

In the first case, the methodology employed centred on modelling the unit commitment and dispatch of the electrical power system, derived from an energy systems model, in a dedicated power systems model to provide insight and feedback to the energy systems model. In this analysis the PLEXOS power systems modelling tool is used to build and solve a model of the Irish power system. PLEXOS is a commercial modelling tool provided by Energy Exemplar[5] which is used for electricity market modelling and planning worldwide. The tool solves hourly or half-hourly chronological problems using deterministic or stochastic programming techniques that aim to minimize an objective function or expected value subject to the modelled cost of electricity dispatch and to a number of constraints including availability and operational characteristics of

[5] See <http://www.energyexemplar.com/> for more details.

generating plants, licensing environmental limits, and fuel costs, operator and transmission constraints.

In the second case the methodology involved the use of detailed agricultural modelling tools, the top-down sector/market based FAPRI-Ireland model and the bottom-up Farm-Level Agricultural Greenhouse Gases Simulation (FLAGGS) model, to provide improved understandings of the relation between energy and the agricultural systems. The FAPRI-Ireland model[6] is a set of econometric, dynamic, multi-product, partial equilibrium commodity models of the Irish agriculture sector which analyse the effect of policy changes on economic indicators such as the supply and use of agricultural products, agricultural input expenditure and agricultural sector income (Donnellan and Hanrahan, 2006; Donnellan et al., 2013). The FLAGGS model is a farm-level model which maximises sectoral gross margins, subject to farm and sector constraints (Breen et al., 2010a). The methodology uses projections of animal numbers, input usage volumes (e.g. fertiliser, feed, fuel, energy), GHG abatement techniques and other indicators produced by FAPRI and FLAGGS to input the Irish TIMES model, by mean of a dedicate new developed agricultural module.

1.3. Thesis in brief

In addition to this introductory chapter, this thesis is divided into two parts, an applied section and a development section. These two sections complement each other as the research issues raised in the first part are addressed in the second. The applied section (Part I) is composed of three chapters (Chapters 2, 3 and 4) and the development section (Part II) is divided into two chapters (Chapters 5 and 6). Chapter 7 concludes.

The key question underpinning the research presented in Part I is as follows:

What technology choices and emission reduction targets are cost-optimal for Ireland in the context of a low carbon economy to 2050?

This question is motivated by the need to deepen the understanding of the dynamics of the energy system moving towards a low carbon economy. As shown throughout this thesis, deep GHG emissions reductions involve radical transformations across the whole energy system, from its supply infrastructures to demand sectors. A least cost modelling approach provides useful metrics and indications to identify key drivers and to support both policy makers and stakeholder in

[6] The FAPRI-Ireland Partnership is a research affiliation between Teagasc (The Irish Agriculture and Food Development Authority) and the Food and Agricultural Policy Research Institute (FAPRI) based at the University of Missouri. See <http://www.tnet.teagasc.ie/fapri> for more details.

identifying cost optimal strategies. Part I assesses in particular the implications of a number of policy targets and targets years, analysing results from the least cost scenarios and comparing with the official projections and targets.

This thesis assesses the implications of the current EU climate framework for 2020 in Chapter 2, where the energy system model of Ireland (Irish TIMES) is developed to examine the implications of Ireland's target for greenhouse gas emissions reductions – particularly in non-ETS sectors as stipulated in the Effort Sharing Decision 2009/406/EC – and to assess consequences of lower GHG emissions reductions from agriculture. The chapter provides indications of the energy trends in the end-use energy sectors, pointing to increased electrification of heating in buildings and biofuels in transport. Results point to the need of reconsider the current renewable energy targets in particular in transport and thermal energy and indicate that the target set for Ireland is far from a cost optimal target.

Chapter 3 presents results from energy system model scenarios to the year 2050, assessing the technical feasibility of the EU commitment of reducing GHG emissions between 80% and 95% relative to 1990 levels. Scenarios identify cost optimal changes in energy technology, energy efficiency and renewable energy which are relevant across each sector of the economy. The results also examine the implications of extending current policy – which focuses on separate targets between ETS and Non-ETS sectors – and highlights that the achievement of GHG reductions between 80% and 95% also requires contributions from non-energy sectors – largely agriculture – not explicitly modelled in Irish TIMES. A new methodology to assess potential emissions reduction in the agriculture sector is analysed separately in detail in Chapter 6.

Chapter 4 presents techno-economic modelling results from a different perspective. This chapter does not scrutinize existing policy targets and commitments; rather, it discusses elements for new policy developments for the year 2030 in the context of an overall 80% reduction in CO_2 emissions by 2050. The scenarios investigate the potential impacts of a range of GHG emissions reduction pathways for 2030 and seek to determine appropriate targets for renewable energy, energy efficiency and sectoral emissions that are consistent with delivering the overall mitigation target at least cost. It discusses implications to be considered in the development of new policy frameworks, such as the possible consequences of reduced availability of sustainable bioenergy for international trade, the implications for energy security and for land use competition between energy and the agricultural system.

The key research question underpinning Part II is as follows:

How can techno-economic modelling techniques be improved and developed to better account for the Irish policy context?

This research question is motivated by the aim of defining new methodologies which may contribute to shed light on the issues highlighted in Part I. The scenario analysis showed that mitigation pathways generally involve increased electricity demand in the end-use sectors associated with the decarbonisation of the electricity sector. The decarbonisation is generally driven by a marked increase in non-dispatchable wind generation and the possible operational implications for such a generation system are evaluated in Chapter 5. This chapter develops a soft-linking methodology which employs a detailed modelling of the unit commitment and dispatch of the electrical power system, derived from the energy systems model. The motivation for this methodology is to verify and gain insight into electricity sector results from energy systems models (Irish TIMES) using a power systems model (PLEXOS). The results demonstrate that in the absence of key technical constraints, an energy systems model can potentially undervalue flexible elements – such as storage – underestimate wind curtailment and overestimate the use of base-load plants.

The other key issue highlighted in Part I is agriculture and its mitigation potential. The analysis presented in Chapters 2 to 4 do not model GHG emissions from agriculture but do take them into account by building scenarios for emissions reduction in the energy system using different targets that use different exogenous emissions growth assumptions for agriculture. Chapter 6 therefore builds a case study for the integration of agricultural systems modelling and energy systems modelling. The motivation is to assess the elements (techniques and technologies) for emissions reduction in the agricultural sector. The methodology implies the development of an agriculture module working in conjunction with the Irish TIMES energy system model and driven by the FAPRI-Ireland model, a dynamic partial equilibrium model of the Irish agriculture sector. The results show the value of having a modelling tool able to generate projections where agriculture and energy are integrated and respond in conjunction to abatement strategies.

Chapter 2, 3 and 5 have been published as papers in peer-reviewed scientific journals (Chiodi et al., 2013a; Chiodi et al., 2013b; Deane et al., 2012a). Chapter 4 and Chapter 6 have been submitted to scientific journals and are currently under review. The chapters are presented as the text submitted for review with minor modification and formatting changes.

1.4. Role of collaborations

This thesis is based on my own work and was written by me, but collaborations had an important role in this research. All aspects of this thesis have received advise and been reviewed by Dr. Brian Ó Gallachóir as research supervisor. Several contributions were also received from the colleagues of the UCC's Energy Policy and Modelling Group and the partners of the Irish TIMES project. A full list of my collaborations and publications is contained in section 1.5.

The chapters presented in Part I and II of this thesis are based on journal papers (three published, two under review) for which I was the lead author with a number of co-authors. This list specifies the extent of my contribution to these chapters.

- **Chapters 2, 3:** I contributed to the development of the computer model (both chapters are based on the same model version) – comprising the update of a number of model inputs (e.g. renewable potentials, demand projections, demand elasticities, user constraints, etc.), the model debugging and the scenario files implementation –; the results production, including figures and tables; and the preparation of manuscript for publication.
- **Chapter 4:** I led the Irish TIMES model development, implementing and debugging a number of new model inputs, as energy prices, demand projections, bioenergy potentials and costs, user constraints and sectorial techno-economic assumptions. I therefore ran the model, produced the results and prepared the manuscript for publication.
- **Chapter 5:** I co-led this research activity, setting the Irish TIMES model configuration for the analysis, extracting the relevant information from the energy systems model and developing a procedure to facilitate the data transfer to power systems model. I contributed moreover to the data control, the consistency cross-check of the power systems model and I wrote the initial paper draft.
- **Chapter 6:** The development of the agriculture module in TIMES is solely my own work, but uses outputs from the FAPRI-Ireland and FLAGGS models. I moreover ran the model, produced the results and prepared the manuscript for publication.

The role of each co-author in the chapters is as follows. Manuscript suggestions and feedback was provided by Dr. Brian Ó Gallachóir on all chapters. Maurizio Gargiulo supported me in the model development of chapters 2, 3 and 4; and contributed to the definition of the methodology of chapters 5 and 6. Dr. J.P. Deane supported me with the data collection and elaboration in chapters 2, 3, 5 and 6; and co-led the research activity of chapter 4, developing the power systems model. Dr. Ullash K. Rout and Dr. Denis Lavigne contributed to the model calibration in chapters 2 and 3, while Dr. Fionn Rogan developed and co-wrote the decomposition analysis of chapter 3. Trevor Donnelan, Kevin Hanrahan and Dr. James Breen provided advice in chapter 6 on inputs for the agriculture module and on aspects of FAPRI-Ireland and FLAGGS models.

1.5. Thesis outputs

Journal Papers

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Part I – Energy scenarios for Ireland

2. Modelling the impacts of challenging 2020 non-ETS GHG emissions reduction targets on Ireland's energy system

Abstract

This paper focuses on Ireland's ambitious target for 2020 to reduce greenhouse gas (GHG) emissions by 20% below 2005 levels for sectors not covered by ETS (Non-ETS). Ireland is an interesting case study due to the role of agriculture (a particularly challenging sector with regard to GHG emissions reduction), that represents 29% of Ireland's GHG emissions compared with less than 10% for the EU. The analysis is carried out with the Irish TIMES model, a bottom-up energy systems modelling tool with detailed characterization of Ireland's energy system. The paper uses scenario analysis to provide pathways that demonstrate how Ireland can meet the non-ETS target at least cost. The paper considers the impacts (in terms of different technology choices and higher marginal abatement costs) arising from higher targets for the energy system to compensate for growth in agriculture activity and low mitigation potential in that sector. The results point to a need to reconsider Ireland's renewable energy focus, with a need for increased effort in renewable transport and renewable heat in particular. The results also point to significant electrification of residential heating. The results also point to a high marginal abatement cost (€ 213/tCO_2), which challenges the analysis carried out at EU level to establish Ireland's non-ETS target.

Nomenclature

	Description	Sector
ETS	Emission Trading Scheme	Industry (large point source emitters), Power generation, Refining.
Non-ETS	Non-Emission Trading Scheme	Agriculture, Industry (the part not included as ETS), Residential, Services, Transport, Waste.

2.1. Introduction

Due to growing concerns regarding the anthropogenic interference with the climate system, the European Union (EU) is committed to limiting the rise in global annual mean surface temperature to 2°C above pre-industrial levels. The latest Inter-governmental Panel on Climate Change (IPCC) Assessment Report shows that in order to reach that objective, global emissions of greenhouse gases must peak by 2020, while by 2050, global greenhouse gas emissions should be reduced by at least 50 % below their 1990 levels (IPCC, 2007b). The EU, in order to meet this objective, has set ambitious greenhouse gas (GHG) emission reduction targets for 2020 (EU, 2009a, b), even in the absence of a wider international agreement on targets for GHG emissions reduction. In the short term the following targets apply within the EU: GHG emissions should be reduced at least to 20% below their 1990 levels by 2020. Approximately half of these emissions (EEA, 2010), essentially large point source emitters (from part of industry, power generation and transformation), are to be regulated under the European Trading Scheme (ETS) (through Directive 2009/29/EC). The remaining greenhouse gas emissions, termed Non-ETS emissions, are currently capped at EU and at Member State (MS) level through Decision 2009/406/EC. The target for ETS emissions is to be at least 21% below 2005 levels by 2020. Individual companies are obliged to contribute to meeting this target through a cap and trade emissions trading scheme. The Non-ETS EU target is a 10% reduction relative 2005 levels and this target is shared out amongst Member States under an effort sharing decision. Individual Member State targets range from a 20% decrease to a 20% increase relative to 2005 by 2020. The Non-ETS targets for individual Member States were determined via a two stage process, using a number of modelling tools (EC, 2008). Firstly, the least cost pathway for meeting the EU target 10% reduction was established, pointing to initial individual Member State emissions reductions. In this ‘cost efficient policy case’ Ireland’s Non-ETS GHG emissions reduction reaches 17% below 2005 levels (Table 4 of SEC(2008) 85 Vol. II). Secondly the ability of individual Member States to invest in mitigation was taken into account to ensure an equitable distribution of effort. Ireland had a relatively high level of GDP per capita in 2005 and was thus allocated a target to achieve a 20% reduction relative to 2005. The analysis suggests that the Non-ETS target can be achieved at a carbon cost of €40-€50/tonne of CO_2.

The scenarios developed in this paper fulfil both Ireland’s ETS and Non-ETS targets, but the main focus is on the energy dimension of Ireland’s non-ETS emissions reduction target as this target represents the most difficult challenge facing Ireland’s energy system in the short term (Walker et al., 2009). Ireland also has a number of targets for energy efficiency (DCENR, 2009) and for renewable energy (DCENR, 2010), but in the absence of a significant reduction in agriculture related GHG emissions, these are insufficient to meet the 20% Non-ETS target.

The purpose therefore of this paper is to determine how Ireland can meet its GHG emissions reduction targets to 2020 at least cost, and to quantify the costs involved. The main focus is on energy-related emissions in sectors outside of emissions trading (i.e. non-ETS emissions). Despite the policy imperative, achieving reductions in energy-related CO_2 emissions in non-ETS sectors has received very limited attention (Böhringer et al., 2009; Harmsen et al., 2011; Tol, 2009) in academic research and this paper addresses this knowledge gap. This paper models technical energy systems pathways to deliver target emissions reductions in a least cost manner, using partial equilibrium modelling. It does not address the policy instruments which are required to achieve the technology solutions or address the behavioural challenges to be overcome in order for these technologies to be developed.

This paper is structured as follows. Section 2.2 introduces the reasons why Ireland was chosen as a case study. Section 2.3 presents and discusses the methodology, introduces the model used to undertake this analysis and describes the scenarios used. Section 2.4 presents and discusses results, while Section 2.5 concludes with a brief discussion and overview of results.

2.2. Context

2.2.1. Ireland's energy sector

Throughout the 1990s and early 2000s economic growth in Ireland was particularly strong, especially from 1993 onwards. This resulted in Gross Domestic Product (GDP) in 2007 being almost three times that of 1990. In 2008 the economy experienced a downturn which deepened into 2009. Despite this recent economic recession, over the period 1990 – 2009 Ireland's total annual primary energy requirement grew in absolute terms by 57% (versus 70% in the period 1990-2007) (Howley et al., 2010; Howley et al., 2008).

This increased energy demand was supplied mainly by fossil fuels, which accounted for 95% of all energy used in Ireland in 2009. Oil is the dominant energy source with a share of 52% in 2009 (was 47% in 1990), followed by natural gas with a share of 29% and coal (8.5%). Renewable energy passed from a low base of 1.8% of primary energy requirement, to about 4.5%, largely driven by increase in wind energy capacity.

The rapidly increasing consumption of energy in Ireland, combined with the decreasing domestic production, has resulted in a significant increase in energy imports in recent years. Ireland exhibits a significant dependence on imported fossil fuels, which accounted for 89% in 2009. The UK is the major source of oil and natural gas for Ireland (IEA, 2012b, c).

Categorising energy use by its mode of application, in 2009, transport accounted by its own for about one third of energy use (the share was 34%), thermal (includes residential, services and industry sector) for another 34%, while energy use for electricity generation for 32%. Since 2001 gas has become the most important fuel for electricity generation in Ireland, gradually replacing oil and coal. In 2009 this resulted with a generation share of 57%, followed by coal and peat, 17.6%

and 11.8% respectively. Recent years showed a rapid expansion of renewable generation, largely dominated by wind energy. Renewable energy passed from a low basis of 1.9% in 1990 to about 3.5% in 2005. This progression continued in 2009 (7.7% of generation share) and 2011 (11.5% of which 8.4% wind) (Howley et al., 2010; Howley et al., 2012; Howley et al., 2006).

2.2.2. Ireland's policy context

A key focus of Ireland's energy policy is the implementation of the National Energy Efficiency Action Plan (NEEAP) and the National Renewable Energy Action Plan (NREAP) that provide Ireland's contribution to EU targets of achieving a 20% improvement in energy efficiency and a 20% renewable energy share of gross energy consumption in 2020. Ireland's NREAP establishes individual sectoral renewable targets for heat, transport and electricity, namely 12% of heat from renewable sources (12% RES-H), 10% for road and rail transport (10% RES-T) and 42.5% of electricity consumption from renewables (42.5% RES-E) by 2020. An overall 20% reduction[7] (33% in public sector) in energy demand is expected through energy efficiency measures. All these targets contribute to efforts to an overall 20% emission reduction.

Recent energy forecasts (Clancy et al., 2010) for Ireland suggest however that if the energy efficiency targets and these individual modal renewable energy targets are met, Ireland's overall energy-related CO_2 emissions will be reduced by 26.4% below 2005 levels by 2020, comprising a 35% reduction of energy-related CO_2 emissions in ETS sectors and a 17% reduction in Non-ETS sectors.

2.2.3. Ireland's emissions balance

This paper focuses on Ireland which is an interesting case study for a number of reasons. Firstly, one distinguishing characteristic of Ireland is the significant share of GHG emissions arising from agriculture. Within the EU-27 in 2005 energy accounted for 79% of GHG emissions and agriculture was responsible for approximately 11% (9.5% non-energy). In Ireland, however, as shown in Figure 2-1, energy accounts only for 66% of emissions (green areas), while agriculture has an important role on the emissions balance contributing to approximately 28.5% (27.1% non-energy related) of total GHG emissions (EEA, 2010). About 56.6% (in terms of $CO_{2,eq}$) of these emissions are released as methane (CH_4), while 37.9% as Nitrous Oxide (N_2O) (EPA, 2012).

[7] As compared to average energy use over the period 2001 – 2005

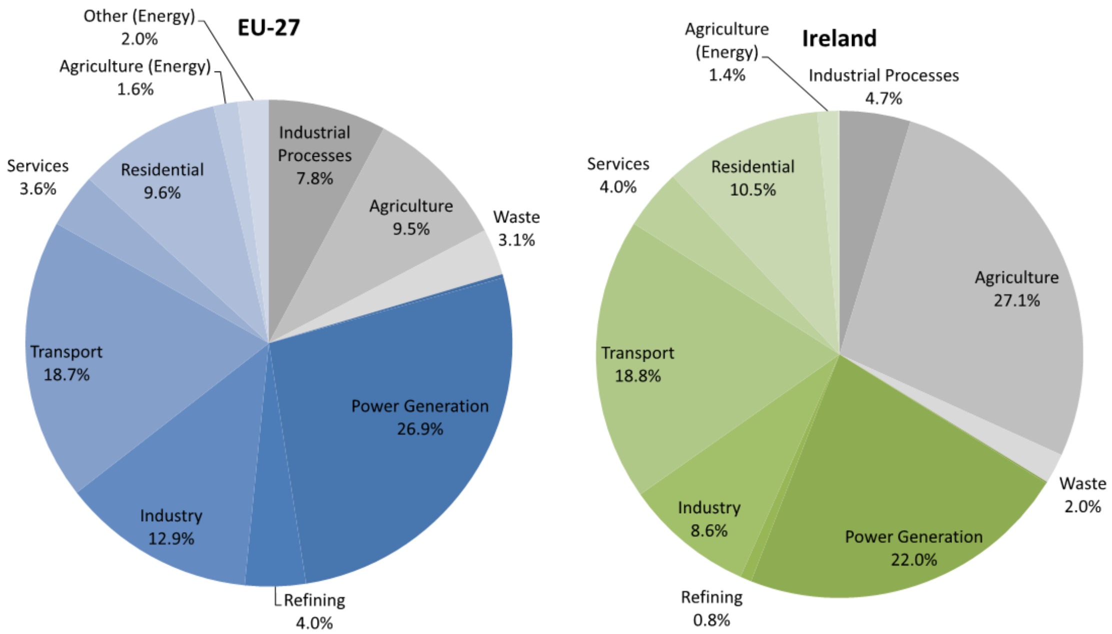

Figure 2-1. Comparing 2005 GHG emissions share in EU-27 and Ireland

The role of agriculture is more pronounced in the context of the target for Non-ETS emissions. In 2010, agriculture accounted for 42.5% of Ireland's Non-ETS emissions. These emissions levels are strongly related to the land use in the country and the nature of its activities. The agriculture sector occupies approximately 61% of total land area and agri-food contributes approx. 7% to Ireland's economy (in terms of GDP), representing Ireland's largest indigenous industry. The largest contribution to GHG emissions is from the beef and dairy sector, most of which (over 80%) is exported. Recent projections (EPA, 2011b) indicate that, in order to meet the targets of agricultural policy, the Food Harvest 2020 Policy (DAFF, 2010), GHG emissions from agriculture in Ireland will be reduced by only 4.4% in the period 2005-2020, passing from 18.7 to 17.8 Mt of equivalent CO_2. Beef and dairy farming is particularly challenging in terms of climate mitigation with very few options for emissions reduction (Schulte et al., 2012), hence, it is very difficult to reconcile growth in beef and dairy farming with a low carbon economy. Set against this backdrop it is reasonable to assume that the energy system (Non-ETS sectors, other than agriculture, comprise of transport, residential, services, waste and part of industry[8]) may face a Non-ETS emissions reduction target greater than 20% to compensate for agriculture not achieving a 20% reduction.

This paper does not model GHG emissions from agriculture but does take them into account by building scenarios for emissions reduction in the energy system using different targets that use different exogenous emissions growth assumptions for agriculture.

The second distinguishing feature of Ireland is that emissions in many sectors rose sharply (for example a doubling of emissions from transport) over the past decade (EEA, 2010), driven

[8] About 14% in 2005

primarily by strong economic growth. This emissions growth in the period 1990 - 2005 that Ireland has experienced is in marked contrast to other industrialised countries between 1990 and 2005, as evident from EU-27 emissions figures that decreased by about 8%. This contextual factor also makes the achievement of the 20% Non-ETS emissions reduction target very challenging.

Thirdly, Ireland's energy system exhibits some unique characteristics compared with other EU Member States. The role of industry is relatively low (on-site CO_2 emissions in industry representing 12.8% of total energy-related CO_2 emissions in 2005), while the role of transport is relatively high (32% of energy-related CO_2 emissions in 2005). Irish industry is characterized by low energy intensity manufacturing, comprising food and beverage, ICT and pharmaceutical production.

2.3. Methodology

In recent years energy modelling has been used to provide instruments to policy makers for decision making on GHG emissions reduction. Many detailed assessments in various regions around the world have been undertaken and are summarized in Gargiulo and Ó Gallachóir (2013), Mendes et al. (2011), Das et al. (2007). Previous modelling work on GHG emissions mitigation packages has been undertaken at global levels in IEA studies (IEA, 2010) and within EU FP7 projects (SECURE). The TIAM WORLD model has been used for scenarios assessment (Ekholm et al., 2008) and for stochastic analysis (Labriet et al., 2012; Loulou et al., 2009; Syri et al., 2008) to analyse the role of nuclear energy (Vaillancourt et al., 2008), of carbon capture and storage (CCS) and renewables (Føyn et al., 2011; Koljonen et al., 2009). At European level, the Pan European TIMES model has be used to analyse security of energy supply scenarios in the region (Kanudia et al., 2013); to investigate the role of certain technologies such as CCS (Ramírez et al., 2011) and to evaluate the effects of climate and energy policy on the future structure of the European energy system (Blesl et al., 2010). Medium-term modelling of the EU 2020 climate energy policy package has been undertaken using the TIMES model to establish whether the individual allocations to Member States of renewable energy and emissions reduction delivers a least cost solution at EU level (Gargiulo et al., 2008; Giannakis, 2007). The TIMES model has also been used at Member State level to model the impacts of energy efficiency on emissions reduction (Blesl et al., 2007), to model the cost optimal way of meeting renewable energy targets (Ó Gallachóir et al., 2012) and long term emissions reduction targets (Chiodi et al., 2013b). National level studies have used MARKAL and TIMES models to investigate carbon constrained cost optimal solutions for UK (Anandarajah and Strachan, 2010) and for France (Assoumou and Maïzi, 2011).

2.3.1. Modelling approach using Irish TIMES model

The tool used to carry out this analysis is the Irish TIMES model, the Irish energy system model, developed with TIMES (The Integrated MARKAL EFOM System) energy systems modelling tool. TIMES is a widely applied linear programming tool supported by ETSAP (Energy Technology Systems Analysis Program), an Implementing Agreement of the International Energy Agency (IEA).

TIMES is an economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but may also be applied to study individual sectors in detail. TIMES computes a dynamic inter-temporal partial equilibrium on integrated energy markets. The objective function maximizes the total surplus. This is equivalent to minimizing the total discounted energy system cost while respecting environmental and many technical constraints. This cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon. TIMES combines all the advanced features of MARKAL (Market Allocation) models, and to a lesser extent of EFOM (Energy Flow Model Optimization) models. The equations of the initial MARKAL model appear in Fishbone and Abilock (1981) and numerous improvements of the model have been developed since then for various applications (Kanudia et al., 2005; Kanudia and Loulou, 1999; Labriet et al., 2005). The full technical documentation of the TIMES model is available in (Loulou et al., 2005). The TIMES/MARKAL family of models is widely used internationally and therefore has the significant advantage that the results can be compared with other countries.

The Irish TIMES model has been developed to build a range of medium (to 2020) to long term (to 2050) energy and emissions policy scenarios in order to inform policy decisions. Irish TIMES was originally extracted from the PET[36] model (Pan European TIMES model that includes EU27, Iceland, Norway, Switzerland and Balkans countries) and then updated with local and more detailed data and assumptions specific to Ireland. The PET model in turn was developed under the EU supported NEEDS (New Energy Externalities Development for Sustainability) project (NEEDS). The model has been subsequently expanded and improved within Intelligent Energy - RES2020 (Renewable Energy Sources, "Monitoring and Evaluation of the RES directives implementation in EU27 and policy recommendations for 2020)(RES2020) project to generate a detailed and accurate quantitative analysis of the targets for the share of renewables in the EU primary energy supply in 2020 (Giannakis, 2007). The PET structure has more recently been developed and enriched within REALISEGRID (REseArch, methodoLogIes and technologieS for the effective development of pan-European key GRID infrastructures to support this achievement of a reliable, competitive and sustainable electricity supply)(REALISEGRID) and REACCESS

(Risk of Energy Availability: Common Corridors for Europe Supply Security)(REACCESS) projects carried out with EU FP7 support to provide improved analysis on transmission infrastructure and energy security of supply.

The Irish TIMES model has a time horizon that ranges from 2005 to 2050, with time resolution of four seasons with day-night time resolution, the latter comprising day, night and peak time-slices. It is driven by exogenous macro-economic forecasts (Bergin et al., 2010) as demand drivers in conjunction with GEM-E3's[9] industry Autonomous Energy Efficiency Improvement (AEEI)(GEM-E3). Fuel prices assumptions for conventional fuels are based on IEA's reference scenario in World Energy Outlook 2008 Report (IEA, 2008).

The Irish energy system is characterized and modelled in terms of its supply sectors, its power generation sector, and its demand sectors as shown in Figure 2-2. The supply component is characterized by fuel mining, primary and secondary production, exogenous import and export. The power generation sector includes the combined heat and power generation; and different voltage levels (high/medium/low) which accounts the different grid transmission losses. The demand component is driven by 60 different energy service demands (ESD), namely 20 for the residential sector, 12 for services, 13 for industry, 13 for transport, 1 for energy-related agriculture and 1 for other non-energy. More details on model structure and assumption can be found in Chiodi et al. (2013b).

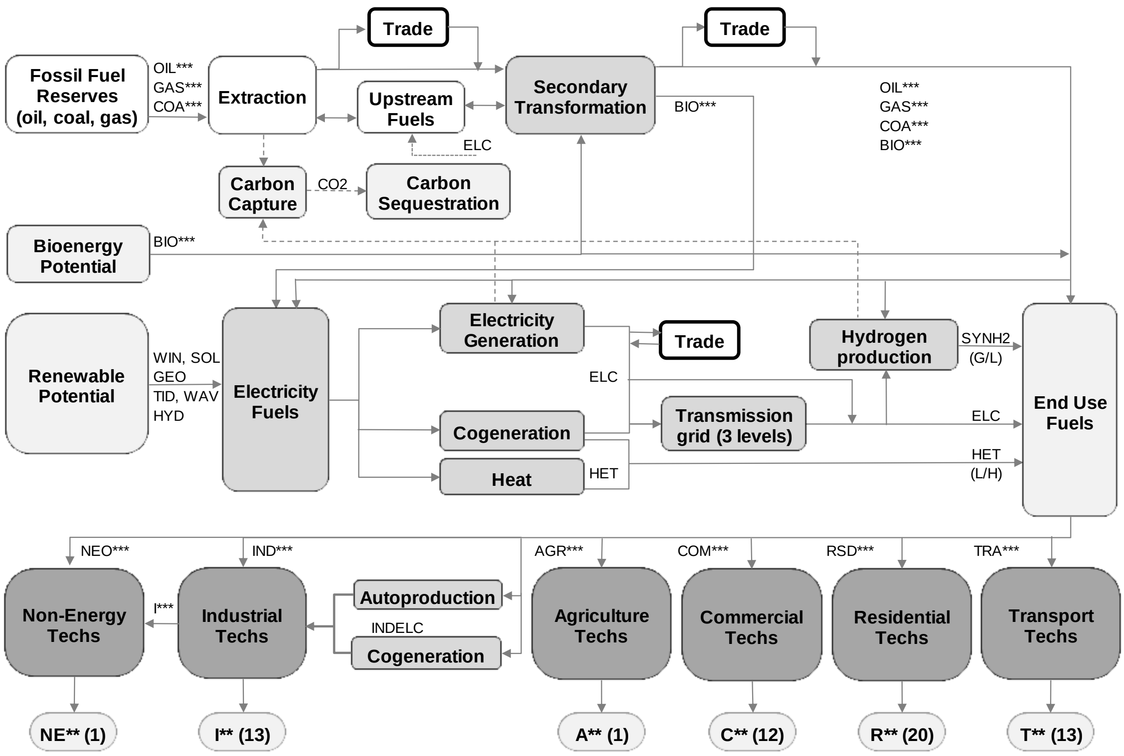

Figure 2-2. Irish TIMES Reference Energy System

[9] GEM-E3 acronym stands for *General Equilibrium Model for Economy, Energy and Environment*.

The core model contains a large database of energy supply-side and demand-side processes (over 1600), in which commodities (about 700) are transformed, transported, distributed and converted into energy services. The database contains technical data (e.g. thermal efficiency, capacity), environmental data (e.g. emission coefficients) and economic data (e.g. capital costs) that vary over the entire time horizon. Between demand sectors, higher levels of detail are used in the residential sector, in the transport sector and in the industry sector, in which explicit technologies have been represented for most of the end use sectors; while aggregate (black-box) end-use processes are defined for the energy-related agriculture and the non-energy industry sectors. For these processes flexible input fuel shares are included to provide options to the model of reducing GHG emissions.

Technologies are distinguished between existing and new technologies. The existing technologies are calibrated to reproduce the current consumption levels and stocks, based on energy balances. The alternative technologies database contains all currently available technology options plus a large number of appliances which are likely to be available in future. For each of them technology learning may be assumed in reducing costs and/or increasing efficiency. An extract of the residential heating database for urban existing dwellings is presented in Table 2-1.

Efficiency measures, such energy conservation for the existing building stock (i.e. additional building insulation) are modelled as additional proxy technology options (with associated costs) and are available options in the least-cost optimization. The use of smart metering systems is not explicitly modelled.

The cost assumptions for renewable energy technologies are from the values in the PET model used in the Intelligent Energy-RES2020 project (RES2020) and where available, data changes were made based on updated information. In the case of wind and ocean energy, the data used in the model are based on analysis of international trends (including wind turbine capital costs) and costs specific to Ireland (for example grid connection costs) (Chiodi, 2010; Ó Gallachóir et al., 2010d).

On the supply side, given the importance of renewable energy for the achievement of mitigation targets, Ireland’s renewable potentials were updated and based on the most recently available data. The total resource capacity limit for domestic bioenergy (considering both available resource and technical potential) has been set at 1,230 ktoe for the year 2020, based on the estimates from the Bioenergy Strategy Group (2004) and Smyth et al. (2010). The potential for each individual commodity is summarized in Table 2-2. Commodities like biogas or woody biomass are directly consumed between different energy sectors, while secondary productions steps are required for the production of bioethanol from starch crops, biodiesel from rape seeds and biomethane from woody biomass or waste.

Based on results from ESBI and UCD (2004), Tanbke and Michalowska-Knap (2010) and on current development trends of approved, licensed and planned projects (EirGrid), the upper capacity limit of wind energy been quantified in 5.3 GW by the year 2020 for onshore wind and 1 GW for offshore. The ocean energy resource potential in Ireland is aligned with the ocean energy roadmap (SEAI, 2010b), while the potential for additional large hydro plants is limited but further deployment of small hydro plants is possible (ESBI and ETSU, 1997). The maximum capacity for hydro energy has been set at 224 MW for large plants and at 250 MW for run of river plants. The existing 292 MW pumped hydro storage plant is also modelled. The use of solar and geothermal energy in Ireland is limited only to small installations in the residential and services sector mostly for space and water heating purposes. Because solar and geothermal energy contribute marginally to scenarios outputs, no maximum potentials have been provided in the model.

Based on work undertaken by EirGrid (2010)[10], the level of intermittent (non-dispatchable) renewable generation (namely wind, solar and ocean energy) is limited here to 70% within each timeslice to account for operational issues associated with such high levels of variable generation in the power system. The installations of new coal or nuclear power plant capacities are not permitted reflecting other national policy constraints. Investment subsidies and feed-in-tariffs for renewables, when not explicitly indicated, are included and based on policies currently in practice. No trading of green certificate is assumed.

	Code	Description
Existing	*RHUEBIO100*	Biomass Stove - Base Year
	RHUEBIO200	Biomass Dual Boiler (Heat+Water) - Base Year
	RHUECOA100	Coal Furnace - Base Year
	RHUEELC100	Electric Resistance - Base Year
	RHUEELC200	Electric Heat Pump - Base Year
	RHUEELC300	Electric Resistance (Heat+Water) - Base Year
	RHUEGAS100	Gas Boiler - Base Year
	RHUEGAS200	Gas Heat Pump - Base Year
	RHUEGAS300	Gas Boiler (Heat+Water) - Base Year
	RHUEGEO100	Geothermal System - Base Year
	RHUELPG100	LPG Boiler - Base Year
	RHUELTH100	Heat Exchanger (District Heating) - Base Year
	RHUEOIL100	Oil Furnace - Base Year
	RHUEOIL200	Oil Furnace (Heat+Water) - Base Year
	RHUESOL100	Solar Thermal - Base Year
New	*RHUEBIO101*	Biomass Fireplace
	RHUEBIO201	Biomass Boiler
	RHUEBIOL101	Biodiesel Boiler (Heat+Water)
	RHUEELC101	Electric radiator
	RHUEELCHP201	Air heat pump - electric
	RHUEELCHP202	Air heat pump - electric (Heat+Cooling)
	RHUEELCHP301	Advanced Air heat pump - electric
	RHUEELCHP302	Advanced Air heat pump - electric (Heat+Cooling)
	RHUEELCHP401	Groundheat pump - electric
	RHUEELCHP402	Ground heat pump - electric (Heat+Cooling)
	RHUEGAS101	Natural gas stove
	RHUEGAS201	Natural gas boiler
	RHUEGAS301	Natural gas boiler (Heat+Water)
	RHUEGAS401	Natural gas boiler condensing

[10] Ireland Transmission System Operator (TSO).

RHUEGAS501	Natural gas boiler condensing (Heat+Water)
RHUEGASHP601	Air heat pump - natural gas
RHUEGASHP701	Air heat pump - natural gas (Heat+Cooling)
RHUEHYD110	Hydrogen burner
RHUELPG101	LPG stove
RHUELPG201	LPG boiler
RHUELPG301	LPG boiler (Heat+Water)
RHUELPGHP401	Air heat pump - LPG
RHUELPGHP501	Air heat pump - LPG (Heat+Cooling)
RHUELTH101	District heat exchanger (Heat+Water)
RHUEOIL101	Oil stove
RHUEOIL201	Oil boiler
RHUEOIL301	Oil boiler (Heat+Water)
RHUEOIL401	Oil boiler condensing (Heat+Water)
RHUESOLD101	Solar collector with electric backup (Heat+Water)
RHUESOLE601	Solar collector with diesel backup (Heat+Water)
RHUESOLG201	Solar collector with gas backup (Heat+Water)
RHUEWOO101	Wood-pellets boiler (Heat+Water)

Table 2-1. Extract of the residential heating technology database in Irish TIMES

Commodity	Process code	Unit	2005	2010	2020	Reference
Agricultural waste	*MINBIOAGRW1*	ktoe	25	153	188	(BSG, 2004)
Starch crop	*MINBIOCRP11*	ktoe	0	32	47	(BSG, 2004)
Grassy crop (Miscanthus)	*MINBIOCRP31*	ktoe	3	4	28	(BSG, 2004)
Woody crop (Willow)	*MINBIOCRP41*	ktoe	13	20	138	(BSG, 2004)
Forestry residues	*MINBIOFRSR1*	ktoe	62	94	109	(BSG, 2004)
Biogas	*MINBIOGAS1*	ktoe	31	38	285	(Smyth et al., 2010)
Municipal waste	*MINBIOMUN1*	ktoe	71	142	156	(BSG, 2004)
Rape seed	*MINBIORPS1*	ktoe	2	7	14	(Smyth et al., 2010)
Industrial waste	*MINBIOSLU1*	ktoe	0	2	7	(BSG, 2004)
Wood processing residues	*MINBIOWOOW1*	ktoe	259	259	259	(BSG, 2004)

Table 2-2. Bioenergy potential in Irish TIMES

2.3.2. Scenario definition

For the purpose of this paper, the following four scenarios were defined as being relevant to the policy debate on delivering Ireland's ambitious Non-ETS GHG emissions reduction target.

1. ***Reference*** scenario **(*REF*):** Least cost optimal pathway delivers the energy system demands in the absence of emissions reduction targets. This scenario has been calibrated in the short term to national energy forecasts and is used as benchmark: it provides a starting point against which other scenarios can be measured. In this scenario investment subsidies and feed-in-tariffs for renewables and additional conservation measures (retrofit) in the end use sectors are not included.
2. ***NETS-CO2*** scenario: In this scenario, a 20% emissions reduction constraint (relative to 2005 levels) is imposed on energy-related non-ETS CO_2 emissions in 2020 as stipulated in EU Decision 406/2009. This implicitly assumes that the other sectors of the economy (notably

agriculture) also meet a 20% non-ETS emissions reduction target. The 21% ETS emissions reduction is here applied in Ireland as a proxy for the EU-wide target as specified in Directive 2009/29/EC.

3. ***NETS-GHG*** scenario: This scenario explores the effect on the energy system of additional non-ETS emissions reduction measures to compensate lower reduction levels in agricultural non-energy (notably methane and nitrous oxide) emissions. Assuming agriculture emissions will reduce by 4.4% by 2020 relative to 2005 levels (EPA, 2011b), a 31.5% emissions reduction target (16.7 Mt $CO_{2,eq}$) relative to 2005 levels for 2020 is hence imposed here on non-ETS energy-related CO_2 emissions. Similarly to the previous case a 21% ETS emissions reduction is also applied.
4. ***CO2-20*** scenario: This scenario imposes an overall energy-related CO_2 emissions cap by 2020 of 35.5 Mt (-20.5% relative to 2005). This achieves the same overall emissions reduction as scenario 2, but does not impose separate ETS or Non-ETS targets. The purpose of this scenario is to illustrate how the separate targets impact on the costs of meeting emissions reduction. For non-energy emissions similar assumptions to those in scenario 2 apply in this case.[11]

The paper uses Irish TIMES model to determine the least cost energy system configuration to achieve the Directives targets on ETS and Non-ETS emissions, without setting distinct targets between end-use sectors. The different reductions for individual sectors are merely result of this optimization process.

Moreover, in all scenarios in this paper no specific constraints are introduced to mirror the EU and national 2020 policy framework on renewable energy (DCENR, 2010; EC, 2009c) or on energy efficiency (DCENR, 2009; EC, 2006a). The achievement of these targets in certain scenarios should be interpreted only as a consequence of least cost dynamics and of meeting the GHG mitigation targets.

2.4. Results and analysis

The section presents and discusses results for the emissions reduction scenarios for Ireland in the period to 2020 in three sub-sections. Firstly results of the *NETS-CO2* scenario are compared to the *REF* scenario as this provides insight on how to optimally achieve the binding greenhouse gas emission reduction targets for the year 2020 for the full energy system. Secondly, given the limited

[11] It is worth nothing that *CO2-20* scenario is not aligned with National or European legislation, but has been presented in this paper with the purpose of showing how emissions would be optimally allocate between sectors without any specific target between sectors. It should deliver a results similar to *NETS-CO2* based on the *cost efficient policy case* approach adopted in modelling for EU using the PRIMES model (EC, 2008)

options for reducing agricultural emissions, the impact of a higher emissions reduction target for the energy system is discussed comparing the *NETS-CO2* scenario and the *NETS-GHG* scenario. Thirdly *NETS-CO2* and *CO2-20* energy system are compared focussing mostly on the impact of having these distinct ETS and Non-ETS emissions reduction targets. The implications for the economy of meeting these emissions reduction targets are then discussed for all scenarios, focussing on marginal CO_2 abatement costs, total energy system costs and investments costs.

2.4.1. REF and NETS-CO2 energy systems

Figure 2-3 compares total energy-related CO_2 emissions in 2005 with those from the *REF* and *NETS-CO2* scenarios in 2020. The contribution of each individual sector to emissions reduction is shown. In the *REF* scenario, energy-related CO_2 emissions reach 38.7 Mt CO_2 in 2020, representing a 13.4% reduction on 2005 levels, in which transport is responsible for 38.3% of total emissions and the power sector for 24.5%. Conversely in the *NETS-CO2* scenario total emissions are 35.5 Mt CO_2 in 2020, representing a 20.5% reduction relative to 2005 levels. This total emissions reduction is achieved by a 20% emissions reduction in Non-ETS sectors and 21% emissions reduction in ETS. In this *NETS-CO2* scenario more than two thirds of emissions are accounted for by the transport and power sectors (37.2% and 33.7% respectively). Most of the emissions reductions in 2020 are achieved in the residential (2.1 Mt) and transport (1.6 Mt) sectors, representing a 37.5% and 10.8% reduction respectively, relative to the *REF* scenario. While the services sector and industry provide additional reduction of 1.9 Mt of CO_2, increased emissions occur in electrical generation (26.6% higher than in the reference case).

By 2020 total emissions reduce in both scenarios (Figure 2-3), while in the *REF* scenario Non-ETS emissions slightly grow (+1.0%). Focussing on Non-ETS sectors emissions, Figure 2-4 illustrates with sectoral detail how the 20% energy-related Non-ETS emissions reduction is achieved. Comparing both scenarios it can be seen that the residential sector delivers most significant reductions, delivering 42.1% of the savings. Transport and services provide 31.3% and 24.4% of the emissions reductions respectively. Non-ETS industry accounts for the remaining 2.2% of emission reduction contribution.

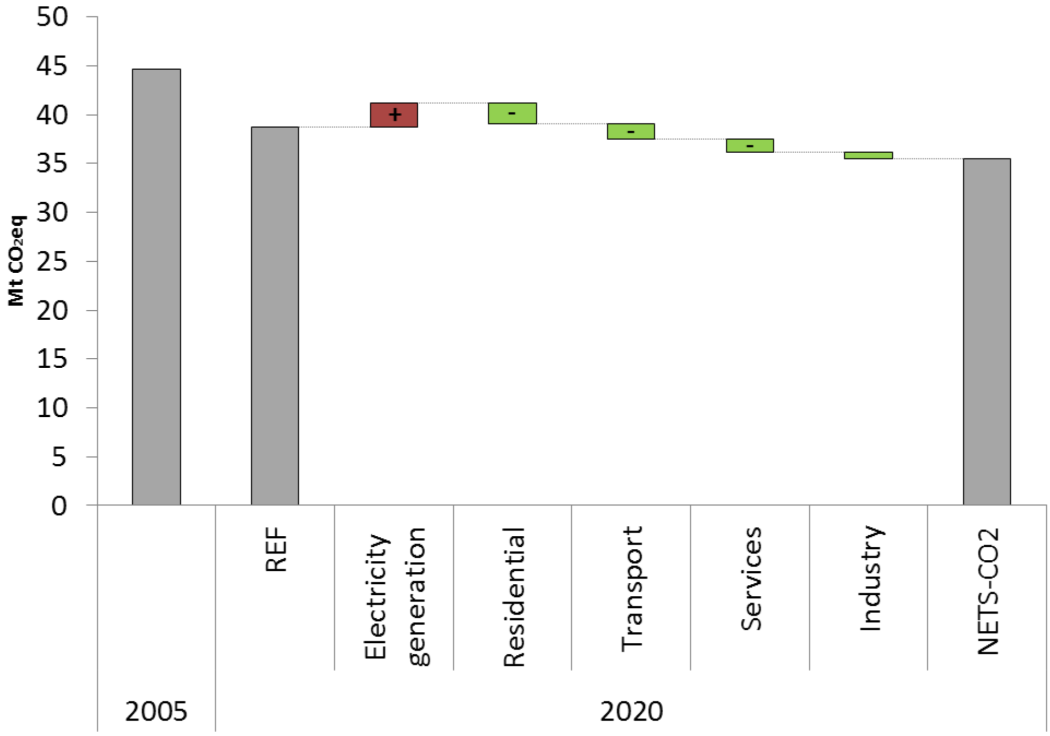

Figure 2-3. Sectoral decomposition of total CO_2 emissions in REF and NETS-CO2 2005-2020 (Mt)

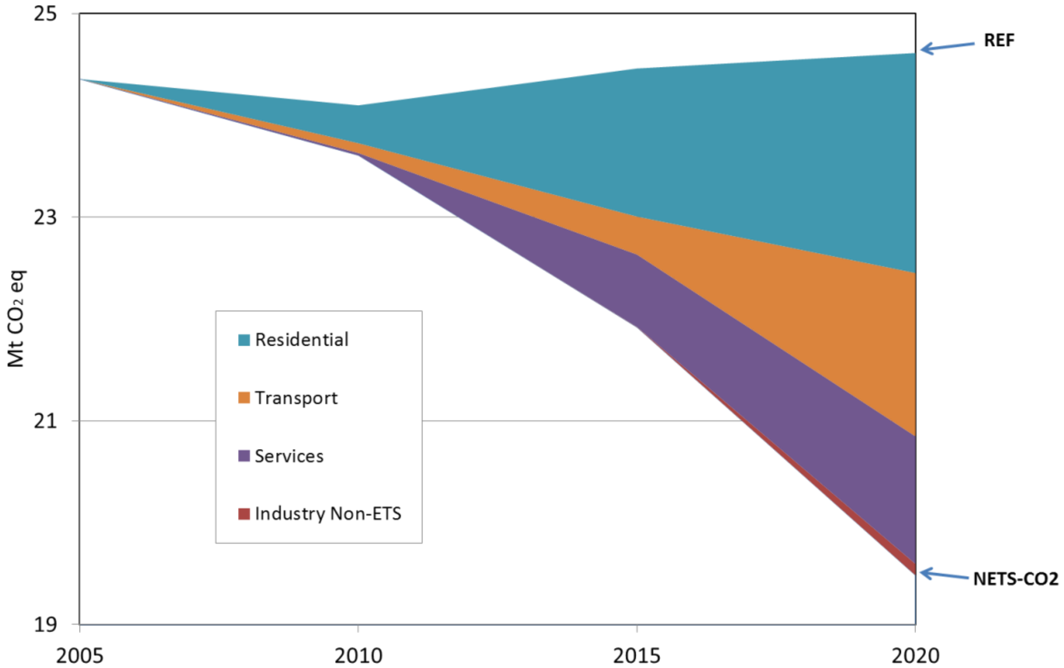

Figure 2-4. Comparing Non-ETS CO_2 emissions in REF and NETS-CO2 (Mt)

Transport

Focussing on individual Non-ETS sectors, Figure 2-5 compares the transport energy system for both scenarios. In *REF* and *NETS-CO2* total fuel consumption (TFC) is expected to increase by 19% and 17.1% respectively by 2020, due to the increased transport activity.

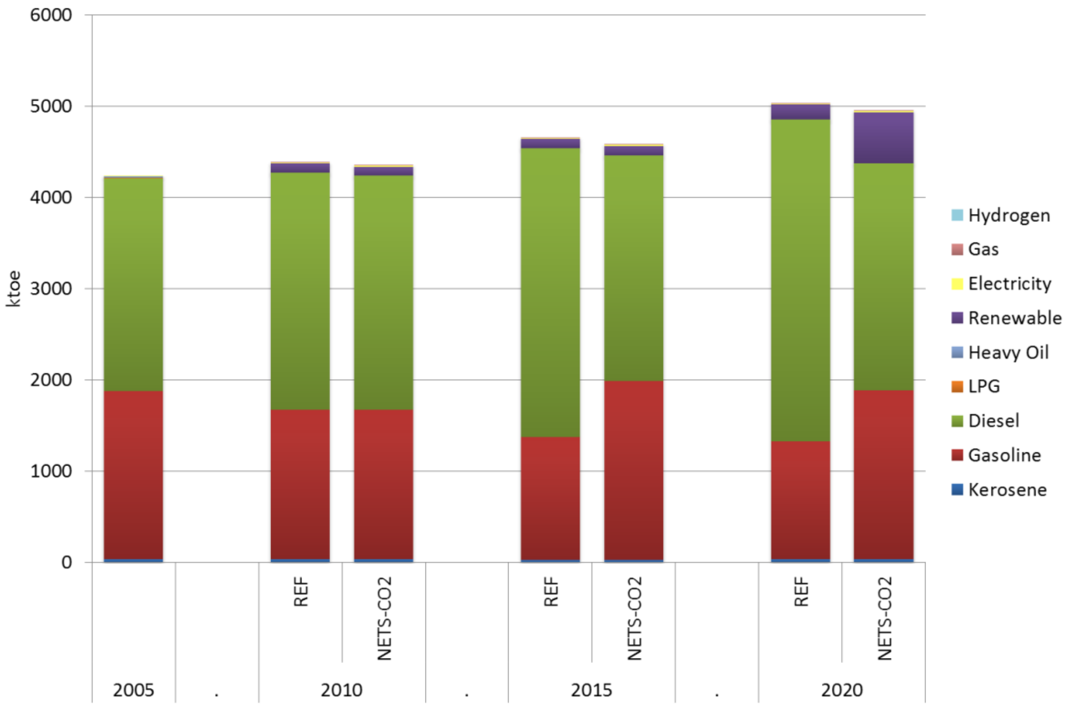

Figure 2-5. Transport TFC in REF and NETS-CO2 (ktoe)

The *REF* scenario indicates that most of petrol (gasoline) fleet will be displaced by diesel (51.5% of the total by 2020). This concurs with separate analysis pointing to the dieselisation of the car fleet (Daly and Ó Gallachóir, 2011; Ó Gallachóir et al., 2009; Rogan et al., 2011). Significant differences emerge between the *REF* and *NETS-CO2* energy systems in the penetration of biofuels[12] which in 2020 account for 3.3% of transport TFC in *REF* and 11.3% in *NETS-CO2*. Biofuels in *NETS-CO2* comprises mostly of biodiesel, approximately 51% by 2020, and biogas, 33.7%. Bio-ethanol accounts for the remaining 15.2%. Most of biodiesel (about 97%) and bioethanol consumed in the *NETS-CO2* are imported. Domestic biofuels productions are of biogas and limited productions of biodiesel from rape seeds. It is worth noting that these results do not fully account for other policy barriers affecting future use of certain biofuels (Smyth et al., 2010).

In *NETS-CO2* the penetration of renewable fuels reduces diesel consumption, while gasoline (petrol) consumption is similar to the base year. Differences in renewable fuel consumption are also related to the transition from only biogas fleets in *REF*, to 100% biodiesel fuelled[13] and blended technologies, biogas and blended (with gasoline) bioethanol fleets in *NETS-CO2*.

[12] Classed as *Renewable* in the figure

[13] More than half of biodiesel fuelled fleets.

Although there are some electric vehicles in both scenarios, electrification of transport remain over the period 2005-2020 very limited delivering no more than 0.31% of TFC by 2020 in *NETS-CO2*.

Residential and services (Energy in Buildings)

Focussing on the residential sector, Figure 2-6 compares the residential TFC over the period 2005-2020. Both scenarios (*REF* and *NETS-CO2*) incorporate assumptions regarding the improved energy performance of new houses based on separate analysis (Dineen and Ó Gallachóir, 2011). The results for both scenarios point to electrification of heating from 2010 mostly displacing oil and coal based systems. By 2020 electricity accounts for 26.3% of residential TFC in *REF* increasing by 26.9% relative to the base year, while in *NETS-CO2* electricity grows to 44.7% of the total, more than twice the base year consumption. Interestingly natural gas, biogas and biomass shares[14], increase too over the whole period for both scenarios contributing to a reduction in emissions and providing approximately 36.5% (*REF*) and 38.6% (*NETS-CO2*) of 2020 TFC.

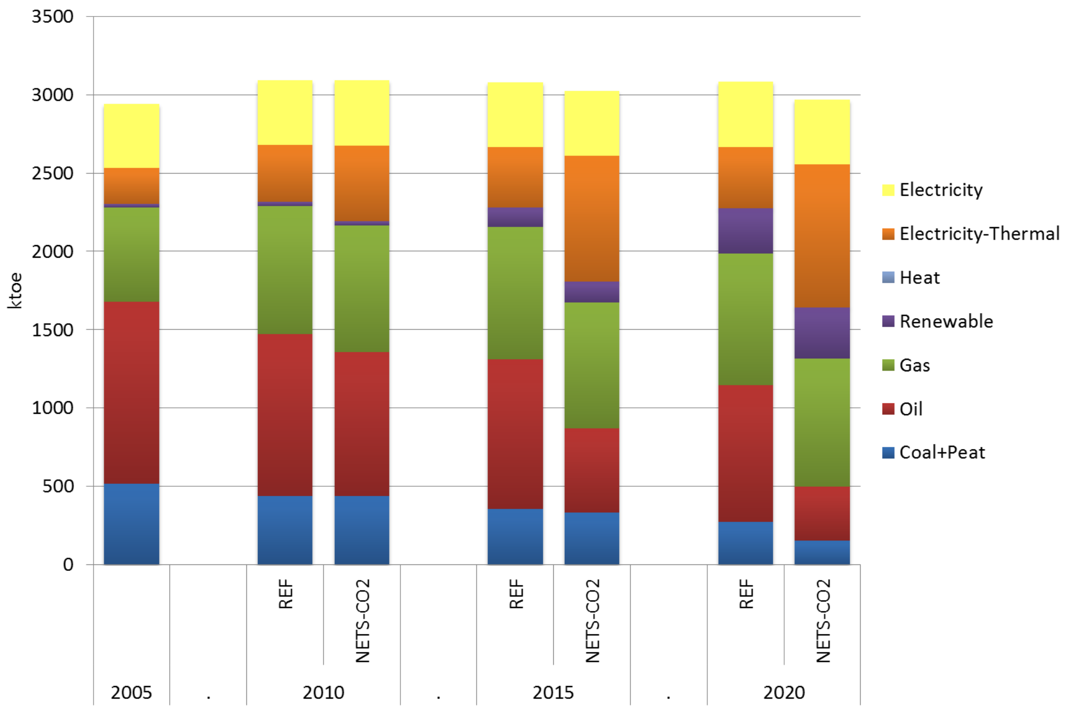

Figure 2-6. Residential TFC in REF and NETS-CO2 (ktoe)

Looking at the services sector (Figure 2-7), the results (as for the residential sector) also point to increasing shares of electricity, renewables and gas in the period 2005-2020, displacing coal, peat and oil use. The effect of Non-ETS emissions reduction target is to accelerate this trend and to improve efficiency in the sector. While in the *REF* scenario, TFC grows by 3.2% in 2020, *NETS-CO2* suggests a decreasing trend (13.7% lower than *REF*) mostly due to further efficiency

[14] Classed as *Renewable* in the figure

improvement driven by the growth in electricity (electric radiators and some heat pumps) and renewables appliances (biogas and biomass) for heating. In *REF* electricity accounts for about 43.3% of TFC, followed respectively by natural gas (25.2%), oil (23.7%) and biogas and biomass (7.5%)[15], while in *NETS-CO2* electricity provides about 59% of TFC, followed respectively by natural gas (25.4%) and biogas and biomass (11.9%). Oil accounts for just 3.7%.

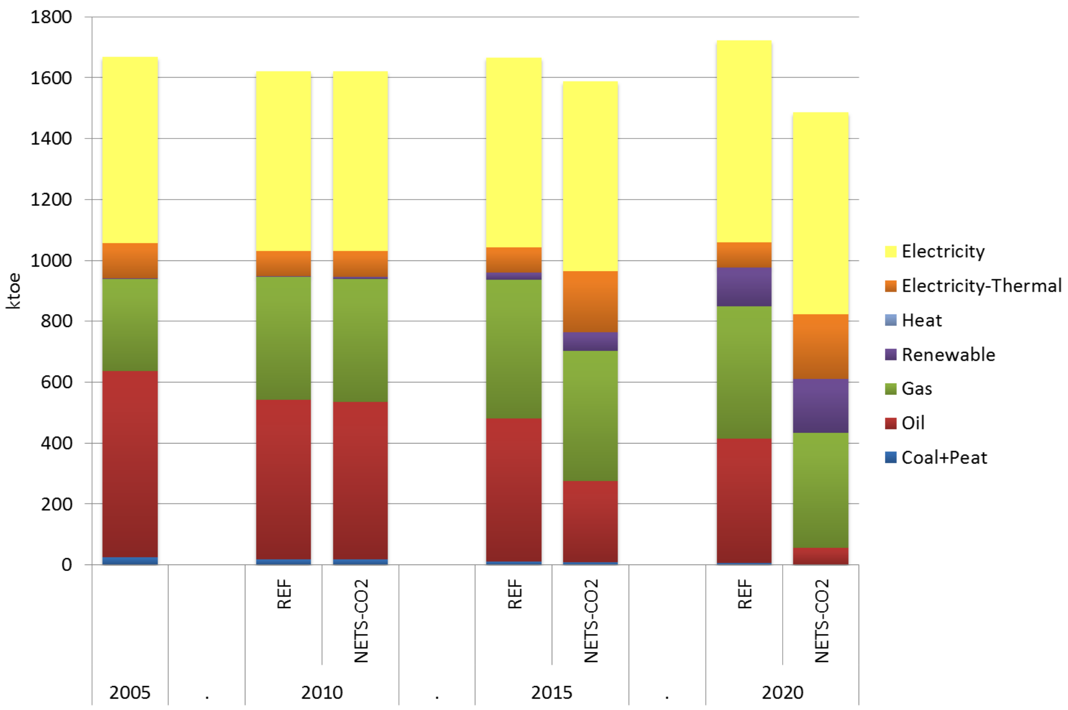

Figure 2-7. Services TFC in REF and NETS-CO2 (ktoe)

Electricity overview

Figure 2-8 shows the trends in sectoral electricity consumption. The *REF* scenario sees increasing electricity demand trends passing from 2,038 ktoe (23,707 GWh) in 2005 to 2,213 ktoe (25,741 GWh) in 2020. Meeting the *NETS-CO2* targets increases electricity demand by 2020 to 2,866 ktoe (33,337 GWh), with average growth rates over the period of 2.7% per annum. Electricity consumption, as a share of overall final energy demand (TFC), was 17.7% in 2005 and grows to 17.9% by 2020 in the *REF* scenario and to 24% in the *NETS-CO2* scenario. In the *REF* scenario 36.6% of electricity is consumed in the residential sector in 2020, 33.7% in services and 25.7% in industry. In *NET-CO2* nearly half of electricity use is in the residential sector (46.2%), followed by services (30.6%) and then industry (19.8%). Electricity demand in the transport sector remains marginal, accounting for less than 0.5% of electricity usage in both scenarios.

Regarding the electricity generation fuel mix (shown in Figure 2-9), the model results show that, compared to the base year, in which electricity generation is dominated by natural gas generation

[15] Classed as *Renewable* in the figure

(CCGT and GT plants), by 2020 the *REF* scenario shows a certain amount of decarbonisation of the power sector through the substitution of coal plant production (76.1% lower than 2005 levels) with cost effective gas fuelled CCGT plant and wind power (60.5% and 23.9% of GEC in 2020). Interestingly the mitigation scenario results indicate that the increased levels electricity demand are supplied by higher fossil fuel productions, such gas CCGT (+33.6% by 2020 relative to *REF*) and peat (+19.9%)[16], and electricity imports. From this, combined with emissions shown in Figure 2-3, we can deduce that ETS emissions reduction target is already overachieved in the *REF*. This provides in the mitigation cases the flexibility for the model to move emissions from Non-ETS to ETS sectors without necessary reducing total emissions. This and more details are more extensively discussed in Section 2.4.3.

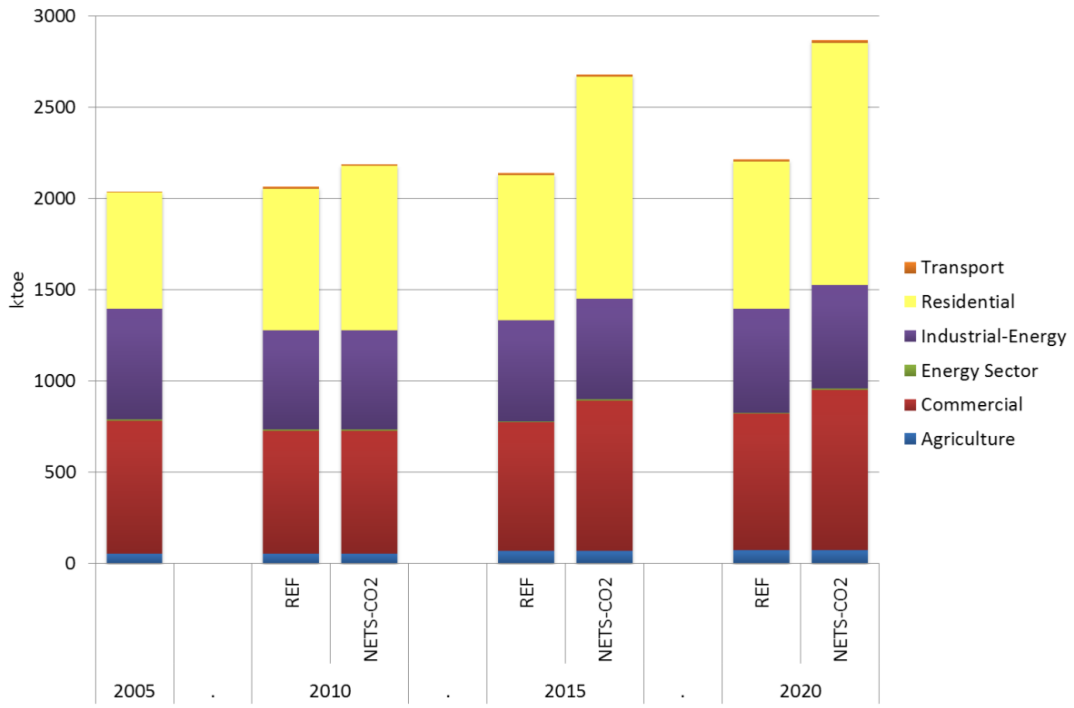

Figure 2-8. Electricity consumption in REF and NETS-CO2 (ktoe)

[16] Classed as *Coal + Peat* in the figure

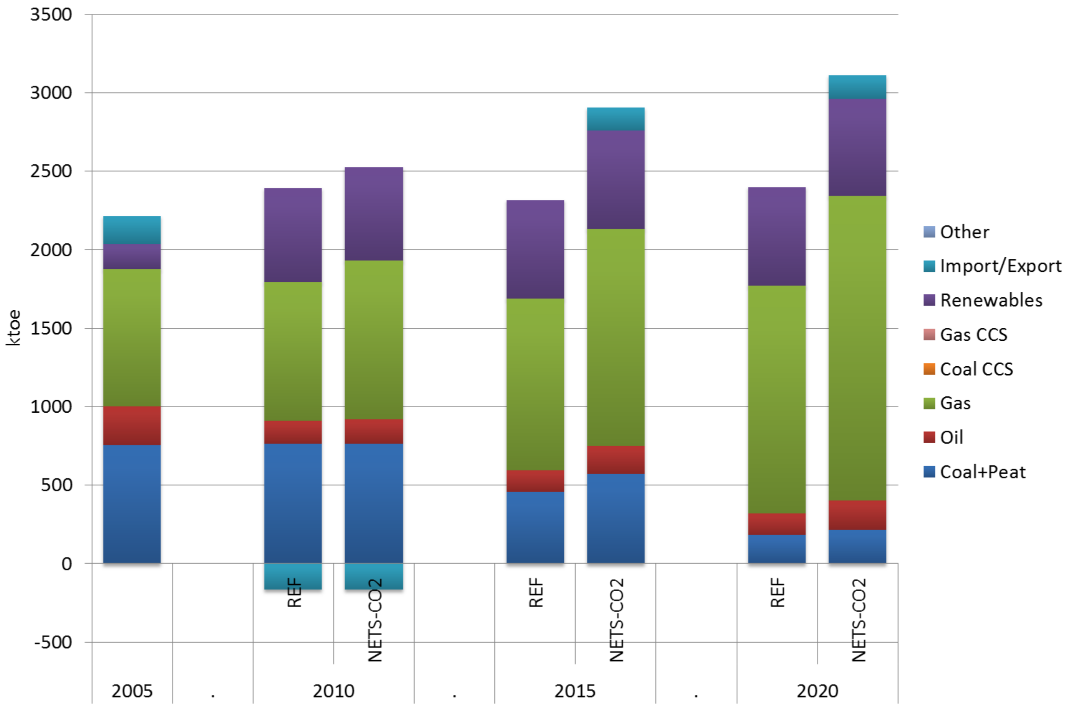

Figure 2-9. Electricity generation by fuel in REF and NETS-CO2

2.4.2. Delivering deeper emissions reduction in energy to compensate for agriculture

Figure 2-10 compares the *NETS-CO2* and *NETS-GHG* scenarios, i.e. comparing a 20% and 31.5% energy-related CO_2 emissions reduction by 2020 relative to 2005 for the non-ETS sectors. In the *NETS-GHG* scenario an additional 2.8 Mt $CO_{2,eq}$ of Non-ETS emissions reduction are required from the energy system to compensate for lower reductions in agriculture in order to still achieve the overall 20% Non-ETS emissions reduction, compensating for a 4.4% reduction in agriculture GHG emissions. For the energy system this translates to an overall 26.8% CO_2 emissions reductions relative to 2005 levels (21.0% in ETS sectors and 31.5% in Non-ETS sectors). The transport and residential sectors deliver most of further emissions reductions (by 2020 50.7% and 41.2% of emissions reductions respectively). Increased efficiency (residential TFC is 7.9% lower than *NETS-CO2* by 2020) and fuel switching from coal and oil to electricity (increased electrification of heating) are the main causes of the reduction in the residential sector. Renewable energy use generally increases in transport mainly in the period 2015-2020 due to the conversion from oil based products to biofuels in public transport and in freight.

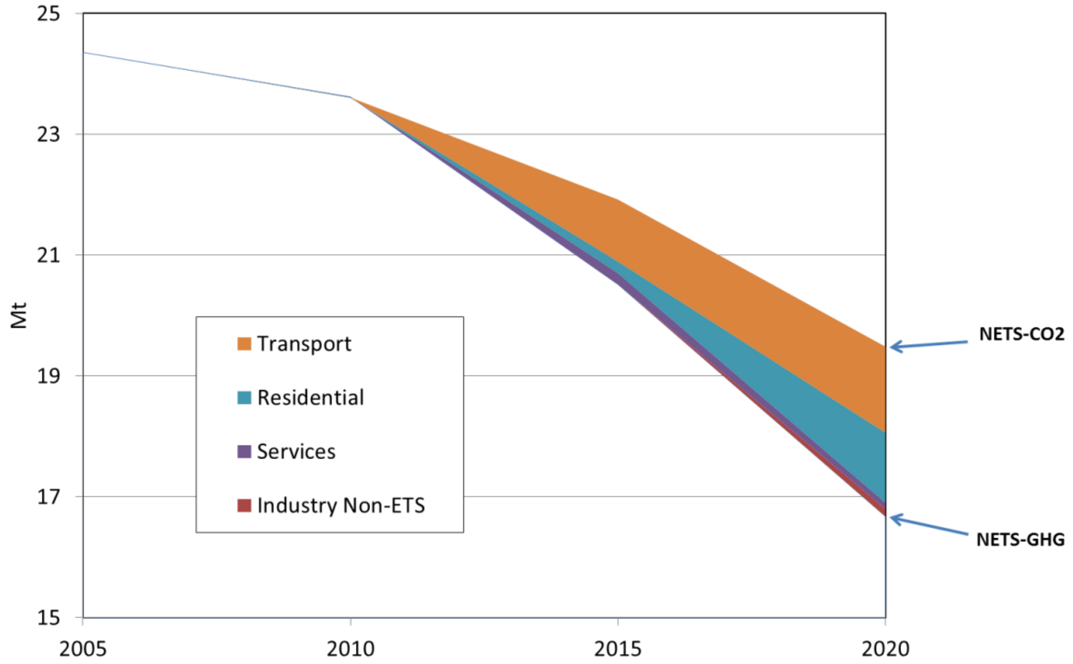

Figure 2-10. Comparing Non-ETS CO_2 emissions in NETS-CO2 and NETS-GHG (Mt)

Figure 2-11 compares *NETS-GHG* renewable energy shares in 2020 with the *NETS-CO2* scenario. It is worth noting that the share of renewable energy in the *NETS-CO2* scenario falls short of the mandatory EU Directive 2009/28/EC 16% renewable energy target (reaching 14.2%) while in the *NETS-GHG* scenario the 16% target is exceeded (reaching 18.4%). The *NETS-GHG* scenario results for 2020 point to an increased consumption of biofuels for transportation (+86% in RES-T, mainly biodiesel) and biomass for heating purposes (+9% in RES-H), mainly in ETS industry. Electricity generation (RES-E) in both scenarios are similar with equal levels of wind and hydro use. In the *NETS-GHG* scenario cost-effective CCGT technologies are used to meet the higher electricity demand (6.2% higher than *NETS-CO2* scenario) driven by the electrification of residential and services.

It is worth noting that Ireland's National Renewable Energy Action Plan establishes 2020 modal targets for renewable energy that are quite different from the results of the *NETS-GHG* scenario. When calculated as a share of gross energy consumption, these NREAP targets are 8.3% RES-E, 3.6% RES-T and 4.1% RES-H. This compares with the NETS-GHG results, which point to 4.4% RES-E, 7.5% RES-T and 6.6% RES-H. This suggests that current renewable energy targets are not aligned with a least cost approach to meeting Ireland's 2020 non-ETS target.

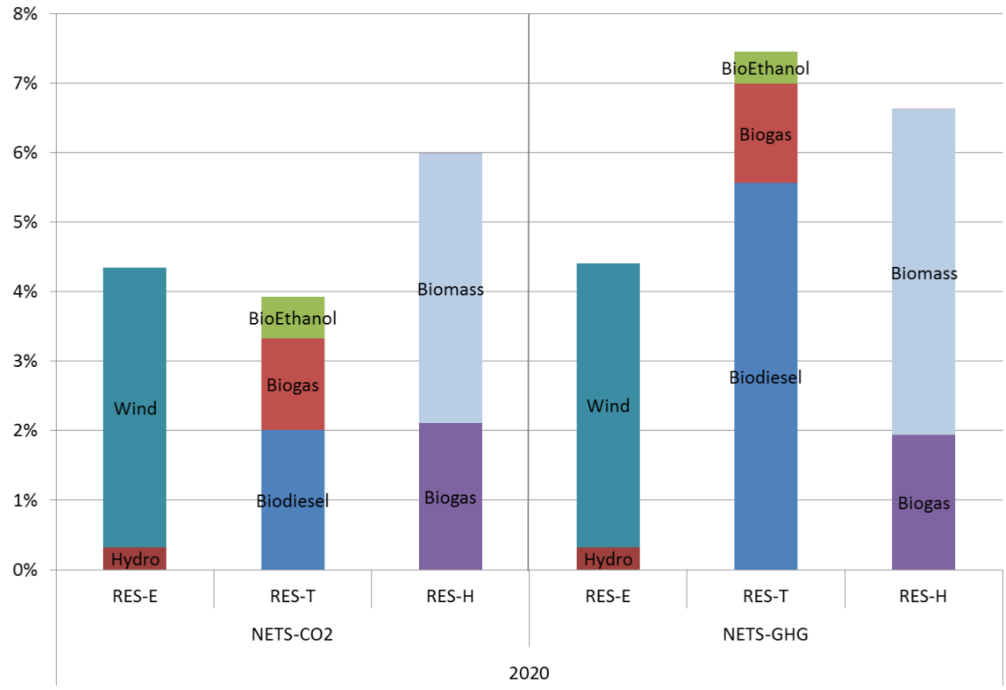

Figure 2-11. Renewable shares in NETS-CO2 and NETS-GHG 2020 (% of gross fuel consumption)

2.4.3. Comparing alternatives to deliver 20% emissions reduction target

Figure 2-12 illustrates emissions pathways for the *REF*, *CO2-20* and *NETS-CO2* scenarios. In all scenarios the 21% ETS target is achieved with 30.6% of ETS emissions reduction already evident in the *REF* scenario. Between the *CO2-20* and the *NETS-CO2* scenarios the significant difference is the emissions share between the ETS and the Non-ETS sectors. While Non-ETS emissions are slightly reduced in the *CO2-20* scenario, in 2020 ETS emissions reduce by 44.7% relative to the base year. There is a significant discrepancy between the results shown here and those generated for Ireland using the *cost efficient policy case* approach adopted in modelling for EU using the PRIMES model (EC, 2008). Even ignoring the considerable impact of agriculture (which, if included, would point to further relaxation of the Non-ETS target), Figure 2-12 suggests that a more appropriate target for Non-ETS emissions in 2020 would be to return to 2005 levels, rather than a 20% or even 17% reduction.

As shown in Figure 2-13, the effect of moving from a cost optimal approach *(CO2-20)* to the current ETS / Non-ETS targets for Ireland *(NETS-CO2),* means a greater use of biofuels in transport (two and a half fold increase in RES-T), with a dramatic increase of imported biodiesel and bioethanol consumption, and greater electrification of heating in Non-ETS sectors. Renewable electricity generation share grows from 618 ktoe (7.2TWh) to 770 ktoe (9.0 TWh) in *CO2-20* by 2020, while gross electricity consumption decreases almost to 2005 levels, accounting for 2,348 ktoe (27.3 TWh), compared with 3,113 ktoe (36.2 TWh) in *NETS-CO2*. Renewable consumption for heating purposes (RES-H) is 5.9% lower in *CO2-20* than in *NETS-CO2*.

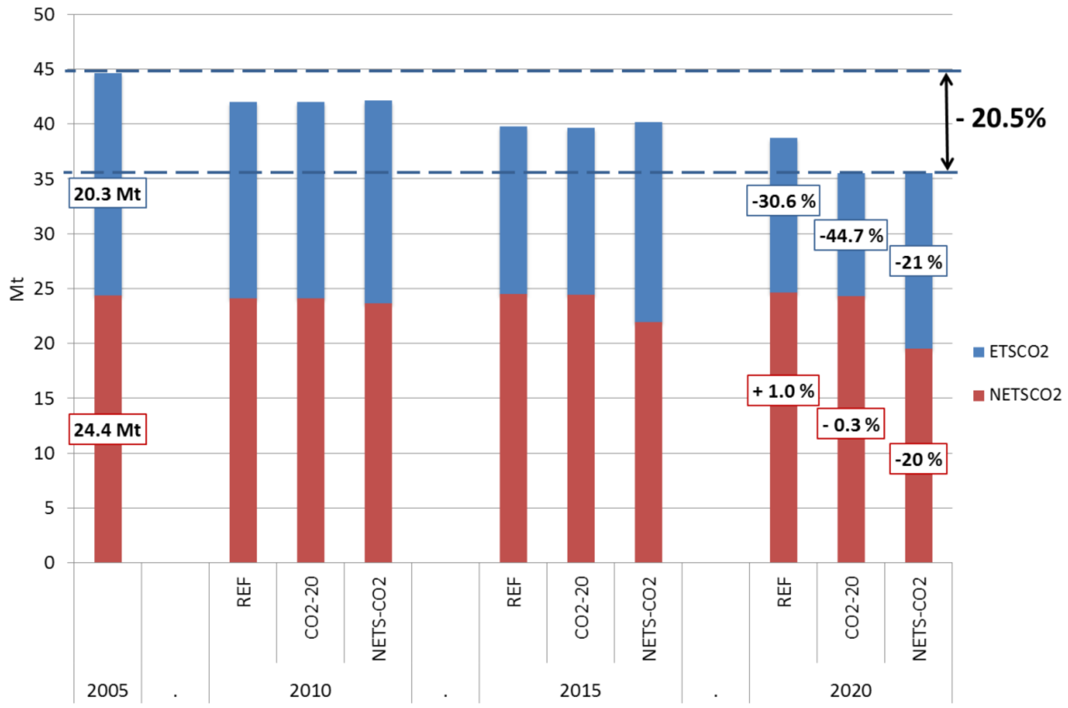

Figure 2-12. ETS and Non-ETS emissions in REF, CO2-20 and NETS-CO2 (Mt)

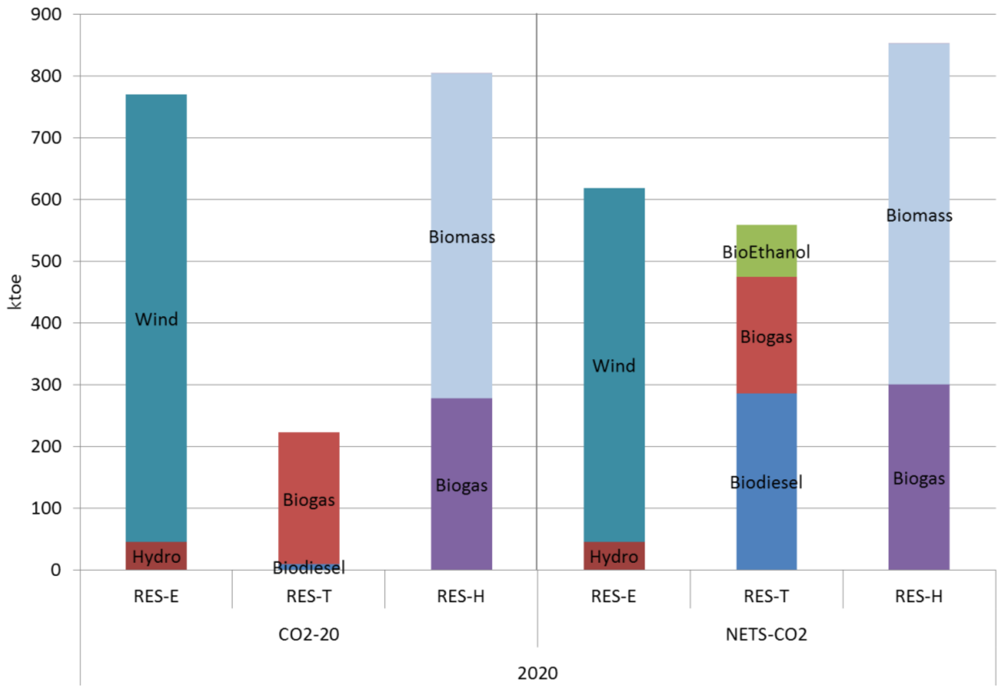

Figure 2-13. Renewable consumption by mode in CO2-20 and NETS-CO2 2020 (ktoe)

2.4.4. Economics

Marginal CO_2 abatement costs

Focussing on cost of delivering CO_2 emissions reduction, Table 2-3 shows the model extraction of CO_2 marginal shadow prices for *CO2-20*, *NETS-CO2* and *NETS-GHG*.

[€$_{2000}$/ton CO_2]	**Scenario**	**2015**	**2020**
Non-ETS emissions	*CO2-20*	0	46
	NETS-CO2	89	158
	NETS-GHG	97	213
ETS emissions	*CO2-20*	0	46
	NETS-CO2	7	35
	NETS-GHG	13	40

Table 2-3. CO_2 shadow prices in *CO2-20, NETS-CO2* and *NETS-GHG* (€$_{2000}$/tonne)

According to model results, the impact of the distinct ETS and Non-ETS targets agreed for Ireland has a dramatic impact on the cost of emissions reduction. In *NETS-CO2,* the marginal abatement cost for Non-ETS emissions reaches €158/tonne CO_2 in 2020, more than 3 times higher than in *CO2-20*. This further challenges the results of the analysis underpinning Ireland's Non-ETS target (EC, 2008), which indicated that the marginal cost of abatement would be between €40-€50 /tonne. Comparing this price range with the *CO2-20* marginal abatement cost of 45.7 reinforces the point previously made that a more appropriate target for Non-ETS emissions for Ireland would have been to return to 2005 levels by 2020, rather than the 20% reduction agreed.

Impact on the economy of delivering emissions reduction

This section discusses how the relationship between the economy and the energy system evolves during the time horizon. It is worth noting that currently, in the Irish TIMES model, there is no feedback between the model and the economy. The impacts of the marginal abatement costs presented in Table 2-3 on economic growth are hence not captured.

According to Bergin et al. (2010), ROI Gross Domestic Production (GDP), after the period of economic recession 2008-2010, will recover in the period to 2020. In the period 2005-2020, GDP is expected to grow on average at 1.8% per annum (2.6% p.a. in the period 2010-2020). Over the same time horizon the *REF* energy system indicates that total energy consumption is set to grow by 0.46% p.a., compared with growth rates in *CO2-20* and *NETS-CO2* of 0.41% p.a. and 0.18% p.a. respectively. In the *NETS-GHG* scenario, energy consumption remains stable (reduction of 0.03% p.a.). For comparison, Ireland's GDP grew by 6.5% p.a. while energy TFC grew by 3.6% p.a. (Howley et al., 2008). This suggests that Ireland's future energy system is more productive (lower energy intensity) than the historical system, in the *REF* scenario and in all other scenarios.

This improvement in energy productivity contributes to a reduction in the energy system costs for all scenarios. Figure 2-14 compares the total system costs (i.e. the total net present value of the stream of annual costs discounted to a reference year (2000 in this case)), and the investment portion[17] for the scenarios presented. The differences in costs across the scenarios provide an indication of the costs associated with different levels of mitigation. In the *REF* scenario, system costs remain at approximately stable levels in the period 2010-2015, then reduce by 8.7% in 2020 relative to 2005 levels (-0.58% p.a. over the whole horizon). The *NETS-CO2* and *NETS-GHG* scenarios also show decreasing energy systems costs, with average decrease rates of 0.24% and 0.04% p.a., while the *CO2-20* accounts for -0.4% per annum. Focusing on investments costs, for all scenarios, over the entire time horizon the contribution of investments costs grows, increasing from about 22% of total system costs by 2010 to between 50% (*REF* scenario) and 52.7% (*NETS-GHG* scenario) by 2020 (reflecting a lower operation and maintenance costs due to the installation of newer and more efficient plant. Fuel costs remain largely stable as consumption decreases but fuel prices increase). Investments levels in the NETS scenarios by 2020 are between 3.5% (*NETS-CO2*) and 5.5% (*NETS-GHG*) higher than *REF*. In *CO2-20* they are 2.2% lower. It is worth noting that the total energy system costs do not fully capture that cost of additional infrastructure (for example additional electricity transmission lines or additional gas pipelines).

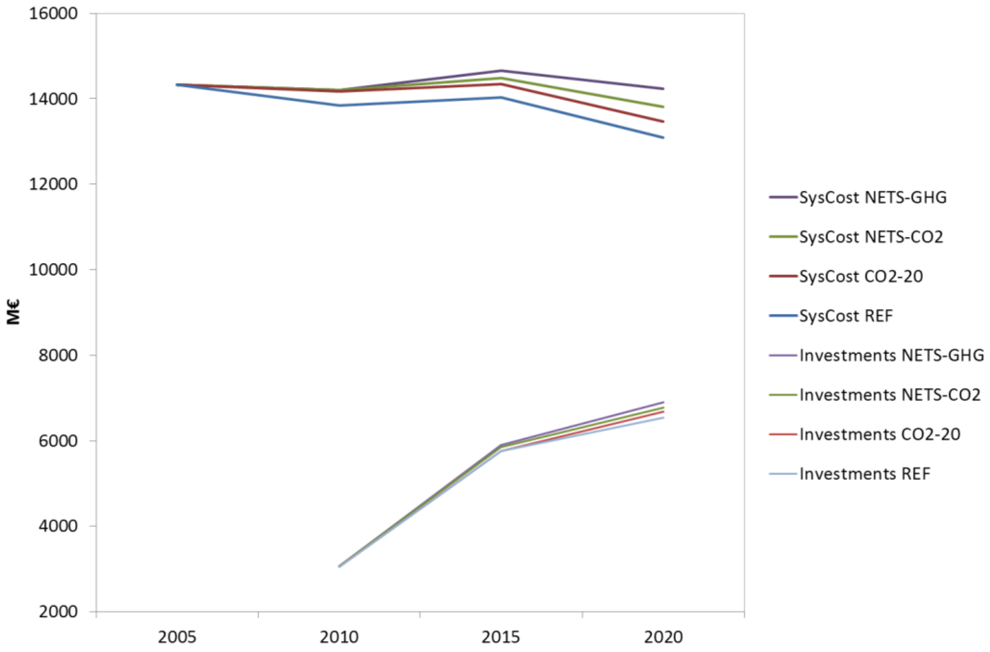

Figure 2-14. Comparing system costs with investments (M€)

Even though these energy system costs don't include infrastructural costs, it is useful to relate these costs to GDP levels to have a sense of the relative costs, as provided in Table 2-4. Energy system costs are shown as a percentage of GDP and separately investments costs (which contribute to GDP) are also shown as a percentage of GDP. In the *REF* scenario energy system costs are

[17] Undiscounted costs by period. It is not allowed to sum different periods

anticipated to decrease from 11.2% in 2005 to 7.9% of GDP in 2020, while investments account for about 3.9% of GDP by 2020. The mitigation scenarios (*NETS-CO2* and *NETS-GHG*) point to a system cost that will range between 8.3% (*NETS-CO2*) and 8.6% (*NETS-GHG*) of GDP, driven by additional investments that represent respectively 4.1% and 4.2% (€ 230 million and €363 million higher than *REF*) of GDP. However, it is interesting to note that the net additional cost of delivering emission reductions targets never overtakes 0.7% of GDP. The *CO2-20* scenario delivers overall emissions reduction with total system cost that accounts for 8.1% of GDP and investment of 4.0% (145 M€ higher than *REF*).

		2005	2010	2015	2020
SysCost	REF/GDP	11.21%	10.44%	9.42%	7.87%
	CO2-20		*+0.25%*	*+0.21%*	*+0.23%*
	NETS-CO2		*+0.27%*	*+0.30%*	*+0.44%*
	NETS-GHG		*+0.27%*	*+0.42%*	*+0.69%*
Investments	REF/GDP	0.17%	2.30%	3.86%	3.93%
	CO2-20		*+0%*	*+0%*	*+0.09%*
	NETS-CO2		*+0.01%*	*0.07%*	*+0.14%*
	NETS-GHG		*+0.01%*	*+0.10%*	*+0.22*

Table 2-4. Comparing system costs with GDP

2.5. Conclusion and Discussion

The analysis here raises a number of questions regarding Ireland's obligations under the Effort Sharing Decision 2009/406/EC. One significant finding is that imposing a 20% target on Non-ETS energy-related CO_2 emissions target results in a high marginal abatement cost (€158/tonne) which suggests the target set for Ireland is far from a cost optimal target. This is before incorporating the fact that agriculture represents nearly half of Non-ETS emissions in Ireland, with few mitigation options. When this is taken into account (by imposing a larger emissions reduction target on the energy system), the marginal abatement cost increases further to €213/tonne. This challenges the findings of analysis for EU using the PRIMES model (EC, 2008), which found that in the *cost efficient policy case* Non-ETS emissions reduction of 17% below 2005 levels could be achieved at a marginal abatement cost of €40-€50/tonne.

The results from the *NETS-CO2* scenario suggest that significant non-ETS emissions reductions may be achieved within the residential, transport and services sector through two key pathways, namely electrification of heating in buildings (i.e. shifting CO_2 emissions from the non-ETS sectors to the ETS sectors (namely electricity generation)) and significantly increasing the amount biofuels used in transport. The results also show that ETS companies in Ireland will are likely to have significant amount of emissions allowances to sell and trade with other companies across the EU. Comparing *NETS-CO2* with *CO2-20* demonstrates the additional costs in meeting separate ETS and non-ETS targets compared with an overall emissions reduction target. The *NETS-GHG* scenario underlines the significant role of agriculture in Non-ETS sector emissions and quantifies the costs associated with imposing a 31.5% non-ETS emissions reduction target on Ireland's energy system to compensate for the fact that agriculture delivers a reduction of 4% by 2020 relative to 2005 levels.

Finally, the results point to the need to reconsider Ireland's renewable energy targets. In particular, the paper suggests that to meet Ireland's non-ETS target at least cost requires more ambition and focus on renewable energy in transport and renewable thermal energy.

In this analysis we do not model non energy-related emissions associated with agriculture but rather take projections from other sources and use them to exogenously establish the target for the energy system. Further research work is required to model energy-related and agriculture-related GHG emissions in order to establish an overall least cost strategy.

3. Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system

Abstract

The Copenhagen Accord established political consensus on the 2°C limit (in global temperature increase) and for deep cuts in greenhouse gas (GHG) emissions levels to achieve this goal. The European Union has set ambitious GHG targets for the year 2050 (80 – 95% below 1990 levels), with each Member State developing strategies to contribute to these targets. This paper focuses on mitigation targets for one Member State, Ireland, an interesting case study due to the growth in GHG emissions (24% increase between 1990 and 2005) and the high share of emissions from agriculture (30% of total GHG emissions). We use the Irish TIMES energy systems modelling tool to build a number of scenarios delivering an 80% emissions reduction target by 2050, including accounting for the limited options for agriculture GHG abatement by increasing the emissions reduction target for the energy system. We then compare the scenario results in terms of changes in energy technology, the role of energy efficiency and renewable energy. We also quantify the economic impacts of the mitigation scenarios in terms of marginal CO_2 abatement costs and energy system costs. The paper also sheds light on the impacts of short term targets and policies on long term mitigation pathways.

3.1. Introduction

3.1.1. Policy context

The most recent Assessment Report from the Inter-governmental Panel on Climate Change (IPCC) (IPCC, 2007a) shows that eleven of the last twelve years (1995-2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850). The report concludes that the warming of the climate system is 'unequivocal' and that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gases (GHG) concentrations. Growing worldwide concerns regarding the anthropogenic interference with the climate system resulted in the Copenhagen Accord that established political consensus on the 2°C (global temperature increase) limit and for deep cuts in greenhouse gas (GHG) emissions levels to achieve this goal. Since December 2009, 140 countries have associated themselves with the Copenhagen and of these, 85 countries have pledged to reduce their emissions or constrain their growth up to 2020 (UNEP, November 2010).

In order to reach that objective an IPCC Assessment Report shows that global GHG emissions must peak by 2020, while by 2050, global GHG emissions should be reduced by at least 50 % below their 1990 levels (IPCC, 2007b). The European Union perspective is that industrialized countries should contribute to this global emissions reduction target by reducing GHG emissions by 30% by the year 2020 and between 80% and 95% by the year 2050, relative to 1990 levels. Even in the absence of wider international agreement on climate policy in order to meet this objective the EU has set ambitious greenhouse gas (GHG) emission reduction targets for 2020 (EU, 2009a, b) and 2050 (EC, 2009d). Some analysis has been commissioned by the European Commission to establish what the contribution of individual sectors should be to contribute to an overall 80% reduction goal. Table 3-1 summarises the results from the EU Low Carbon Roadmap (EC, 2011c), highlighting that certain sectors (notably electricity generation and energy in buildings), can achieve deep emissions cuts more readily than others (notably agriculture and transport).

Sectors	**2005**	**2030**	**2050**
Power (CO_2)	-7%	-54 to 68%	-93 to -99%
Industry (CO_2)	-20%	-34 to -40%	-83 to -87%
Transport (incl. CO_2 aviation, excl. maritime)	30%	+20 to -9%	-54 to -67%
Residential and services (CO_2)	-12%	-37 to -53%	-88 to -91%
Agriculture (non-CO_2)	-20%	-36 to -37%	-42 to -49%
Other non-CO_2 emissions	-30%	-72 to -73%	-70 to -78%
Total	-7%	-40 to -44%	-79 to -82%

Table 3-1. EU Low Carbon Roadmap GHG reduction compared to 1990 (Source EC)

Within the EU, the short term GHG emissions reduction targets for 2020 have been allocated to Member States (MS) under an effort sharing decision (EU, 2009a, b), but not the longer term target. However, some Member States have already established or are planning long term emissions targets. The United Kingdom has legislated for an 80% GHG emissions reduction target while France is planning to reduce emissions by 75% over the period 1990-2050 (CCC, 2008; Environment Round Table, 2009).

3.1.2. Focus of paper – why Ireland?

This paper focuses on one Member State, Ireland, and is based on analysis carried out to inform discussion regarding the Climate Change Response Bill 2010, which proposed an 80% GHG emissions reduction target by 2050 relative to 1990 (Gormley, 2010). Ireland is an interesting case study relative to other Member States for two distinct reasons. Firstly, in contrast to the EU generally, greenhouse gas emissions increased by 24% between 1990 and 2005 as shown in Table 3-2 (EEA, 2010; EPA, 2011a)

	1990		2005		
	EU-27	***IE***	***EU-27***	***IE***	
Total GHG Emissions	5588.8	55.6	5148.8	69	[$MtCO_{2eq}$]
Variation relative to 1990	-	-	*-7.90%*	*24.10%*	
2050 Target	1117.8	11.1	1117.8	11.1	[$MtCO_{2eq}$]
Reduction required	*-80%*		*-78%*	*-84%*	
Energy-related CO_2	4283.9	30.2	4084.5	45	[$MtCO_{2eq}$]
Variation relative to 1990	-	-	*-4.70%*	*49.00%*	
2050 Target	856.8	6.0	856.8	6.0	[$MtCO_{2eq}$]
Reduction required	*-80%*		*-79%*	*-87%*	

Table 3-2. GHG Emissions in EU-27 and Ireland (Data sources: EEA for EU-27, EPA for IE)

Ireland experienced high levels of emissions growth in line with buoyant economic growth (Walker et al., 2009), with overall levels of GHG emissions growing from 55.6 to 69.0 Mt. The impact of this is shown in Table 3-2, i.e. an 80% emissions reduction target relative to 1990 levels is equivalent in Ireland to an 84% emissions reduction target relative to 2005 levels. This emissions growth in the period 1990 - 2005 that Ireland has experienced is in marked contrast to other industrialised countries between 1990 and 2005, as evident from EU-27 emissions figures that decreased by approximately 8%. These trends have been changing since 2008 by the impacts of the economic recession in Ireland, with emissions reducing from 69.0 Mt CO_2 equivalents in 2005 to 62.3 Mt in 2009 (Howley et al., 2010).

The situation for energy-related emissions is even more striking. Energy demand grew by 3.7% per annum on average between 1990 and 2005 (Howley et al., 2006) and energy-related CO_2 emissions in 2005 were 49% higher than 1990 levels. An 80% emissions reduction target relative to 1990 levels by 2050 for the energy system is thus equivalent to an 87% emissions reduction target relative to 2005 levels. A significant proportion of the fall in total GHG emissions in 2009 due to the economic recession was a reduction in energy-related emissions (by 12% relative to 2005), delivering for the energy system an equivalent target of 85% emissions reduction target relative to 2009 levels.

The second distinguishing characteristic of Ireland is the significant share of GHG emissions arising from agriculture, which according to the EU Low Carbon Roadmap, provides limited scope for deep emissions cuts. Within the EU-27, in 2005 energy accounted for 79% of GHG emissions and agriculture is responsible for approximately 11% (9.3% non-energy). In Ireland, however, as shown in Figure 3-1. energy accounts only for 66% of emissions (green areas), while agriculture has an important role on the emissions balance contributing to about 28.5% (27.1% non-energy related) of total GHG emissions (EEA, 2010).

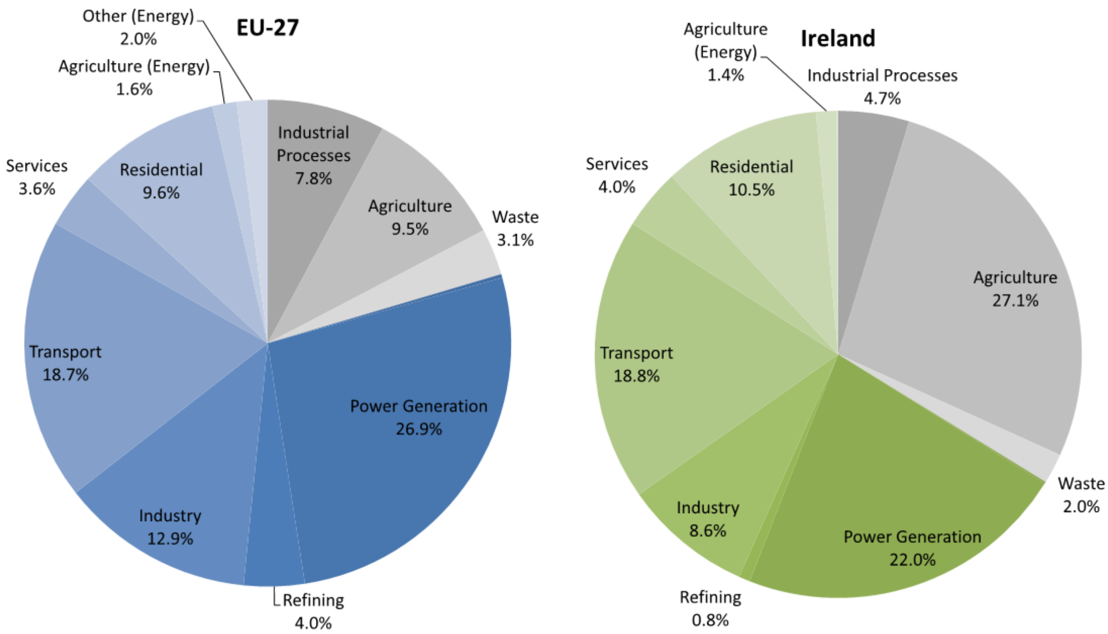

Figure 3-1. Comparing 2005 GHG emissions share in EU-27 and Ireland (Data source: EEA)

Ireland has not established a firm mandatory target for the year 2050, but does have ambitious and legally binding targets for GHG emissions reduction targets for the year 2020 (this is dealt with in detail in a separate paper (Ó Gallachóir et al., 2010b)). Under Directive 2009/29/EC approximately half of GHG emissions are due to large point source emitters (within part of industry, power generation and transformation) and are regulated under the European Emissions Trading Scheme (ETS). The collective target for all participants in the EU ETS is a 21% reduction in GHG emissions relative to 2005 levels[18] by 2020. Under the EU Effort Sharing Decision 2009/406/EC for the remaining half of greenhouse gas emissions (including agriculture), i.e. non-ETS emissions, the target for Ireland is to achieve a 20% reduction relative to 2005 levels. Recent national projections suggest that agriculture GHG emissions will be reduced by 4.4% in the period 2005-2020 (EPA, 2011b). There are no published projections for agriculture GHG available for Ireland for the period beyond 2020. If agriculture emissions remains at similar levels to those reached in 2020[19], the energy system must deliver a 127% reduction in emissions (relative to 1990 levels) in order to reach an overall 80% GHG emissions reduction target by 2050. According to the EU Low Carbon Roadmap, (Table 3-1), GHG emissions in agriculture are anticipated to reduce at EU level by 36% - 37% by 2030 and by 42% - 49% by 2050. According to this Roadmap, the other (primarily energy) sectors are anticipated to achieve more significant reductions than agriculture. This suggests that the share of GHG emissions from agriculture will grow in time and the role of

[18] For the period beyond 2020, Directive 2009/29/EC assumes ETS emissions reduce by 1.74% per annum (i.e. equivalent to a cumulative reduction of 31.3% relative to 1990 by 2050)
[19] i.e. assumed here to remain constant over the period 2020-2050.

the energy sector will reduce. This suggests that while most climate mitigation modelling tends to focus on energy, it is very important that agriculture is not ignored.

The combination of these two contextual points (emissions growth to 2005 and the significance of agriculture) results in a considerable challenge for Ireland to meet its emissions reduction targets for 2050 and makes Ireland an interesting case study for analysis.

3.1.3. Motivation and Paper outline

The purpose of this paper is to increase the evidence base necessary to inform policy discussions within Ireland regarding the choice of GHG emissions reduction target for 2050. The particular focus is on the feasibility (from a technical perspective) of an 80% GHG emissions reduction target for Ireland and on quantifying the costs associated with meeting such a target. The paper also assesses the implications of different short term targets on long term pathways, with particular emphasis on the separate targets for ETS and non-ETS sectors. The paper models technical energy systems options to deliver target emissions reductions in a least cost manner, using partial equilibrium modelling. It does not address the policy instruments which are required to achieve the technology solutions or address the behavioural challenges to be overcome. The paper focuses on energy-related CO_2 emissions but also takes into account the impacts of limited GHG reductions potential in agricultural (as indicated by separate literature analysis) on the targets for the energy system. Particular attention will be given to the implications for renewable energy, energy efficiency and more broadly for the economy.

This paper is structured as follows. Section 3.2 describes the methodological approach based on the MARKAL-TIMES modelling tools and introduces the Irish TIMES model used to carry out this analysis. Section 2 also presents some of the key inputs such renewable sources assumptions and introduces the different scenarios modelled. Section 3.3 presents the results, comparing the different mitigation scenarios in terms of impacts on the energy system and economic impacts. Section 3.4 draws some conclusions, discussing the relevance and the main recommendations for policy makers in Ireland.

3.2. Methodology

In recent years energy modelling has been used to provide policy makers instruments for decision making on GHG emissions reduction. Many detailed assessments into various regions around the world have been undertaken and are summarized in Clarke et al. (2009) and Das et al. (2007). Previous modelling work on GHG emissions mitigation package has been carried at global levels in

IEA studies (IEA, 2010) and within EU FP7 projects (SECURE). The TIAM[20] global model has been used for scenario assessment (Ekholm et al., 2008) and for stochastic analysis (Labriet et al., 2008; Loulou et al., 2009; Syri et al., 2008); to analyse the role of nuclear energy (Vaillancourt et al., 2008), of carbon capture and storage (CCS) and renewables (Koljonen et al., 2009). At EU level studies on mitigation targets have been undertaken using energy simulation models (Heaps et al., 2009) and least cost optimizations models such as the Pan European TIMES model which has been used to analyse security of energy supply (REACCESS), to investigate the role specific technologies such CCS (Ramírez et al., 2011) and to evaluate effects on future structure of the European energy system (Blesl et al., 2010). At national level, studies with MARKAL and TIMES models have been carried out for the UK (Anandarajah and Strachan, 2010) and for France (Assoumou and Maïzi, 2011).
Over the medium-term, modelling has been carried on the EU 2020 climate energy policy package using TIMES, establishing whether the individual allocation to Member States of renewable energy and emissions reduction delivers a least cost solution at EU level (Gargiulo et al., 2008; Giannakis, 2007). TIMES has also been used at Member State level to model the impacts of energy efficiency on emissions reduction (Blesl et al., 2007), to model the cost optimal way of meeting renewable energy targets (Ó Gallachóir et al., 2010a) and emissions reduction targets (Ó Gallachóir et al., 2010b).

3.2.1. Modelling approach using the Irish TIMES model

TIMES (The Integrated MARKAL-EFOM System) is a widely applied linear programming tool supported by ETSAP (Energy Technology Systems Analysis Program), an Implementing Agreement of the International Energy Agency (IEA) [21].
TIMES is an economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but may also be applied to study in detail single sectors. TIMES computes a dynamic inter-temporal partial equilibrium on integrated energy markets. The objective function to maximize is the total surplus. This is equivalent to minimizing the total discounted energy system cost while respecting environmental and many technical constraints. This cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon.

[20] <http://iea-etsap.org/web/applicationGlobal.asp>
[21] <http://iea-etsap.org/>

TIMES combines all the advanced features of MARKAL (Market Allocation) models, and to a lesser extent of EFOM (Energy Flow Model Optimization) models. The equations of the initial MARKAL model appear in Fishbone and Abilock (1981) and numerous improvements of the model have been developed since then for various applications (Kanudia et al., 2005; Kanudia and Loulou, 1999; Labriet et al., 2005). The full technical documentation of the TIMES model is available in Loulou et al. (2005). The TIMES/MARKAL family of models is widely used internationally and therefore has the significant advantage that the results can be compared with other countries.

In this paper, the Irish TIMES model has been used, which has been developed to build a range of medium (to 2020) to long term (to 2050) energy and emissions policy scenarios in order to inform policy decisions. Irish TIMES was originally extracted from the PET[36] model (Pan European TIMES Model that includes EU27, Iceland, Norway, Switzerland and Balkans countries) and then updated with local and more detailed data and assumptions (Howley et al., 2010).

The Irish-TIMES model represents the energy system of Ireland and its possible long term evolution. The core model contains a large database of (approximately 1600) energy supply side and demand side technologies. The database contains technical data (e.g. thermal efficiency, capacity), environmental data (e.g. emission coefficients) and economic data (e.g. capital costs) that vary over the entire time horizon.

The actual system encompasses in a network of technologies all the steps from primary resources in place to the supply of the energy services demanded by energy consumers, through the chain of processes which transform, transport, distribute and convert energy into services, as shown in Figure 3-2. The Irish energy system is characterised and modelled in terms of its supply sector (fuel mining, primary and secondary production, exogenous import and export), its power generation sector (including also the combined heat and power description), and its demand sectors (residential, commercial and public services, agricultural, transport and industry).

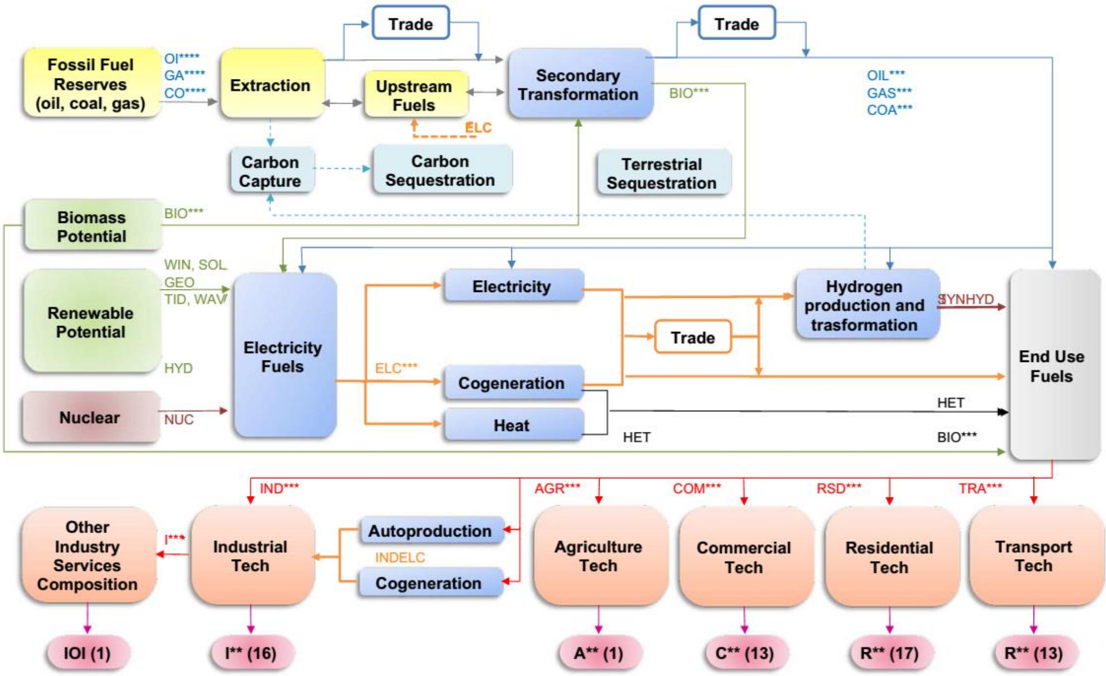

Figure 3-2. Irish TIMES Reference Energy System (Source: (Gargiulo et al., 2010))

The key inputs to Irish TIMES are the demand component (energy service demands), the supply component (resource potential and costs), the policy component (scenarios) and the techno-economic component (technologies and associated costs to choose from).

3.2.2. Demand component

The model is driven by exogenous demand specified by the list of each energy service demands (ESD), actual values in the base year (calibration) and values for all milestone years until 2050 (projection). The number of energy service demands can vary between different models and the level of detail of data available for each sector. In the Irish TIMES model, the demand component is driven by 60 different ESD (specified by the list in Table 3-3), namely 20 for the residential sector, 12 for services, 13 for industry, 13 for transport, 1 for agriculture and 1 for non-energy. Higher levels of detail are used in the residential sector, in which heat and water end-users are classified according to 6 different dwellings types, specified as new or existing and also distinguishing between urban, rural and multi-apartment; and in the case of services sector, in which the model distinguishes between 4 types of dwelling (new/existing, large/small). In the transport sector, mean car and motorcycle size is used to describe private transport, while public transport distinguishes between urban and intercity services. In the industry sector, standard production chains have been used to design specific sectors such for example *Cement* and *Iron and Steel*, while aggregate end-users are defined for the *Other Non-Energy Intensive* industry and the agriculture sector. Table 3-3 also indicates the unit used to represent each demand driver, which varies across ESD (for example the amount of car road travel in passenger kilometres, residential lighting final energy in PJ, cement production in Mt, etc.).

CODE	Description	Unit(*)	CODE	Description	Unit(*)
	RESIDENTIAL (20)			**INDUSTRY (13)**	
RCDR	Clothes Drying.	PJ	IAL	Aluminium	Mt
RCOK	Cooking	PJ	IAM	Ammonia	Mt
RCWA	Clothes Washing	PJ	ICH	Other Chemicals	PJ
RDWA	Dish Washing	PJ	ICL	Chlorine	Mt
RHME	Space Heat.Multi.All.Existing.	PJ	ICM	Cement	Mt
RHMN	Space Heat.Multi.All.New	PJ	ICU	Copper	Mt
RHRE	Space Heat.Single.Rural.Ex	PJ	IFB	Food and Beverages	PJ
RHRN	Space Heat.Single.Rural.New	PJ	IIS	Iron and Steel	Mt
RHUE	Space Heat.Single.Urban.Ex	PJ	ILM	Lime	Mt
RHUN	Space Heat.Single.Urban.New	PJ	INF	Other Non-Ferrous Metals	PJ
RLIG	Lighting	PJ	INM	Other Non-Metallic Minerals	PJ
ROEL	Other Electric	PJ	IOI	Other Non-Energy Intensive	PJ
ROEN	Other Energy	PJ	IPL	Low Quality Paper	Mt
RREF	Refrigeration	PJ			
RWME	Water Heat.Multi.All.Existing.	PJ		**TRANSPORT (13)**	
RWMN	Water Heat.Multi.All.New	PJ	TAI	Aviation International	PJ
RWRE	Water Heat.Single.Rural.Ex	PJ	TAV	Aviation Generic.	PJ
RWRN	Water Heat.Single.Rural.New	PJ	TBI	Road Bus Intercity.	Mp*km
RWUE	Water Heat.Single.Urban.Ex	PJ	TBU	Road Bus Urban.	Mp*km
RWUN	Water Heat.Single.Urban.New	PJ	TCL	Road Car Long Distance.	Mp*km
			TCS	Road Car.Short Distance.	Mp*km
	SERVICES (12)		TFR	Road Freight.	Mt*km
CCOK	Cooking.	PJ	TMO	Road Moto	Mp*km
CCLE	Space Cool.Large.	PJ	TNA	Navigation Generic	PJ
CCSE	Space Cool.Small.	PJ	TNB	Navigation Generic Bunker	PJ
CHLE	Space Heat.Large.	PJ	TTF	Rail Freight.	Mt*km
CHSE	Space Heat.Small.	PJ	TTL	Rail Passengers Light.	Mp*km
CLIG	Lighting.	PJ	TTP	Rail Passengers Heavy.	Mp*km
COEL	Other Electric.	PJ			
CPLI	Public Lighting.	PJ		**AGRICULTURE (1)**	
CREF	Refrigeration.	PJ	AGR	Agriculture, fishery, forestry	PJ
CWLE	Water Heat.Large.	PJ			
CWSE	Water Heat.Small.	PJ		**NON ENERGY (1)**	
ONE	Other Sector.	PJ	NEO	Others	PJ

(*) PJ here means 'PJ of final energy in the base year'

Table 3-3. List of exogenous energy service demands in the Irish TIMES model

Projecting future energy service demands over the time horizon within TIMES require two sets of parameters: demand drivers and elasticities. Both demand drivers (for example population, GDP, number of households) and demand elasticities are mostly linked to economic activity and to energy prices, which are usually exogenously obtained via other models or from accepted other sources. To drive the demand component in Irish TIMES, macro-economic forecasts from the Economic and Social Research Institute (Bergin et al., 2010) are used as demand drivers that are summarised in Table 3-4, in conjunction with GEM-E3's [22] industry Autonomous Energy Efficiency Improvement (AEEI)(GEM-E3). Ireland's published baseline national energy forecasts (Walker et al., 2009) were used to calibrate the elasticities used in the reference energy scenario within Irish TIMES[23].

Driver	Description	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2050
GDP	GDP	0.10%	3.16%	2.12%	1.36%	1.95%	1.98%	1.63%	1.49%
POP	Population	1.49%	0.85%	1.07%	0.89%	0.59%	0.54%	0.47%	0.34%
HOU	Number of Households	2.76%	1.82%	1.92%	1.84%	1.60%	1.14%	0.91%	0.61%
RSD	Residential sector	-1.23%	2.97%	2.19%	1.64%	2.14%	2.17%	1.82%	1.69%
TRA	Transport sector	-0.27%	2.83%	3.34%	2.31%	2.26%	2.27%	1.91%	1.74%
TRAc	Transport demand by Households	-3.52%	2.77%	1.47%	0.98%	2.03%	2.15%	1.78%	1.76%
AGR	Agriculture	-0.06%	0.76%	0.69%	0.72%	0.41%	0.43%	0.08%	-0.07%
IISNF	Industry: Iron&Steel and non-ferro	2.21%	5.35%	2.15%	0.51%	2.22%	2.21%	1.83%	1.64%
ICH	Industry: Chemical	2.21%	5.35%	2.15%	0.51%	2.22%	2.21%	1.83%	1.64%
INMPP	Industry: Other energy intensive (Buildings)	-13.83%	7.33%	3.83%	2.39%	0.69%	0.69%	0.69%	0.69%
IOI	Industry: Other industries	-0.78%	5.44%	2.30%	0.76%	1.89%	1.92%	1.56%	1.41%
COM	Services sector	2.02%	2.00%	1.85%	1.57%	2.01%	2.04%	1.69%	1.56%

Table 3-4. Trends of demands drivers in the Irish TIMES model 2005-2050

Demand drivers rates (DDR) and elasticities constitute the energy service demand driver (ESD Driver) over the period using the following formulas:

$$DDR(t) = \left(\left(\frac{Demand\ Driver(t)}{Demand\ Driver(t-1)}\right) - 1\right)$$

Equation 1

$$ESD\ driver(t) = (1 + DDR(t) * elasticity(t))^{periodlength} * (1 - AEEI)$$

Equation 2

where *t* is the reference year for the demand driver.

[22] GEM-E3 acronym stands for "General Equilibrium Model for Economy, Energy and Environment"

[23] Baseline scenario to 2020 incorporates the expected impact of policies and measures that were in place by the end of 2008. It includes energy efficiency measures such the 2008 Building Regulations, the change in private-car taxation to an emissions-based system and the pilot Home Energy Savings Scheme.

Once the drivers are determined and quantified for each sector and period, the construction of the demand scenario requires computing a set of energy service demands over the horizon (Loulou et al., 2005) according to the following formula:

$$Demand(t) = (Demand(t-1) * Driver(t))$$

Equation 3

To take into account the complexity of residential sector that is characterized by different dwelling types and ages, residential heating demand is modelled differently. The main demand driver here, the number of dwellings, is combined with specific dwelling consumption. For existing rural, urban and multi-apartment dwellings specific consumption is based on historical data, while for new dwellings decreasing consumption over the time horizon is evaluated taking into account the impacts of new building regulations (Dineen and Ó Gallachóir, 2011). Demand for existing and new stock of dwellings is evaluated using the following formulas:

$$Demand(t) = \left(\sum_{t} Number\ Of\ Dwelling(t) * Specific\ Consumption(t) \right)$$

Equation 4

where *t* is the year of construction of the dwelling, while *Specific Consumption* is expressed as (energy/dwelling).

To deliver energy service demands each demand sector is characterized by a large demand technology database. The database contains all technical, environmental and economic data to describe the existing technology stock and all possible future technology options. Table 3-5 presents an extract of this database for private car transport demand sector.

	Code	Description	Activity Unit	Capacity Unit
Existing	*TCARDST100*	Car. Diesel - Base-year	Mp*km	1000vehicles
	TCARGSL100	Car. Gasoline - Base-year	Mp*km	1000vehicles
	TCARLPG100	Car. LPG - Base-year	Mp*km	1000vehicles
New	*TCAR_PIH*	Car. Plug-in Hybrid	Mp*km	1000vehicles
	TCARSBDL101	Car. Biodiesel	Mp*km	1000vehicles
	TCARSDME110	Car. Dimethyl Ether	Mp*km	1000vehicles
	TCARSDST101	Car. Diesel	Mp*km	1000vehicles
	TCARSDST210	Car. Diesel Hybrid	Mp*km	1000vehicles
	TCARSELC110	Car. Electric	Mp*km	1000vehicles
	TCARSETH101	Car. Ethanol	Mp*km	1000vehicles
	TCARSFTD110	Car. FT-Diesel	Mp*km	1000vehicles
	TCARSGAS101	Car. Gas	Mp*km	1000vehicles
	TCARSGH2110	Car. Compr. H_2. Int. Comb.	Mp*km	1000vehicles
	TCARSGH2210	Car. Compr. H_2 Fuel Cell	Mp*km	1000vehicles
	TCARSGSL101	Car. Gasoline	Mp*km	1000vehicles
	TCARSGSL201	Car. Gasoline Hybrid	Mp*km	1000vehicles
	TCARSLH2110	Car. Liquified.H_2.Int. Comb.	Mp*km	1000vehicles
	TCARSLPG101	Car. LPG	Mp*km	1000vehicles
	TCARSMtaH101	Car. Methanol Int. Comb.	Mp*km	1000vehicles
	TCARSMtaH210	Car. Methanol Fuel Cell	Mp*km	1000vehicles

Table 3-5. Private car transport technology database

3.2.3. Supply component

A key input to Irish TIMES on the supply side is the present and future sources of primary energy supply their potentials and fuel prices. The prices for conventional fuels are those inherited from the PET model and are drawn from the IEA's reference scenario in the World Energy Outlook 2008 (IEA, 2008).

Given the importance of renewable energy for the achievement of mitigation targets, Ireland's energy potentials and costs are based on the most recently available data. The upper capacity limit for onshore and offshore wind energy, summarized in Table 3-6, for the year 2050 is 14.4 GW (Chiodi, 2010; DETI & DCENR, 2008; SEI, 2004).

Technology	Process code	Unit	2006	2010	2015	2020	2025	2030	2050
Wind onshore	*EUWINON201*	GW	0.3	2.1	3.1	5.3	5.6	5.9	6.9
Wind offshore	*EUWINOF201*	GW	0.0	0.1	0.6	1.0	2.7	3.8	7.5

Table 3-6. Wind Resource Potential

The ocean energy resource potential is aligned with the ocean energy roadmap (SEAI, 2010b) and set at 29 GW in 2050, while the total resource capacity limit for domestic bioenergy has been set at 1,230 ktoe for the year 2020 and at 3,500 ktoe by 2050. The potential for each individual commodity is shown in Table 3-7, are based on the results of Bioenergy Strategy Group and Smyth et al. (BSG, 2004; Smyth et al., 2010). The potential for additional large hydro plants in Ireland is limited but further deployment of small hydro plants is possible (ESBI and ETSU, 1997). The maximum capacity for hydro energy has been set at 224 MW for large plants and at 250 MW for run of river plants. The existing 292 MW pumped hydro storage plant is also modelled. The use of solar and geothermal energy in Ireland is limited only to small installations in the residential and services sector mostly for space and water heating purposes. Because solar and geothermal energy contribute marginally to scenarios outputs, no maximum potentials have been provided in the model.

Commodity	**Process code**	**Unit**	**2005**	**2010**	**2020**	**2030**	**2040**	**2050**
Agricultural waste[1]	*MINBIOAGRW1*	ktoe	25.0	153.1	188.0	188.0	188.0	188.0
Starch crop[1]	*MINBIOCRP11*	ktoe	0.0	31.6	47.4	79.0	79.0	79.0
Grassy crop (Miscanthus)[1]	*MINBIOCRP31*	ktoe	2.7	4.0	28.0	211.3	394.7	910.3
Woody crop (Willow)[1]	*MINBIOCRP41*	ktoe	13.1	19.7	137.6	284.4	431.2	722.0
Forestry residues[1]	*MINBIOFRSR1*	ktoe	62.3	93.5	109.1	109.1	109.1	109.1
Biogas[1,2]	*MINBIOGAS1*	ktoe	30.8	38.4	284.9	382.6	480.3	578.0
Municipal waste[1]	*MINBIOMUN1*	ktoe	71.1	142.2	155.5	155.5	155.5	155.5
Rape seed[2]	*MINBIORPS1*	ktoe	1.7	7.2	14.3	14.3	14.3	14.3
Industrial waste[1]	*MINBIOSLU1*	ktoe	0.0	2.3	7.0	7.0	7.0	7.0
Wood processing residues[1]	*MINBIOWOOW1*	ktoe	258.9	258.9	258.9	258.9	258.9	258.9

[1] Assumptions based on BSG

[2] Assumption based on Smyth et al.

Table 3-7. Bioenergy potential

The cost assumptions for renewable energy technologies are from the values in the PET model used in the Intelligent Energy - RES2020 project (RES2020) and where available, data changes were made based on updated information. In the case of wind and ocean energy, the data used in the model are based on analysis of international trends (including wind turbine capital costs) and costs specific to Ireland (for example grid connection costs) (Chiodi, 2010; Ó Gallachóir et al., 2010d).

3.2.4. Model sets and assumptions

The Irish TIMES model used here has a time horizon of 45 years that ranges from 2005, the base year, to 2050, with time resolution of four seasons with day-night time resolution, the latter comprising day, night and peak time-slices.

The current version of Irish TIMES does not have an elastic demand module, therefore, the energy system can respond here to emissions constraints through energy efficiency and energy supply technology change but not through demand reduction. Energy conservation for the existing building stock (i.e. additional building insulation) are modelled as additional proxy technology options (with associated costs) and are available options in the least-cost optimization.

The model also embeds several constraints to improve the realism associated with future energy pathways. In fact the intrinsic nature of a linear programming model could otherwise deliver in many cases extreme technology switches. Constraints are designed to take into account physical limitations such the lack of infrastructure, as for example in the case of residential and services sector in which we set a maximum share of gas penetration to take into account the absence of distribution pipelines in many areas in the country. Furthermore, although this analysis does not consider detailed modelling of transmission issues, frequency and inertia issues of voltage stability, constraints are set to reproduce operational constraints within the power system. Based on work undertaken by EirGrid (2010)(Ireland Transmission system operator), the level of intermittent (non-dispatchable) renewable generation (namely wind, solar and ocean energy) is limited here to 70% within each timeslice to account for operational issues associated with such high levels of variable generation in the power system. The model also includes a limited number of diffusion constraints to control the growth rate of certain sectors such electricity generation and industry sectors. For example diffusion constraints are applied to the maximum annual growth of electricity generation capacity and on industrial CHP plants; while a non-decreasing diffusion constraint is applied to wind capacities. No diffusion constraints are introduced in the end-use sectors the results for which are based on least cost considerations.

Finally is worth nothing that all constraints designed in this model (excluding policy constraints described in Section 3.2.5 that characterize single scenarios) are applied in all scenarios, and no constraint are imposed to maintain systems until the end of their lifetime. Regarding policies, investment subsidies and feed-in-tariffs for renewables based on policies currently in practice are assumed here to continue until 2030 and no trading of green certificate is assumed.

3.2.5. Scenario definition

For the purposes of this research work five main energy system configurations have been developed and discussed in this paper: the *Reference* (*REF*) scenario, introduced to provide a starting point against which the four GHG emissions mitigation scenarios can be measured, namely the *CO2-80* scenario, the *CO2-95* scenario, the *NETS-20/CO2-80* scenario and the *NETS-80* scenario.

1. The *Reference (REF)* scenario is the least cost optimal pathway that delivers the energy service demands in the absence of emissions reduction targets. For the period to 2020 national energy forecasts (Walker et al., 2009) are used as a benchmark: it provides a starting point against which other scenarios are compared.

2. In the *CO2-80* scenario the energy system is required to achieve at least an 80% CO_2 emissions reduction below 1990 levels by 2050 (-86.5% relative to 2005). The pathway includes specific interim targets in line with the EU climate energy package and the EU Low Carbon Roadmap, i.e. 20% CO_2 emissions reduction by 2020 relative to 2005 levels, 40% and 60% below 1990 levels by 2030 and 2040. It is implicitly assumed here that non-energy GHG emissions are reducing on a similar pathway to energy related emissions.
3. In the *CO2-95* scenario, the energy system is required to meet a more stringent target by 2050, i.e. 95% emissions reduction target below 1990 levels (-96.6% relative to 2005). This is to achieve the economy wide 80% GHG emissions reduction target while compensating for lower emissions reduction achievements in non-energy sectors (notably agriculture, which is here assumed to meet a 50% emissions reduction by 2050). The pathway imposed on the energy system comprises 26.8% CO_2 emissions reduction by 2020 relative to 2005 levels and then 50% and 70% below 1990 levels by 2030 and 2040 respectively. This trajectory is established based on using exogenous GHG emissions projections from agriculture available from separate literature analysis (EC, 2011c; EPA, 2011b). In this paper, we don't address here the feasibility or the policy measures or technology solution that may be required to achieve these reductions in agriculture.
4. The *NETS-20/CO2-80* scenario combines the 80% CO_2 emissions target by 2050 with interim 2020 targets that distinguish between Emissions Trading Scheme (ETS) sectors and non-ETS sectors (as specified in Directive 2009/29/EC and Decision 2009/406/EC). This scenario delivers, by the year 2020, 21% emissions reduction (relative to 2005 levels) for ETS sectors and 20% reduction (relative to 2005 levels) for Non-ETS sectors. The reduction targets beyond 2020 are as per the *CO2-80* scenario. It is implicitly assumed here that non-energy GHG emissions reducing in a similar pathway to energy related emissions.
5. The *NETS-80* scenario maintains distinct targets for ETS and non-ETS targets over the full time horizon to 2050. This scenario delivers, by the year 2020, 21% CO_2 emissions reduction (relative to 2005 levels) for ETS sectors and 20% reduction (relative to 2005 levels) for Non-ETS sectors. It further delivers 80% energy-related CO_2 emissions reduction by mean of separate 80% targets for ETS and Non-ETS sectors. The pathway comprises reductions of 40% and 60% below 1990 levels for both ETS and non-ETS sectors by 2030 and 2040 respectively. It is implicitly assumed here that non-energy GHG emissions reducing in a similar pathway to energy related emissions.

Clearly it is also possible that GHG emissions from agriculture may remain at similar levels to those reached in 2020, or may increase due to increased agricultural activity and limited abatement options. As already mentioned, if agriculture emissions remains at similar levels to 2020, the energy system must deliver a 127% reduction in emissions (relative to 1990 levels) in order to reach an overall 80% GHG emissions reduction target by 2050. This has not been tested because negative emissions can be delivered only by bioenergy carbon capture and sequestration (CCS) technologies or by trading emissions permits, neither of which are yet available in Irish TIMES.

It is worth noting that in each mitigation scenario we prescribe emissions upper bounds not only in 2050 but also for each time period. In the case of the *CO2-80* and *CO2*-95 scenarios, an upper bound is imposed on overall CO_2 emissions and in the *NETS-20/CO2-80* and *NETS-80* scenarios, upper bounds are imposed separately on ETS and Non-ETS emissions. In all cases, the sectoral share of emissions is the result of endogenous competition.

3.3. Results

This results for the Irish TIMES emissions reduction scenarios for Ireland are grouped into three main sub-sections. Firstly the Reference (*REF*) scenario is compared with two alternative long-term energy pathways, one that delivers an 80% reduction in energy-related CO_2 emissions (*CO2-80*) and another that delivers an 80% reduction in GHG emissions (*CO2-95* i.e. 95% reduction in CO_2 emission assuming a 50% reduction in agriculture emissions). This is followed by a discussion of some of the impacts of different short term policy targets on long term pathways (including having separate ETS and non-ETS targets), comparing *CO2-80* with *NETS-20/CO2-80* and *NETS-80*. Finally, the economic implications of meeting these deep emissions reduction targets is discussed, focussing on marginal abatement costs, total energy system costs and investments costs.

3.3.1. Comparing REF, CO2-80 and CO2-95 scenario energy systems

3.3.1.1. Emissions trajectories

Figure 3-3 illustrates the trajectories of energy-related CO_2 emissions for the *REF* scenario and the constrained emissions mitigation scenarios *CO2-80* and *CO2-95*. In the *REF* scenario, emissions reach 33.9 Mt CO_2 in 2050, representing a 24.2% reduction relative to 2005 levels, but a 12.1% increase relative to 1990 levels. It is worth noting how radical these scenarios are and to get a sense of the scale of effort required. In scenario *CO2-95*, the maximum CO_2 emissions that the energy system can produce in 2050 are 1.5Mt. This is equivalent (in terms of Ireland’s current energy system) to less than 10% of current emissions from electricity generation, noting that electricity accounts for just 18% of energy use.

Figure 3-4 compares the breakdown of CO_2 emission reductions by sector in 2050 for each of the mitigation scenarios. In *CO2-80* most of the emission reductions are achieved in transport and power sector, with reductions respectively of 15.0 and 5.9 Mt of CO_2 equivalent (i.e. reductions of 97.6% and 83.4%) relative to *REF* scenario. The remaining 7.0 Mt of CO_2 emission reductions are provided by industry, comprising a 93.7% reduction relative to *REF* emissions, followed by residential (-49.5%) and services sector (-62.0%). To deliver the 95% CO_2 emissions reduction target, additional reductions are achieved in the electricity generation sector, that moves to almost complete decarbonisation, and by the residential and services sectors, with reductions of 1.8 and 0.7 Mt respectively (reductions of 89.0% and 98.8% relative to *REF*).

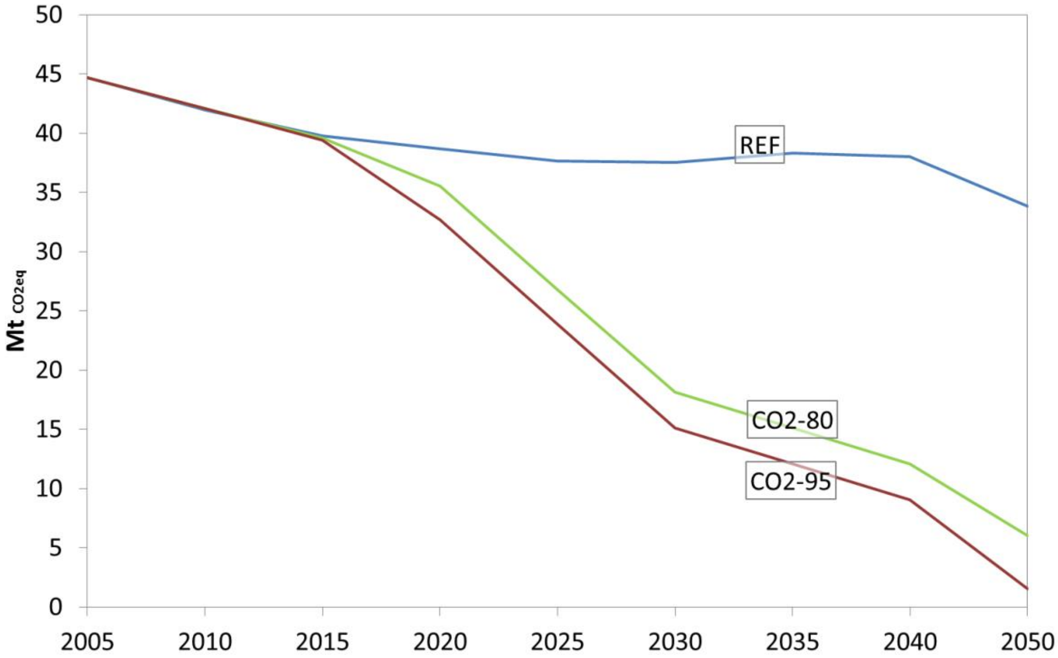

Figure 3-3. Total CO_2 emissions trajectories by scenario (Mt)

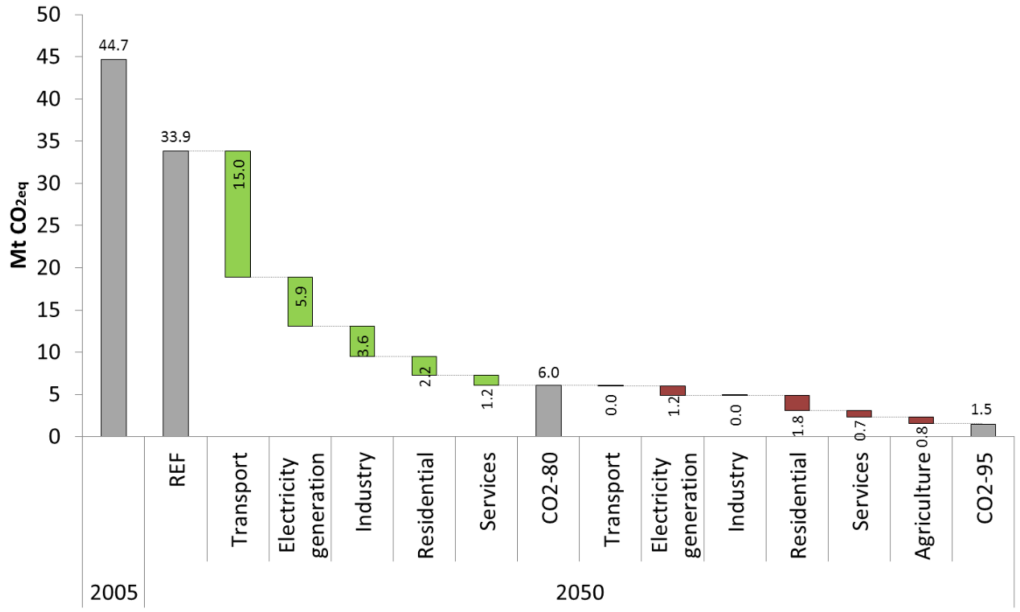

Figure 3-4. Decomposition of total CO_2 emissions in REF, CO2-80 and CO2-95 (Mt)

3.3.1.2. Evolution of final energy consumption

Changes in final energy consumption are driven by economic activity (which affects energy service demands), the type of end use energy (including electricity) and the efficiencies of end-use technologies, in addition to consumer response to changing energy prices and to policy measures.

Figure 3-5 presents the evolution of total final consumption (TFC) of energy by sector for the scenarios. Comparison with Figure 3 demonstrates how energy consumption trends are not always aligned with emissions trends. In the *REF* scenario, TFC will increase by 16.7% in the period 2005-2050, while CO_2 emissions reduce by 24.7% over the same time horizon. This is related to the (cost-effective) fuel switching between high emissions factors fuels (mainly oil based) to lower emissions factors ones, such natural gas and renewables. In the mitigation scenarios (*CO2-80* and *CO2-95*) TFC increases until 2020 (by 6.5% and 5.5% respectively relative to 2005 levels), and then reduces to 7.2% and 10.3% below 2005 levels by 2050. At a sectoral level, this reduction is mostly evident in the transport, residential and services sectors, while industry witnesses stable TFC levels during the whole period 2010-2050.

There is currently no feedback between the Irish TIMES scenario results and the economy and hence in all scenarios, economic growth (measured in terms of GDP) follows the same trend, growing by 1.69% per annum on average over the period 2005 – 2050. TFC grows by 0.37% p.a. in the *REF* scenario and reduces by 0.16% and 0.23% p.a. respectively in the *CO2-80* and *CO2-95* scenarios, illustrating the increased decoupling between economic growth and emissions growth.

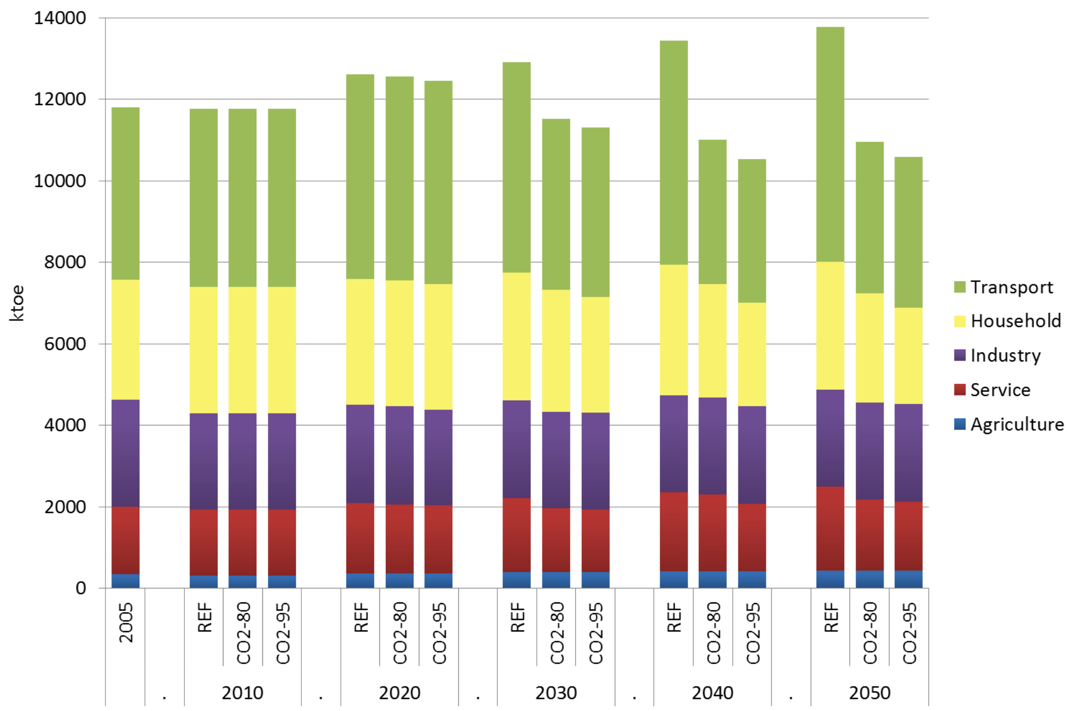

Figure 3-5. Final energy consumption by sector in REF, CO2-80 and CO2-95 (ktoe)

Transport sector

Figure 3-6 compares energy consumption in transport over the period for each scenario. Total fuel consumption is expected to grow by 36.1% in the *REF* scenario by 2050 (relative to 2005 levels), while in *CO2-80* and *CO2-95* transport TFC decreases by 12.5% and 12.7% respectively.

Another significant difference between *REF* scenario and the mitigation scenarios is the fuel share of the transport fleet. In the *REF* scenario, in the period 2010-2040, the petrol (gasoline) fleet (in 2040 only 5.7% of TFC) is gradually replaced by a diesel fleet (in 2040 diesel represents 86.0% of TFC), while in the *CO2-80* and *CO2-95* biofuel vehicles replace the petrol fleet. By 2050 the *REF* scenario allocates about 1264 ktoe (21.9% of TFC) to natural gas vehicles, while diesel consumption reduces to 63.3% of TFC. By contrast, the *CO2-80* and *CO2-95* scenarios face a strong reduction of overall consumption with shares dominated by biofuels that account for 82.5% (3056 ktoe) and 81.2% (3001 ktoe) respectively of TFC.

In the *REF* scenario, biofuels comprise mostly biogas and biodiesel with ratios in 2050 of 98.1% and 1.9% (albeit for a low volume of renewable fuels), while *CO2-80* and *CO2-95* show increasing shares of biodiesel (89.0% and 90.1%), mainly imported, and bio-ethanol (1.7% and 1.8%). Biogas reduces accounting for 9.3% and 8.1% of biofuel consumption.

The penetration of electric vehicles (EVs) remains negligible until 2030, when in *CO2-80* and *CO2-95* pass from 0.2 and 0.6% in 2025 to 4.2% and 4.5% of TFC in 2030. By 2050 this share grows to 14.2% (528 ktoe) in *CO2-80* and 15.6% (577 ktoe) in *CO2-95*, while account only for 0.9% in *REF*.

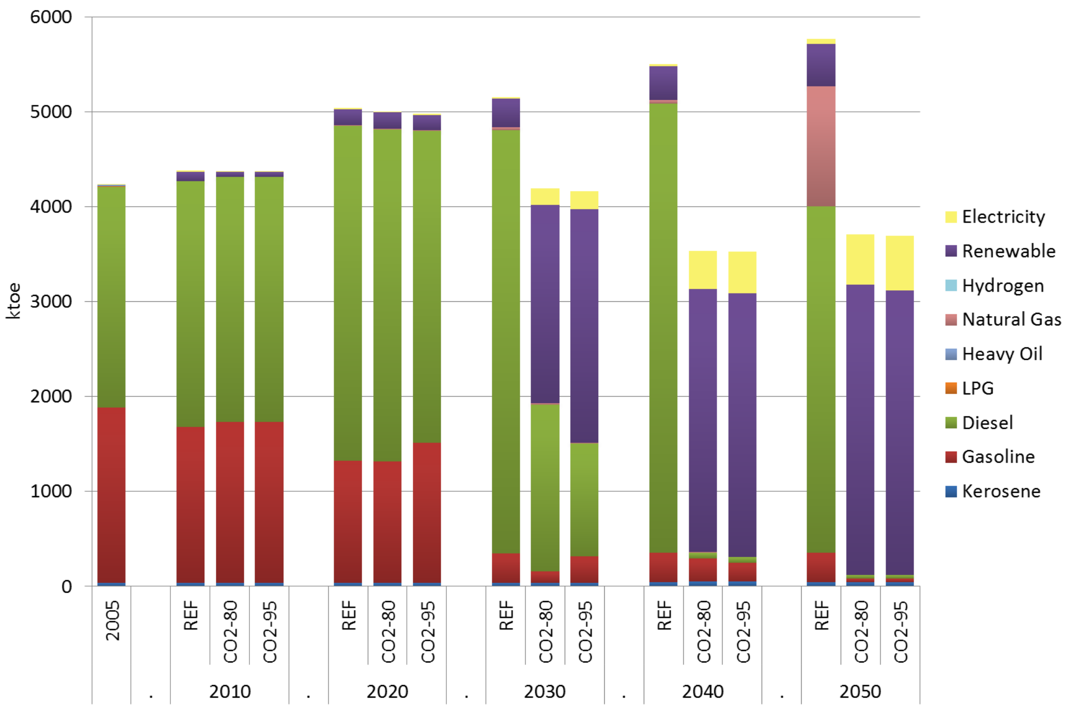

Figure 3-6. Transport final energy consumption in REF, CO2-80 and CO2-95 (ktoe)

Focusing on on-land (i.e. road and rail) transportation, Figure 3-7 separates transport energy use by fuel for the different end uses in the year 2050. In the *REF* scenario, freight is the most energy consuming sector (2328 ktoe), followed by private car transport (2200 ktoe). Public transport accounts for about 2.7% of energy consumption. The mitigation scenarios show radical transformations in fuel shares and consumption, pushing the substitution of diesel and natural gas fleets to biofuels (mainly biodiesel) in freight and public transport; then electrifying the private car transport sector reducing dramatically overall fuel consumption through the efficiency gains.

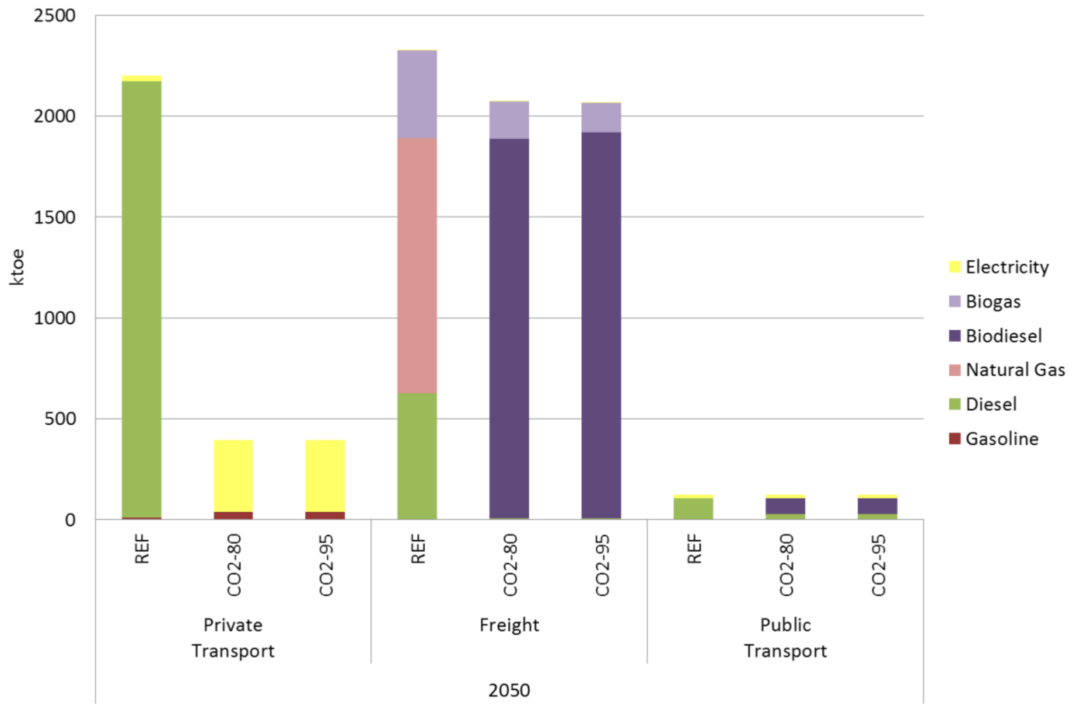

Figure 3-7. 2050 transport energy by end-use in REF, CO2-80 and CO2-95 (ktoe)

Residential and services sector

The residential sector exhibits some differences at TFC level across the scenarios mainly after 2020 (Figure 3-8). In the *REF* scenario, TFC grows slightly (6.5% relative to 2005 by 2050), while the *CO2-80* and *CO2-95* scenarios show significant TFC reductions from 2030. These reductions are endogenously chosen as results of the optimization and are driven by the installation of more efficient appliances (i.e. heat pumps and fluorescent lighting system), investment in conservation (i.e. walls and windows insulation) and fuel switching (i.e. from oil to electricity). By the year 2050, *CO2-80* TFC is 8.7% lower than 2005, while in *CO2-95* this reduction will reaches 19.2%.

In all scenarios, renewables and electricity (mainly for heating) grows, mostly displacing oil-based heating systems. By 2050, electricity accounts for 24.5% of TFC in *REF* (+20.2% relative to 2005), 38.6% in *CO2-80* and 76.82% in *CO2-95* respectively; while renewable energy, mainly biomass and biogas, accounts for 21.3%, 25.6% and 14.6% of TFC in *REF*, *CO2-80* and *CO2-95* respectively. Delivering the more challenging emissions reductions target, as illustrated in the

CO2-95 scenario, the model reduces direct use of bioenergy in addition to gas, in favour of higher electricity consumption (although not shown here, reduced bioenergy in TFC is offset by increased bioenergy used in electricity generation).

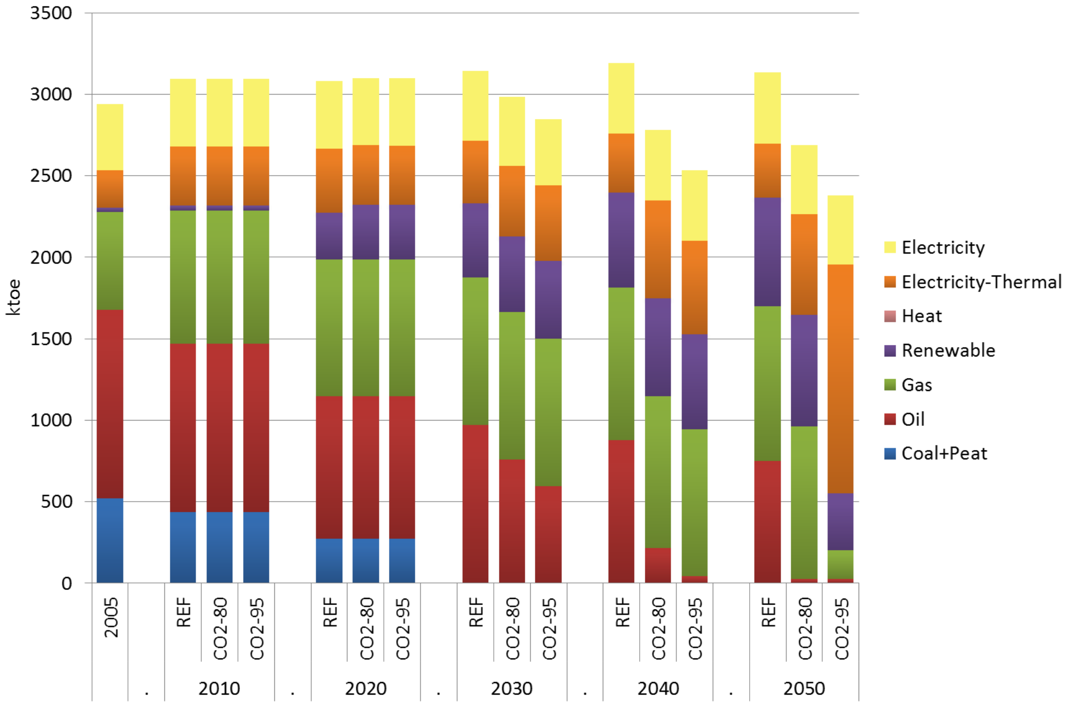

Figure 3-8. Residential final energy consumption in REF, CO2-80 and CO2-95 (ktoe)

For the services sector (Figure 3-9) the results are similar to the residential sector, i.e. an increasing share of electricity, renewables and gas, displacing completely coal and peat[24] and oil use. The effect of the emissions reduction targets is to accelerate this trend and to improve the efficiency. In the *REF* scenario, TFC grows by 23.5% in 2050, while the *CO2-80* and *CO2-95* scenarios indicate lower growth (4.3% and 1.3% above 2005 levels by 2050) mostly due to the effect of installing more efficient technologies and increased building efficiency. Electricity in *REF* represents 49.4% of 2050 TFC, while for *CO2-80* and *CO2-95* electricity accounts for 58.7% and 83.8% respectively. The *CO2-95* scenario interestingly points to a complete decarbonisation of the services sector by the year 2050.

[24] No new coal and peat options are provided in the model after the base year.

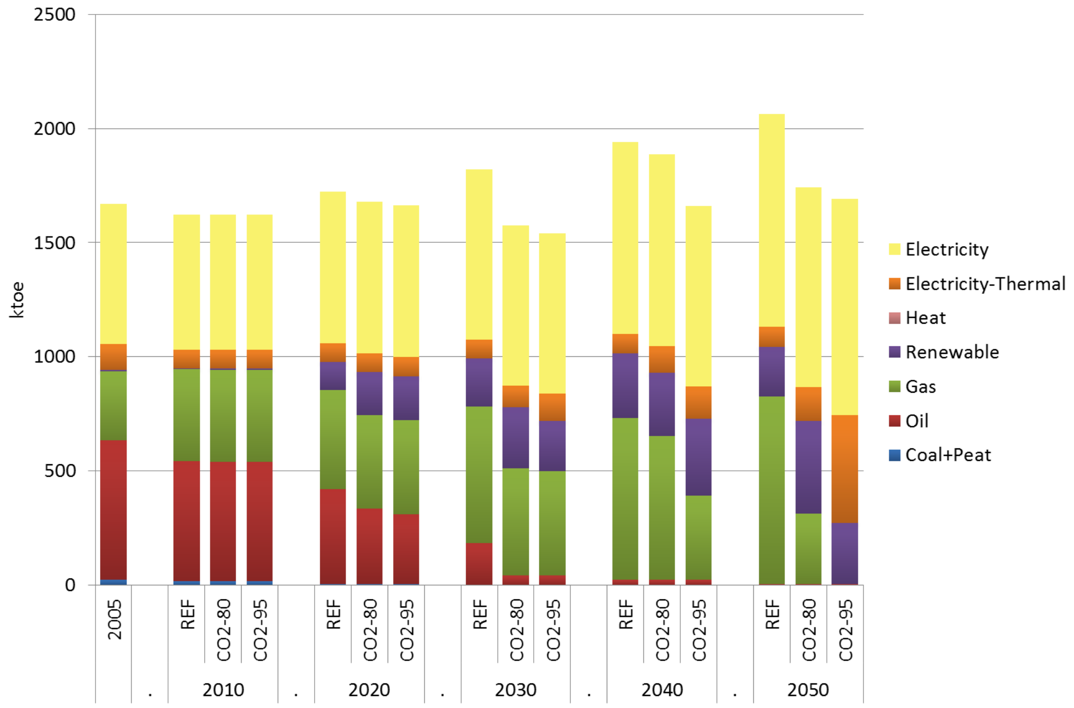

Figure 3-9. Services final energy consumption in REF, CO2-80 and CO2-95 (ktoe)

Industry sector

Moving to industry, Figure 3-10 summarises the TFC fuel mix evolution for the three scenarios. By 2050 industry TFC is about 2400 ktoe, in all scenarios, i.e. similar to 2010 levels. Economic activity in industry increases by 9.6% over the same period indicating the low energy intensity of industry in Ireland, dominated by food and beverage manufacture, information and communication technologies and pharmaceuticals. While the overall TFC is similar in all scenarios, the fuel mix varies between scenarios: in the *REF* scenario, the energy mix is still dominated by oil (28.1%), electricity (26.2%) and natural gas (24.8%), while renewables (mainly biomass) account for 20.9%; for the *CO2-80* and *CO2-95* scenarios by contrast, the fuel mix is dominated by renewables and electricity, with minor contribution of natural gas to fuel CHP plants. In *CO2-80* bioenergy accounts for 1604 ktoe (67.4% of TFC) by 2050, while electricity account for 28.5%. In *CO2-95* the electricity share is higher at 36.6% of TFC (874 ktoe), while bioenergy consumption is 11.2% lower than in *CO2-80*. In all scenarios coal and peat consumption gradually reduce and are phased out from 2030 onwards.

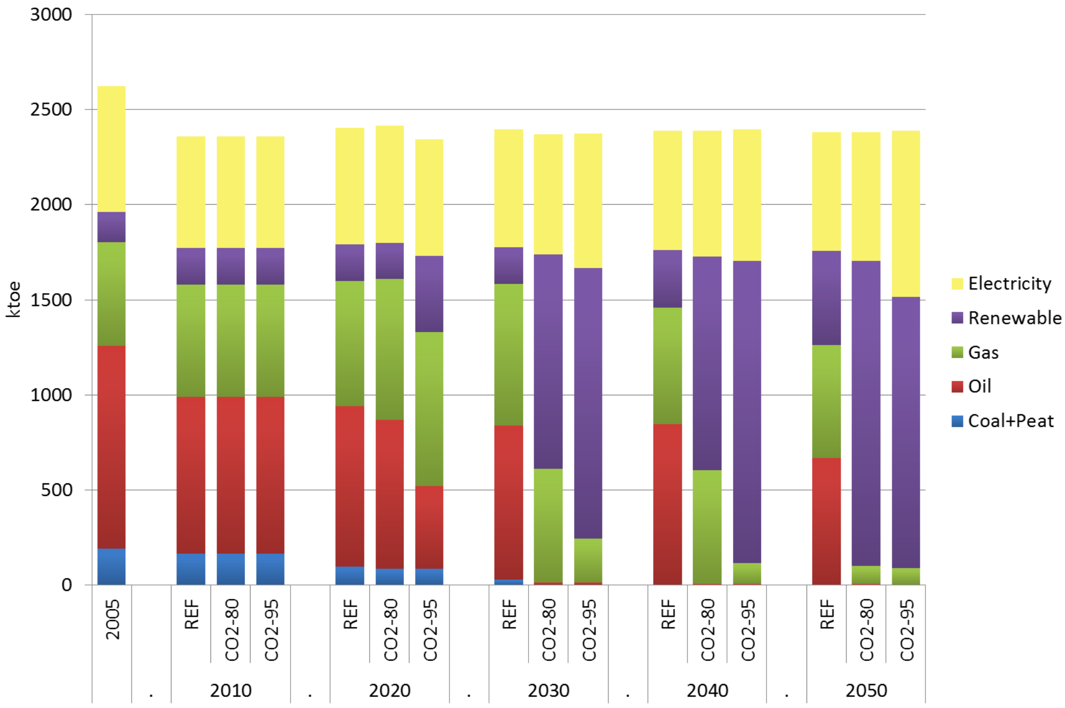

Figure 3-10. Industry final energy consumption in REF, CO2-80 and CO2-95 (ktoe)

Electricity use and fuel mix

Figure 3-11 summarizes the electricity consumption by end-use sectors for the three scenarios. In the *REF* scenario, electricity demand increases from 2038 ktoe (23707 GWh) in 2005 to 2549 ktoe in 2050 (equivalent to an annual average growth rate of 0.6%). In the mitigation scenarios, electrification of transport and heat result in electricity demand reaching 3358 ktoe (39055 GWh) in 2050 in *CO2-80* and 4885 ktoe (56814 GWh) in *CO2-95*, with average growth rates over the period of 1.4% and 3.1% p.a. respectively. The share of electricity consumption in overall final energy consumption, which was 17.7% in 2005, increases by 2050 to 18.8% in *REF*, 31.0% in *CO2-80* and 46.7% in *CO2-95*.

Focussing on the end-use sectoral shares, 40.0% of electricity in 2050 in the *REF* scenario is used in the services sector, 30.1% in residential and 22.6% in industry. In *CO2-80*, due to electrification, 30.9% of electricity is used in the residential sector, the services sector accounts for 30.5%, and transport accounts for 16.0% (compared with 2.0% in *REF*). The additional electrification in *CO2-95* is dominated by residential sector that accounts for 37.4% of electricity, followed respectively by services (29%), industry (16.5%) and transport (12%).

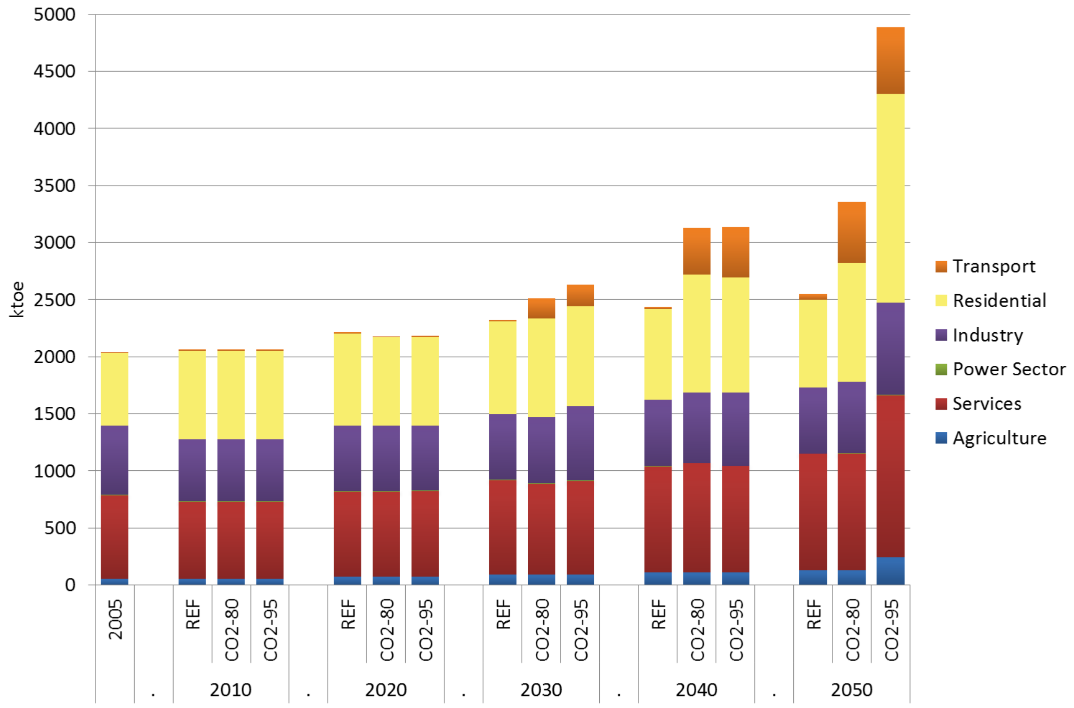

Figure 3-11. Electricity consumption by sector in REF, CO2-80 and CO2-95 (ktoe)

The electricity generation fuel mix is shown in Figure 3-12. In 2005, electricity generation was dominated by natural gas generation (CCGT and GT plants), accounting for 42.9% of total electricity generation, followed by coal and peat steam turbine power plants (37.1%) and oil based power plants (12.0%). The contribution from renewable energy was led by wind power, accounting for 4.6% of electricity generation, followed by hydro power (3.0%) and biogas (0.4%). In the *REF* scenario, renewable generated electricity increases to account for 54.6% of total electricity production (mainly onshore wind), while gas powered plants (mainly CCGT) account for 34.0% and coal plants provide 8.0% of power generation. The *REF* scenario also contains 310 ktoe of net electricity exports to the UK by 2050, in contrast to 2005, which included about 176 ktoe net electricity imports.

In the mitigation scenarios, the requirements for low carbon electricity are increased considerably. In the *CO2-80* scenario, higher electricity requirements (from electrification of heat and transport) are met by renewable production, in which non-dispatchable onshore and offshore wind increase by 50.0% in 2050 (relative to *REF*), accounting for 69.6% of total electricity production, and by natural gas plants with Carbon Capture and Storage (CCS) technology (19.1% of electricity generation). In the *CO2-95* scenario, electricity generation is almost entirely renewable powered, comprising 68.6% non-dispatchable generation (wind energy) and 30.8% dispatchable renewable generation, (25.3% from biomass steam turbine, 3.5% from biogas and 2.0% from hydro power).

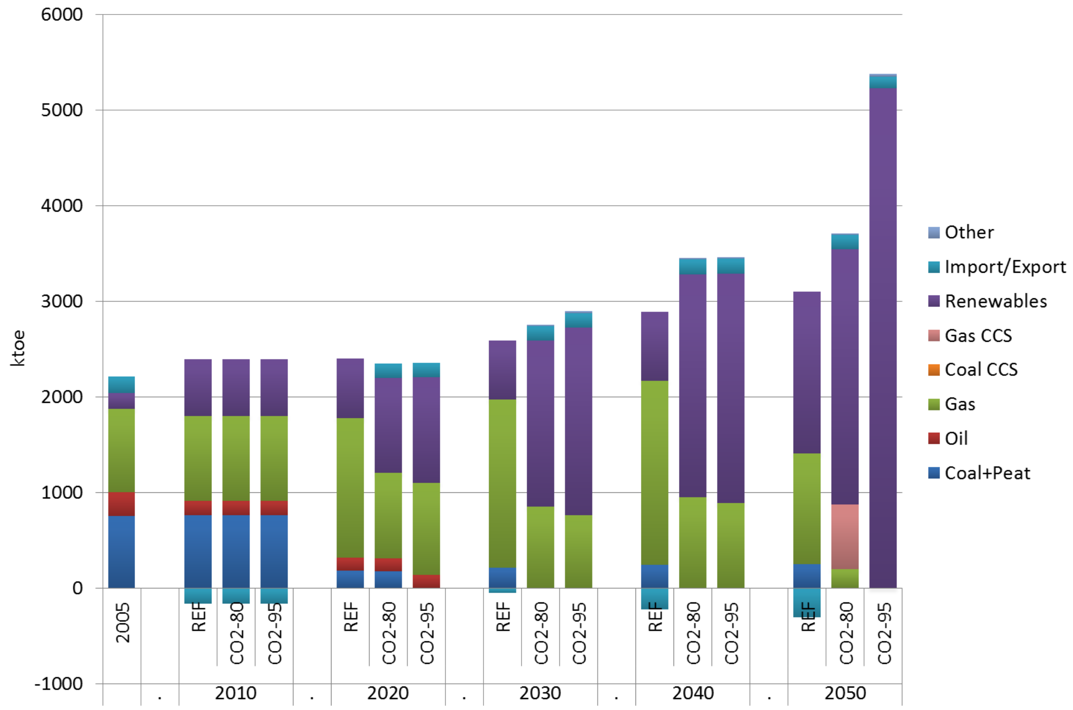

Figure 3-12. Electricity generation by plant in REF, CO2-80 and CO2-95 (ktoe)

Renewable overview

The previous sections discussed the contribution of renewable energy to the different end use sectors. It is also useful to discuss renewable energy in terms of the three modes of energy, i.e. electricity, transport and thermal energy (mainly heat but also cooling). Figure 3-13 presents the renewable energy results by mode for the two mitigation scenarios. In the *CO2-80* scenario, renewable energy is divided roughly evenly across the modes, and renewable energy accounts for 75.3% of total electricity generation, 62.2% of thermal energy and 86.1% of transport energy. The overall contribution from renewable energy to energy use is 71.7% in this scenario, compared with 25.3% in the *REF* scenario and 5.5% in 2010. In the *CO2-95* scenario, the deeper emissions cuts require an increase in renewable use for electricity production (+95.9% in RES-E) to deliver the 100% of electricity generation. Given limited bioenergy resources this results in a reduction in bioenergy use for heating purposes (-18.4% in RES-H) in favour of steeper electrification. In this case, renewable energy accounts for 87.2% of thermal energy and 84.9% of transport energy and the overall contribution from renewable energy is 90.1% of energy use.

This comparison shows an interesting dimension of full energy systems modelling. The achievement of the more stringent target (from *CO2-80* to *CO2-95*) has the effect of migrating amounts of renewables (i.e. biogas and biomass) from the RES-H sector to the RES-E sector, while heating is further electrified. The reason for this behaviour appears to be related to the need to completely decarbonize the electricity generation sector, in order to achieve the 95% reduction target. This complete decarbonisation can be achieved only displacing Gas CCS (as shown previously in Figure 3-12) with additional renewable generation. Because of the 70% constraint on intermittent generation (Section 3.2.4) biomass and biogas are the selected options.

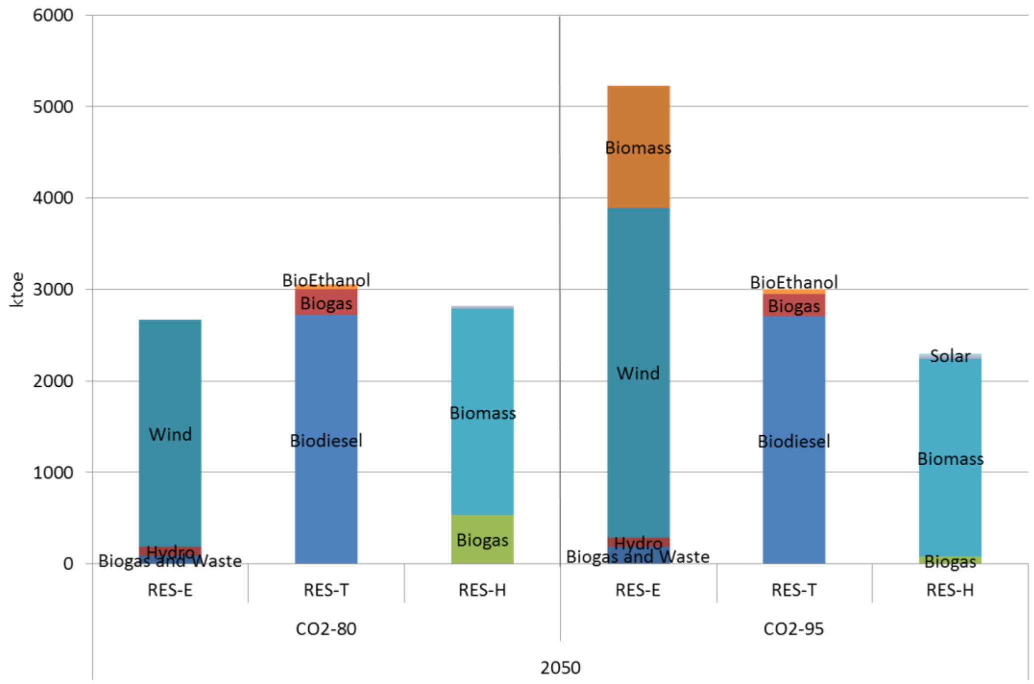

Figure 3-13. Renewables consumption by mode in CO2-80 and CO2-95 (ktoe)

Analysing the driving forces behind changes in CO_2 emissions

Decomposition analysis has been widely and successfully used to analyse the driving forces behind changes in CO_2 emissions and energy consumption. Decomposition techniques have been used to analyse aspects of the results of a TIMES model (Kesicki and Anandarajah, 2011) and in an Irish context decomposition has been used to examine energy consumption in industry (Cahill and Ó Gallachóir, 2012) and the residential sector (Rogan et al., 2012). This analysis uses the Log Mean Divisia Index I (LMDI I) methodology (Ang and Liu, 2001).

Using a simple decomposition identity (Capros et al., 2012), a decomposition analysis for the change in CO_2 emissions was done. For both the 80% and 95% emissions reduction scenario, the change in CO_2 emissions relative to the reference scenario was decomposed into three effects: the change in CO_2 emissions associated with (1) fuel switching of fossil fuels, (2) changes in energy efficiency, and (3) increased use of renewable energy. The results are shown in Figure 3-14 and Figure 3-15.

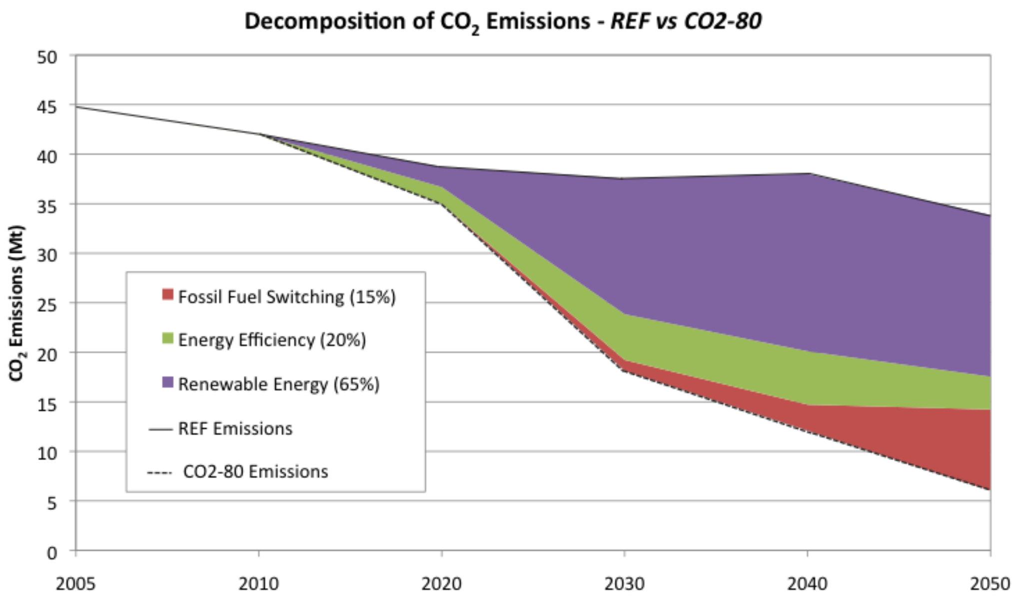

Figure 3-14. Decomposition analysis of CO_2 emissions between REF and CO2-80 scenarios

In the 80% scenario, the impact of fuel switching of fossil fuels (CO_2/fossil fuel energy) is attributable to the increased share of natural gas compared with the dominance of coal and oil in the reference scenario. The impact of energy efficiency (GDP/total energy) is stripped of any hidden structural effects because for both scenarios, GDP is the same. The enlarged share of renewable energy (fossil fuel energy/total energy) has the most significant impact on CO_2 emissions, contributing 65% of the reduction in emissions over the entire period (2005-2050).

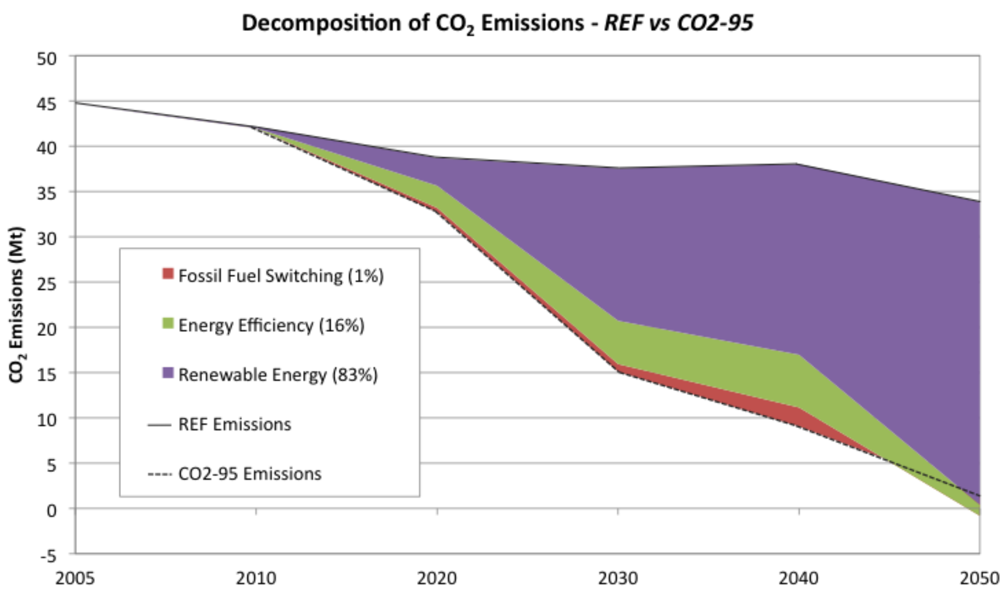

Figure 3-15. Decomposition analysis of CO_2 emissions between REF and CO2-95 scenarios

In the 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. 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.

3.3.2. The role of short term mitigation policies

Figure 3-16 compares the emissions trajectories between three alternative scenarios that all achieve an 80% reduction in energy-related CO_2 emissions by 2050 but follow distinctly different pathways, *CO2-80, NETS-20/CO2-80* (includes separate ETS and non-ETS targets to 2020) and *NETS-80* (extends the separate ETS and non-ETS targets to 2050). The *CO2-80* scenario follows an unconstrained pathway (between ETS and non-ETS sectors) to deliver an 80% CO_2 reduction target by 2050. The *NETS-20/CO2-80* demonstrates how current short term targets impact on the same long term target. The *NETS-80* provides a scenario in which the current policy focus (separating ETS and non-ETS targets) is extended over the entire time horizon.

In the period to 2020, the *NETS-20/CO2-80* and the *NETS*-80 scenarios, driven by their constrained pathways, deliver at least 21% emissions reduction for ETS sectors and 20% reduction for Non-ETS sectors (relative to 2005 levels). The *CO2-80* scenario by contrast allocates most of emissions reductions in the ETS sector (-44.8% relative to 2005 levels), while non-ETS remains almost stable (-0.2% rel. 2005). Beyond 2020, the least cost solution in the *CO2-80* scenario results in an 87% reduction in ETS emissions (relative to 1990 levels) and a 74.2% reduction in non-ETS emissions by 2050. In the *NETS-80* the 80% reduction relative to 1990 is equally allocated to ETS and non-ETS sectors. It is clear from Figure 3-16 that after few periods beyond 2020, the *NETS-20/CO2-80* scenario pathways aligns to that of the *CO2-80* scenario.

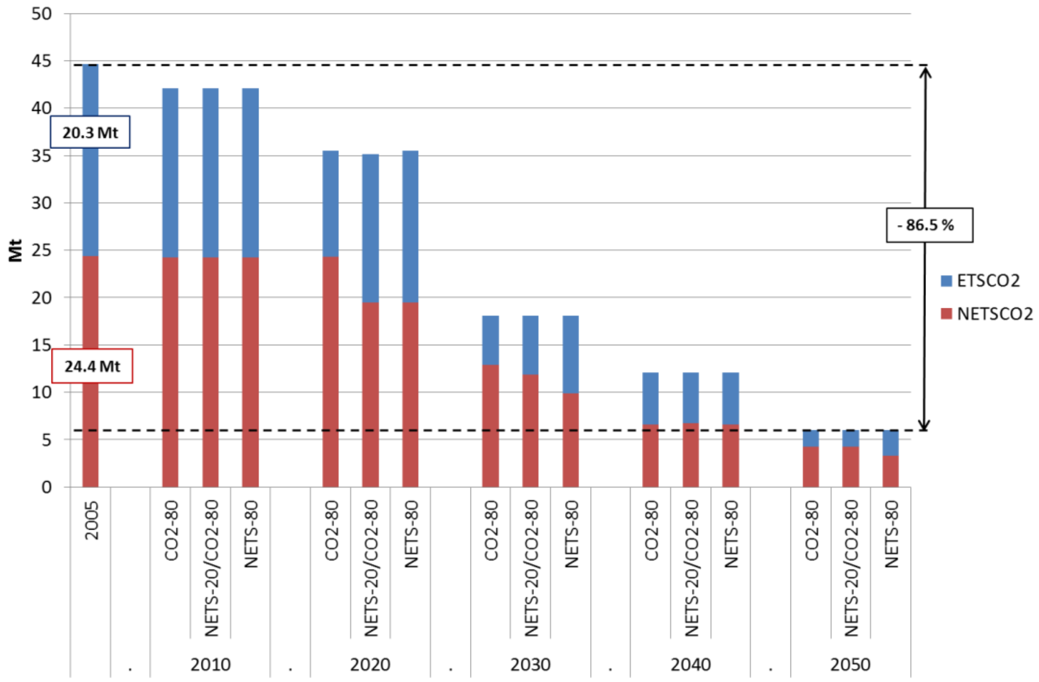

Figure 3-16. ETS and Non-ETS CO_2 emissions trajectories in CO2-80, NETS-20/CO2-80 and NETS-80 (ktoe)

The main impact of the separate ETS and non-ETS mitigation targets is the increased electrification (in particular of heating) within the end-use sectors (as shown in Figure 3-17) and the associated reduction in final energy consumption by improvements in the energy efficiency (Figure 3-18).

The Non-ETS sectors such as residential and services are the most affected to this process, with a marked increase in electricity use for heating already from 2020, which account in *NETS-80* for 40.8% higher than *CO2-80* and in *NETS-20/CO2-80* for 42.9%. Beyond 2020 the separate ETS and Non-ETS target sharpens the already marked electrification shown in *CO2-80* resulting for a 13.4% higher electrification in 2050.

This requires a 29.9% and 31.3% increase (in *NETS-80* and *NETS-20/CO2-80* respectively) in electricity production by 2020 and a 9.1% in 2050 in the *NETS-80* scenario compared with *CO2-80*. In *NETS-80* scenario this additional generation is provided in the short term (2020) by a generation portfolio still dominated by fossil fuel generation, i.e. gas (58.4% of total electricity production, +89.9% relative to *CO2-80*), coal (7.9% of production) and oil (6.2%); while wind accounts "only" for 25.6% of total electricity production (compared with 43.1% in *CO2-80*). In the longer term the generation portfolio aligns with *CO2-80* results that are characterized by high wind share (69.5% of total electricity production), gas (24.6% with 12.3% equipped with CCS), and biogas (now 2.7%).

Moreover these separate targets deliver significant TFC reductions. By 2020 the model indicates fuel consumptions in the residential and services sectors for *NETS-80* and *NETS-20/CO2-80* energy system for 6.5% and 8.5% lower than in *CO2-80* respectively. Beyond 2020 this difference gradually reduces in the *NETS-20/CO2-80* scenario, delivering consumptions of only 2.1% and 1.2% lower than *CO2-80* by 2050; while it increases in *NETS-80*, delivering reductions of 8.9% in residential sector and 3.0% in services by 2050. These differences in fuel consumption are driven by a combination of two contextual points: fuel switching (from oil, gas and some blended biogas to electricity) and efficiency measures (such the installation of some efficient appliances, as heat pumps, and conservation measures, as walls and windows insulation.

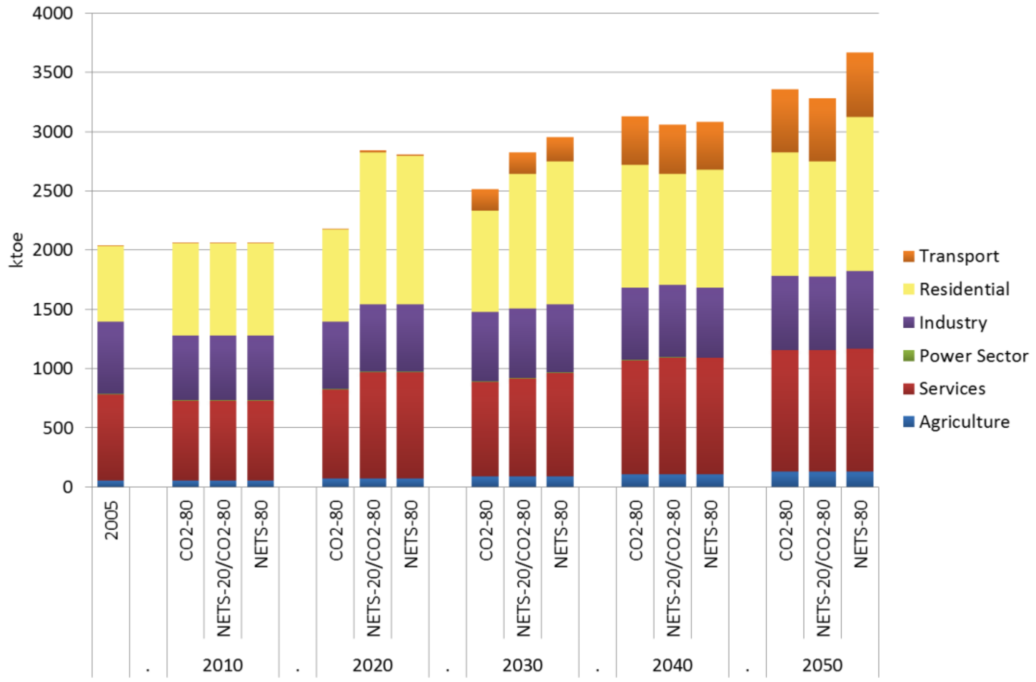

Figure 3-17. Electricity consumption by sector in CO2-80, NETS-20/CO2-80 and NETS-80 (ktoe)

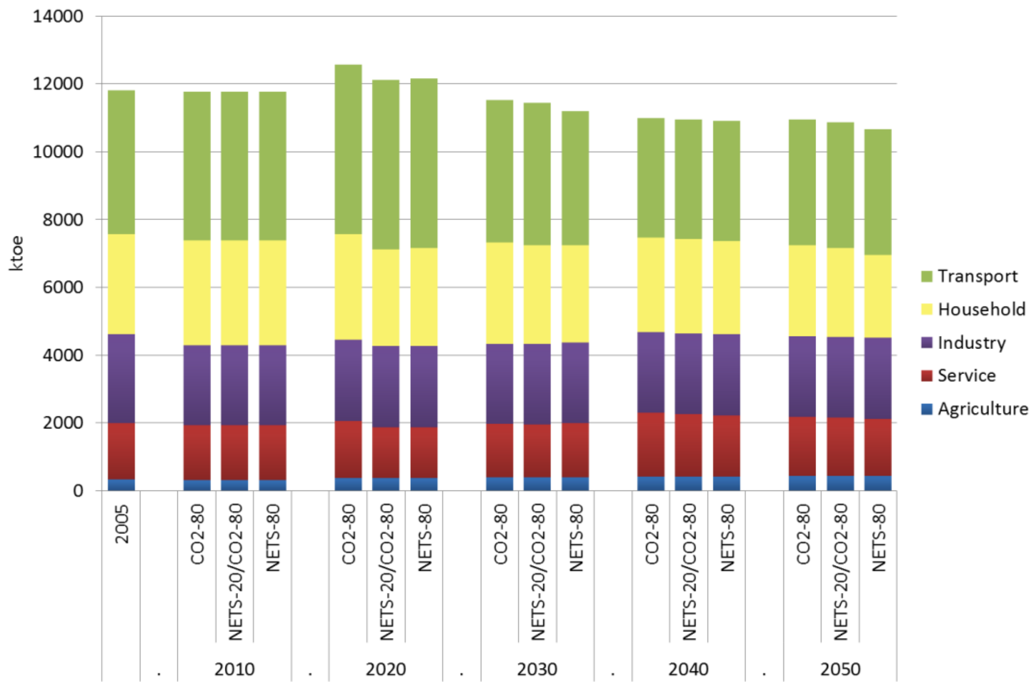

Figure 3-18. Final energy consumption by sector in CO2-80, NETS-20/CO2-80 and NETS-80 (ktoe)

3.3.3. Economic impacts of mitigation

Emissions reduction marginal

One of the main insights that can be gained from energy systems models such as TIMES quantifying the impact of different mitigation targets on marginal CO_2 abatement costs, on the necessary investment required and on the energy system costs over the time horizon considered. Each of these metrics sheds light on the future costs of mitigation but care should be taken in interpreting these results. Marginal abatement provides an indication of the costs of abating the last tonne of CO_2, energy systems costs represent the sum of investment, operation and maintenance and fuel costs, while investments costs represent the cost element that drives the replacement, the substitution and the transformation of current technologies in the energy system.

Table 3-8 summarises the marginal CO_2 abatement costs for the four mitigation scenario clusters presented in this section. Two additional intermediate scenarios with different emissions reduction target (-85% and -90%) are also included as sensitivity.

Scenario	2020	2030	2040	2050	
CO2-80	33	136	99	273	*€$_{2000}$/tonne CO_2*
CO2-85	33	131	158	523	*€$_{2000}$/tonne CO_2*
CO2-90	33	127	158	694	*€$_{2000}$/tonne CO_2*
CO2-95	65	185	173	1308	*€$_{2000}$/tonne CO_2*
NETS-20/CO2-80	167	113	116	273	*€$_{2000}$/tonne CO_2*
NETS-80	141	97	87	554	*€$_{2000}$/tonne CO_2*

Table 3-8. CO_2 shadow prices

Under the *CO2-80* case, the marginal cost rises in the period 2020-2030 from €33/tonne to €136/tonne, then reduces to €99/tonne by 2040. This reduction is arises due to two reasons: firstly the emission pathway is the combination between short term and long term pathways. This results in a pathway in which in the period 2020-2030 the energy system is required to reduce emissions by 17.4 Mt, passing from 20.5% reduction relative to 2005 levels by 2020 (still 17.6% higher than 1990 levels) to -40% (relative to 1990) by 2030; while in the following period, namely 2030-2040, the model is required for a reduction of *only* of 6 Mt. Secondly this reduction reflects a significant development of efficient and cost-effective technologies which replaces existing technologies contributing to the reduction of marginal abatement cost.

By 2050 the marginal abatement costs grow to €273/tonne, testifying how challenging this target is. In the deeper emissions reduction cases (85% and 90% of reduction), the marginal costs are higher from 2040 due to the more challenging abatement trajectory. The 95% emission reduction case indicates, already from 2020, higher CO_2 abatement price due to additional emissions reduction to compensate for lesser reductions in agriculture. The 2050 marginal CO_2 abatement cost reaches

€1308/tonne, illustrating the limited options available to deliver the final part of this challenging target.

Imposing separate ETS and Non-ETS targets has a dramatic impact on the short term (2020) cost of emissions reduction that in *NETS-20/CO2-80 and NETS-80* range between three and four times higher than in *CO2-80*. In fact these scenarios reflect the current short term target more accurately than the *CO2-80* and *CO2-95* scenarios. This difference reduces in the medium term (2030-2040) due to the effect of early actions on efficiency in Non-ETS sectors. By 2050, the *NETS-20/CO2-80* marginal abatement costs returns to levels similar to the *CO2-80* scenario, while in *NETS-80*, the marginal abatement cost increases to €554/tonne almost double that of the *CO2-80* scenario, confirming that delivering high level of emissions reduction in Non-ETS sectors is generally more costly than in ETS ones. These findings are also confirmed by ETS marginal price in *NETS-80* that by 2050 accounts for €266/tonne, in line with *CO2-80* carbon marginal. Equivalent European studies (EC, 2006b; SECURE, 2009) indicate for similar policy assumptions (Johannesburg Agreement scenario and Carbon constraint case) CO_2 marginal prices for EU27 and EU27+ (Europe including Balkans and Turkey) of 312 $€_{2000}$/tonne (392 $€_{2005}$/tonne) and 159 $€_{2000}$/tonne (200 $€_{2005}$/tonne)[25] for the year 2050.

Energy system costs and investments

TIMES models, as with all partial equilibrium models, are driven by macro-economic parameters that represent how the economy will evolve over the time horizon. The impacts of the marginal abatement costs presented in Table 3-8 on economic growth are not captured however, because in the Irish TIMES model there is no feedback between the model and the economy. This section discusses how the relationship between the economy and the energy system evolves during the time horizon. To perform this analysis do we use the TIMES objective function that, as stated in section 3.2.1, represents the total discounted energy system cost. This energy system cost includes the investment component, the operation and maintenance costs, the fuel costs and the residual value of technologies at the end of the horizon.

Figure 3-19 focuses on the total energy system costs and its investment portion[26] for the *REF*, *CO2-80*, *CO2-95* and *NETS-80* scenarios. The hybrid *NETS-20/CO2-80* trend is not included in the graph to avoid cluttering the graph. In the *REF* scenario, we see an interesting reduction in costs until 2020, followed by growth to 2050 by 1.6% p.a. on average (or 0.8% p.a. growth relative to 2005). This reduction arises due to cost effective investments over this period resulting in increased efficiency (reduction of fuel costs). In the *CO2-80* scenario, energy systems costs grow by 1.1% p.a. relative to 2005, while for the *CO2-95* scenario growth is 1.5% p.a. (or 2.5% p.a. from 2020 –

[25] Assumed average inflation of 3.9% based on annual Consumer Price Index provided by Central Statistics Office Ireland (http://www.cso.ie/statistics/conpriceindex.htm).

[26] These represent undiscounted costs by period.

2050). The difference in cost between *CO2-80* and *CO2-95* provides an indication of the additional costs borne by the energy system to compensate for agriculture meeting a 50% reduction in emissions. It is worth nothing that the *NETS-20/CO2-80* and *NETS-80* cases point to higher system costs in the period 2010-2020, but thereafter almost align (in the *NETS-20/CO2-80* this trend is faster) to *CO2-80* case by the year 2050.

The results indicate increasing investments over the time horizon for all scenarios, while operation and maintenance costs and fuel costs (not shown in figure) reduces. In the long term the contribution of investments costs increases passing from 22% of total system costs by 2010 to between 53% (*REF*) and 58% (*NETS-80*) by 2050. Investments in mitigation scenarios by 2050 are 20% (*CO2-80*) and 29% (*CO2-95*) higher than *REF*.

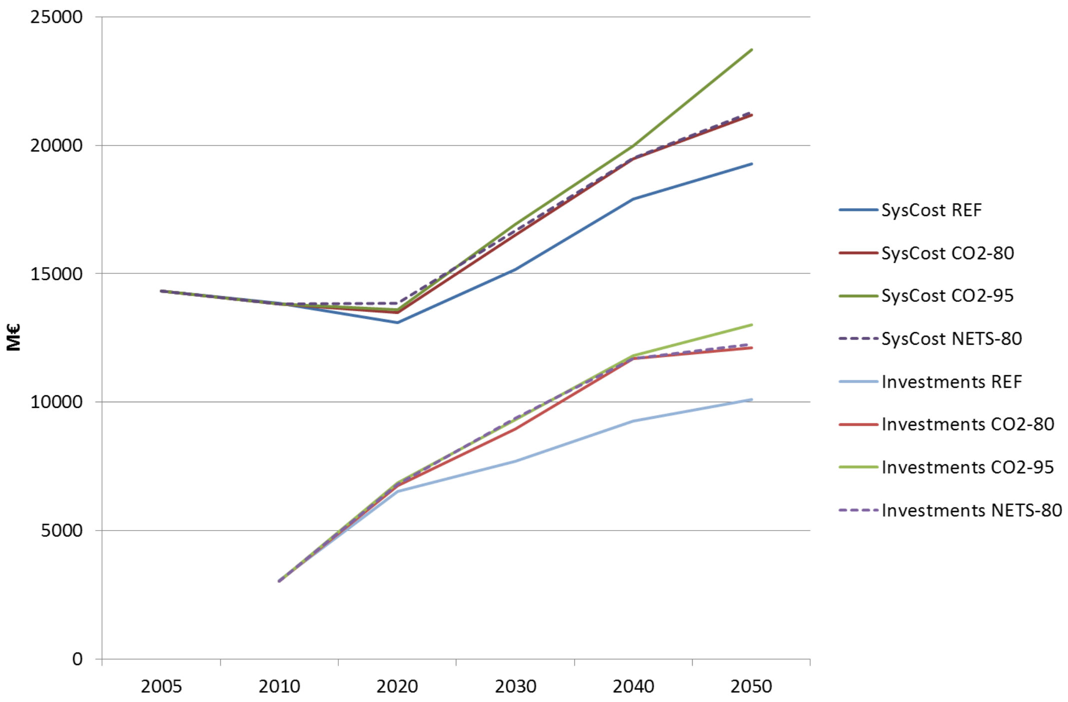

Figure 3-19. Comparing total system costs with investments

Examining energy systems costs in isolation provides limited insights and it is useful to compare these amounts with economic activity levels in the same period. Figure 3-20 presents the ratio of energy systems costs (and of investment costs) and economic growth levels (GDP) in the same period. This provides an indication of the impact, as a percentage of GDP, of delivering emissions reduction targets. It is worth nothing that these ratios do not represent the net cost for the society as they are systems costs rather than end user costs. In the *REF* scenario the energy system cost are reduced in the period 2005-2020 passing from 11.2% to 7.9% of GDP. This reduction continues in the following periods reaching 7.0% of GDP by 2050. Investments, which accounted for about

2.3% of GDP in 2010[27], grow to 3.9% of GDP in the period 2020-2040 and then slightly reduce to 3.7% by 2050.

In the *CO2-80* scenario, the energy system costs account for about 7.7% of GDP by 2050, suggesting that (relative to the *REF* scenario) the additional cost[28] to achieve the mitigation represent less than 1% of GDP in 2050. The energy system costs to deliver 95% of emissions reduction account for 8.6% of GDP by 2050, hence the additional cost to achieve the *CO2-95* mitigation target (again relative to the *REF* scenario) is less than 2% of GDP in 2050. The *NETS-80* and *NETS-20/CO2-80* result in higher system costs in the period 2020-2030. In all mitigation scenarios increased systems costs are driven by higher investments. The cost for investments will range between 4.4 and 5.0% of GDP in the period 2030-2050.

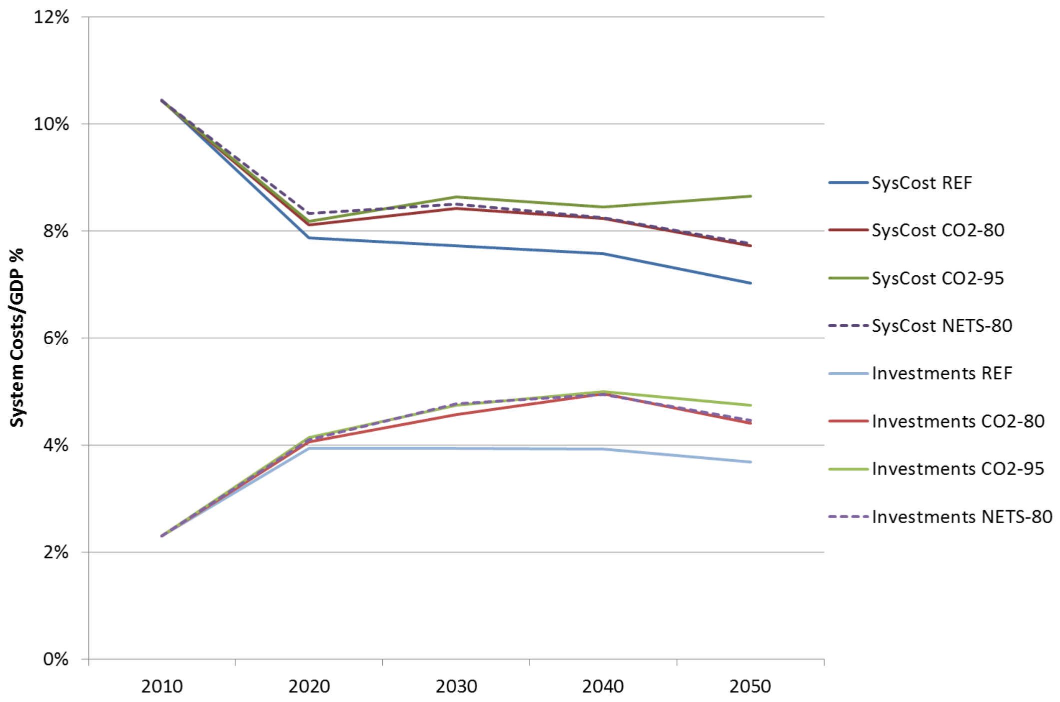

Figure 3-20. Comparing system costs with GDP

3.4. Conclusion

This paper reports results on ambitious mitigation target in the period to 2050 for the Irish energy system. The analysis have been performed using the Irish TIMES model, a technology rich, cost optimizing, linear programming energy systems model. This work indicates that challenging emissions reductions such 80% and 95% relative to 1990 levels can be technically achieved in

[27] In the base year (2005) no investments are allowed.

[28] It doesn't correspond to the full macroeconomic cost of mitigation.

Ireland and which energy efficiency and renewable energy technologies will have a determining role to deliver the target at least cost.

The results show that an 80% CO_2 emissions reduction target by 2050 is technically achievable with an additional emissions reduction of 27.8 Mt relative to least cost reference scenario. Reductions are important across the whole energy system, but mostly in transport, a sector which has not seen a significant policy focus in Ireland. In this scenario, renewable energy grows from current levels of 5.5% of energy use to reach 71.7% by 2050. More than two-thirds of this renewable energy is from biomass used for heat and transport, although wind generated electricity dominates the current policy debate on renewable energy in Ireland. This scenario also includes electrification of heat and transport, resulting in electricity representing 31% of energy use compared with 18% today. The marginal CO_2 abatement costs reaches nearly €$_{2000}$300 / tonne CO_2 by 2050 and the cost of achieving this mitigation target represents less that 1% of GDP in 2050. A key recommendation from this paper is that further analysis be focused on analysing the technical feasibility of an electricity generation sector constituted by nearly 70% intermittent wind generation.

The results also suggest that additional mitigation in the energy system is possible to compensate for the limited options available in the agriculture sector. According to the EU Low Carbon Roadmap (COM/2011/112) 50% GHG emissions reductions in agriculture are achievable by 2050 across the EU. Applying this reduction in Ireland requires a 95% CO_2 emissions reduction from the energy system to achieve an overall 80% GHG emissions reduction target. The additional efforts to meet this target are mainly concentrated in electricity generation and in the residential and services sector. In this scenario, renewable energy accounts for 90.1% of energy use in 2050, with an almost doubling of electricity generation from renewable compared with the *CO2-80* scenario. This results in the complete decarbonisation of the electricity generation sector and delivers an interesting result for the end-use sectors, which show a reduction in bioenergy consumptions in favour of further electrification of heat representing nearly half of total energy use in Ireland by 2050. The additional costs involved are significant, with the marginal CO_2 abatement cost reaching more than €$_{2000}$1300 / tonne CO_2 in 2050 and the costs of mitigation reaching close to 2% of GDP by 2050. It is worth noting that if a 50% GHG emissions reduction is not achieved in agriculture, this pushes Ireland's energy system towards negative emissions, possible only delivered by extensive use of bioenergy carbon capture and storage (CCS) technologies. A key recommendation from this paper is that further analysis be carried out to compare energy systems and agriculture mitigation options for Ireland.

This paper also illustrates some initial impacts of short term targets and policies on the longer term mitigation pathway for Ireland's energy system. This is an area that warrants further investigation. Ireland has an ambitious short term target for emissions reduction in non-ETS sectors (20% below 2005 levels as per EU Decision 2009/406/EC). Extending current policies beyond 2020 i.e.

separate 80% CO_2 emissions reduction targets for ETS and non-ETS sectors, results in greater electrification and efficiency measures (already important in the previous cases) to reduce emission in end use sectors (mainly residential sector), but also results in the short term with higher emissions from the electricity generation sector. The marginal abatement cost in 2050 in this scenario reaches levels similar to an 85% CO_2 emissions reduction scenario with no ETS / non-ETS distinction.

It is important to note that the results presented here are based on a single set of macro-economic projections generated in 2010 and that there have been significant changes in economic projections since 2008 as the extent of the economic recession has been realised. Further analysis is required in this area and on the feedback between the energy system and the economy, to better assess the economic impacts of deep mitigation. We also recommended that the infrastructure costs required to enable the energy technology changes envisaged in some of these scenarios be investigated further and better captured within the model.

4. Moving towards a low carbon economy – implications of 2030 targets for Ireland's energy system

Abstract

The European Union has set ambitious greenhouse gas (GHG) emission reduction targets for the year 2020 – 20% below 1990 levels – and, separately, for 2050 – 80 to 95% below 1990 levels – and is currently preparing targets for 2030. While GHG emissions reduction targets for 2020 have been allocated to Member States under an effort sharing decision, no effort sharing decision has yet been agreed at EU level for the longer term targets. This paper investigates the potential implications for the energy system of three potential GHG emissions reduction targets for 2030 in the context of a single longer term (2050) emissions reduction target. The focus of this analysis is Ireland, which is unique among MS due to its relatively high share of GHG emissions from agriculture. The purpose of this paper is to provide evidence for energy and climate policy makers in Ireland to underpin any negotiations regarding what targets might be appropriate in a 2030 effort sharing agreement. The tool used to carry out the analysis is the Irish TIMES energy systems model, which optimises Ireland's entire energy system to deliver future energy service demands at least cost. The implications of different GHG emissions reduction targets for energy efficiency, renewable energy and for the economy are presented. In addition this paper highlights implications which should be considered in the development of a new policy framework – namely the possible consequences of reduced availability of sustainable bioenergy for international trade, the implications for energy security and for land use competition between energy and the agricultural system.

4.1. Introduction

The Inter-governmental Panel on Climate Change (IPCC) Assessment Report (IPCC, 2013) recently confirmed that the increase in anthropogenic greenhouse gas (GHG) concentrations is one of the key drivers for climate change. To hold the increase in global temperature below 2 degrees Celsius the global GHG emissions must peak by 2020, while by 2050, global GHG emissions should be reduced by at least 50 % below their 1990 levels (IPCC, 2007b). A recent report from the International Energy Agency (IEA, 2013b) concludes that the world is not on track to meet this target. Global GHG emissions are increasing rapidly and, in May 2013, recorder carbon-dioxide (CO_2) levels in the pacific exceeded 400 parts per million for the first time in several hundred millennia. The weight of scientific analysis tells us that our climate is already changing and that

that we should expect extreme weather events (such as storms, floods and heat waves) to become more frequent and intense, as well as increasing global temperatures and rising sea levels. Policies that have been implemented, or are now being pursued, suggest that the long-term average temperature increase is more likely to be between 3.6°C and 5.3°C (compared with pre-industrial levels), with most of the increase occurring this century. The IEA report further states that this 2°C target remains technically feasible, though extremely challenging. To keep open a realistic chance of meeting the 2°C target, intensive action is required before 2020, the date by which a new international climate agreement is due to come into force. Energy is at the heart of this challenge: the energy sector accounts for around two-thirds of greenhouse-gas emissions, as more than 80% of global energy consumption is based on fossil fuels.

To limit atmospheric warming to below 2°C, the European Union (EU) perspective is that industrialized countries should contribute to this global emissions reduction target by reducing GHG emissions by 20% by the year 2020 and between 80% and 95% by the year 2050, relative to 1990 levels. Even in the absence of a wider international agreement on climate policy, the EU has set an ambitious climate policy framework for 2020. This framework integrates different policy objectives and in particular commits the EU to a 20% reduction relative to 1990 levels (EU, 2009a), equivalent to a 13% reduction relative to 2005 levels. While the EU is making progress towards meeting the 2020 targets, creating the internal market for energy and meeting other objectives of energy policy, there is a need now to reflect on a new 2030 framework for climate and energy policies (EC, 2013). The 2030 framework must draw on the lessons from the current framework and should also take into account the longer term perspective which the European Commission (EC) laid out in 2011 in the Roadmap for moving to a competitive low carbon economy in 2050 (EC, 2011c), the Energy Roadmap 2050 (EC, 2011b), and the Transport White Paper (EC, 2011a). The roadmaps suggest that for the EU to be on track to reach a GHG reduction of between 80-95% by 2050, GHG emissions would need to be reduced by 40% in 2030. Moreover the policy scenarios in the Energy Roadmap 2050 indicate a renewables share of around 30% in 2030. Although Member States have not yet agreed collectively on their individual targets for 2030, some Member States have individually established low carbon energy strategies with specific targets in place for the periods 2020 - 2050, i.e. Denmark (Danish Government, 2011), France (Environment Round Table, 2009), Finland (Government of Finland, 2013), Germany (BMU, 2010) and the UK (CCC, 2008).

The purpose of this paper is to inform the setting of an appropriate 2030 GHG emissions reduction target for Ireland. The paper is timely given discussions at EU level regarding 2030 targets and the analysis can be replicated in other Member States. The paper assesses the implications of GHG emissions reduction targets for the energy system. Using energy systems modelling, the paper explores the implications of different targets for 2030 on transitioning to a low carbon economy by

2050. The paper seeks to determine the implications (and point to appropriate targets) for renewable energy, energy efficiency and for sectoral emissions reduction that are consistent with delivering the overall mitigation target at least cost. A number of additional implications are also discussed that are key to policy choices, notably implications for the economy (energy costs and investment opportunities), implications for sustainability (land-use and bioenergy availability) and implications for energy security (fuel and import dependency). This paper is thus structured as follows. Section 4.2 provides some context for the analysis. Section 4.3 presents the Irish TIMES model and the methodology employed in this paper. Section 4.4 introduces the scenarios. Section 4.5 presents and discusses the results of the analysis. Section 4.6 concludes the paper with a brief discussion.

4.2. Context

4.2.1. The Irish context

Ireland is an interesting case study relative to other Member States. This section presents a background and context to the energy and climate challenge and highlights the importance of the agricultural sector in the energy and climate debate.

Ireland's energy demand is largely dependent by fossil fuels, which accounted for 94% of all energy used in Ireland in 2011. Given the absence of significant domestic fossil fuel resources approximately 88% of these were imported (Howley et al., 2012). Transitioning towards to a low carbon economy will require significant efforts to move from high carbon concentration fuels (e.g. coal and oil), to lower carbon ones (e.g. natural gas) and renewable energy; but could positively contribute to reducing energy import dependency and in stimulating new economic activity. Recent years have seen a rapid expansion of renewable electricity generation, largely dominated by onshore wind energy (growing from 1% of electricity generation in 2001 to 14% by 2011). A more recent policy focus on biofuels resulted in a 2.6% contribution of renewable energy to road and rail transport of in 2011, from a low base of 0.03% in 2005. Bioenergy for thermal use – mainly biomass – grew from 2.6% in 1990 to 4.8% of fuel consumption in 2011 (Howley et al., 2012).
Focussing on GHG emissions, Ireland faces considerable challenges in transitioning towards a low carbon economy. Firstly in the period 1990-2010 Ireland's GHG emissions grew while EU emissions declined. Secondly, Ireland has a relatively high share of its GHG emissions from agriculture which has little scope for emissions reduction. Regarding the first point, Figure 4-1 shows that Ireland's emissions in 2005 (2010) were 26% (11%) above 1990 levels while EU[29]

[29] EU-28

emissions were 8% (16%) below 1990 levels (EEA, 2013). If we reference GHG emissions reductions against 1990 levels rather than 2005 levels results in a very different scale of challenge. For example within the EU a 20% reduction by 2020 relative to 1990 levels is equivalent to a 13% reduction relative to 2005 levels. In Ireland by contrast a 20% reduction relative to 1990 levels is equivalent to a 36% reduction relative to 2005 levels.

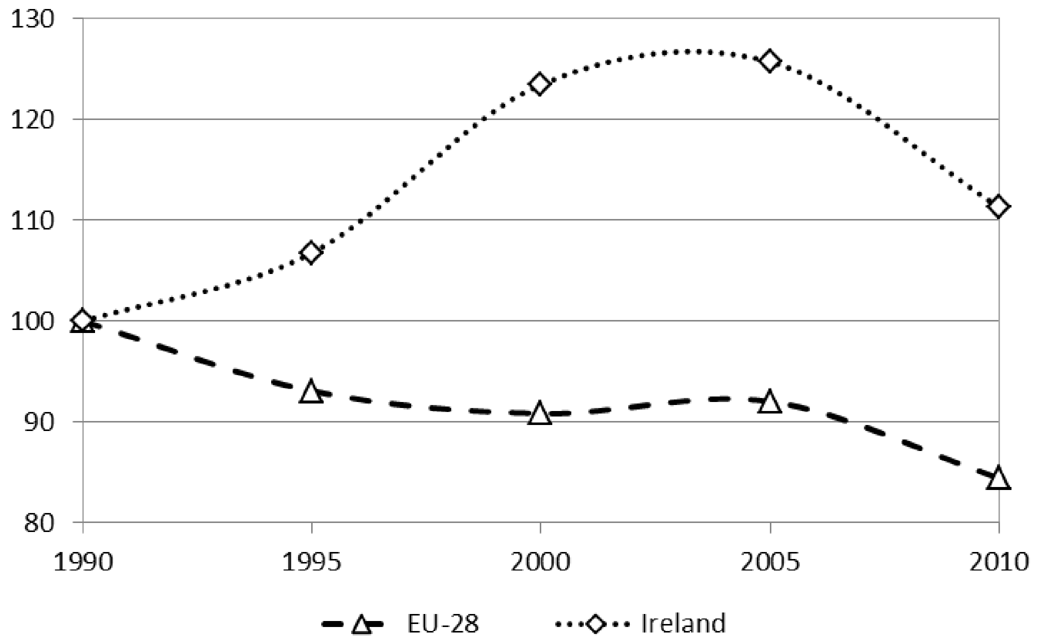

Figure 4-1. Historical GHG Emissions in EU-28 and in Ireland indexed to 1990

The current climate framework for the year 2020, which references targets against 2005 – 21% below 2005 levels by 2020 for ETS sectors (EU, 2009b) and for Ireland a 20% reduction for remaining (i.e. non-ETS) emissions (EU, 2009a) – means for Ireland a 1.1% reduction in GHG emissions overall compared to 1990 levels. There are very significant challenges for Ireland in achieving these 2020 targets, which are discussed separately (Chiodi et al., 2013a).

In the context of emissions reduction targets for 2030, the EU Low Carbon Roadmap points to an overall 40% GHG emissions reduction relative to 1990 levels. For the EU this is equivalent to a 35% reduction in emissions relative to 2005. *Applying* the EU Low Carbon Roadmap 2030 target to Ireland, i.e. applying a 40% GHG emissions reduction target relative to 1990 levels to Ireland is equivalent to targeting a 52% reduction in 2030 relative to 2005 levels. Another approach is to *align* the EU Low Carbon Roadmap 2030 target, i.e. by applying the 35% GHG emissions reduction relative to 2005 levels to Ireland. This is then equivalent to an 18% GHG emissions reduction target for Ireland relative to 1990 levels. This paper considers three separate 2030 GHG emissions reduction targets for Ireland, namely a 20%, 30% and 40% emissions reduction target relative to 1990 levels (equivalent to a 36%, 44% and 52% target relative to 2005 levels) as shown in Figure 4-2. This emulates aligning with the EU Roadmap, applying the EU Roadmap and an intermediate scenario.

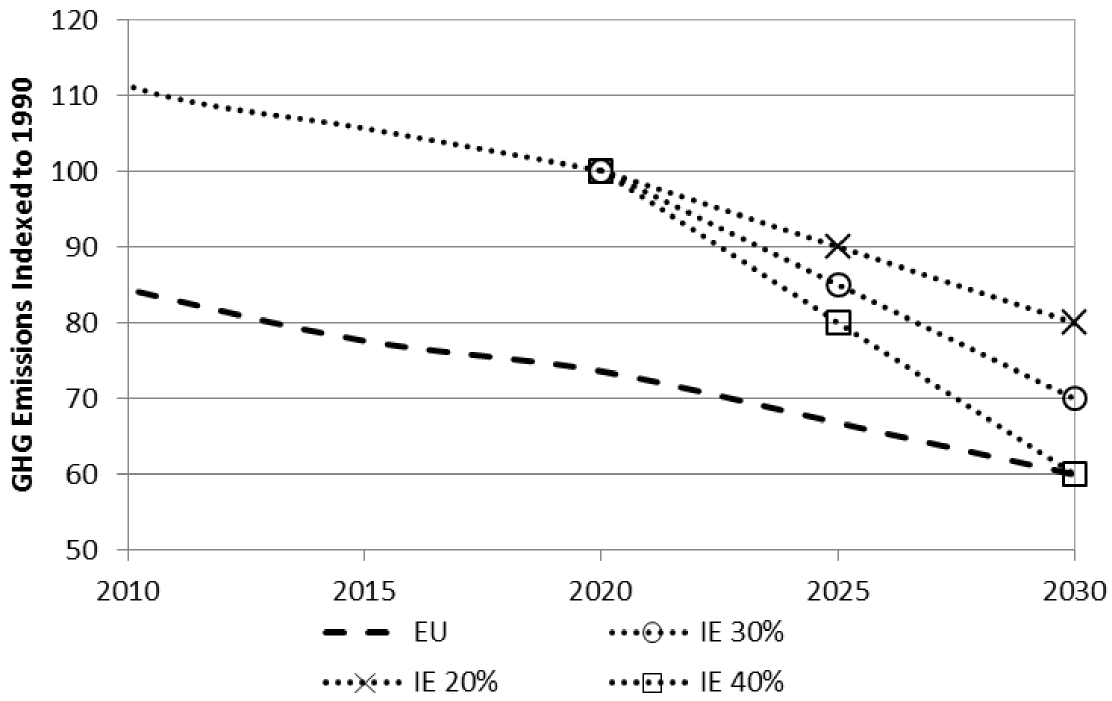

Figure 4-2. GHG emissions pathways for Ireland and EU-28

Regarding the second point, agriculture in Ireland is predominantly based on dairy and beef production from ruminant animals, most of which (over 80%) is exported. The agri-food sector contributes approximately 7% to Ireland's economy (in terms of GDP), but at the same time agriculture accounts for 31% (in 2010) of total GHG compared with just 11.5% for the EU (average across EU-28) (EEA, 2013). Of these emissions only 5% are associated with energy (for combustion) while the remaining originates as non-combustion emissions (namely methane and nitrous oxide). Beef and dairy farming is particularly challenging in terms of climate mitigation with very few options for emissions reduction (Schulte et al., 2012). Hence, it is very difficult to reconcile growth in beef and dairy farming with a low GHG emissions economy. This results in a considerable challenge for Ireland to meet deep emissions reduction targets for 2050. Set against this backdrop, this paper makes a simple assumption regarding GHG emissions in agriculture, namely that agriculture emissions in 2020-2050 are the same as current national projections (+1% relative to 1990) (EPA, 2013) for 2020. This anticipates growth in agricultural activity in conjunction with the implementation of some level of mitigation.

In the context of emissions mitigation targets for the year 2030, if we assume that the energy system compensates lower reduction levels in agricultural non-energy, a 20%, 30% and 40% GHG emissions reduction targets relative to 1990 are equivalent for the energy system respectively to

29% (49.4%), 44.8% (60.6%) and 60.5% (71.8%) emissions reduction targets compared to 1990 (2005) levels.

4.2.2. Bioenergy and mitigation

Renewable energies are one of the key drivers for significant reductions in GHG levels. Bioenergy in the form of bioliquids, biogas and solid biomass may have a major role to play and represent one of the major options for substituting fossil fuels in the energy mix. However there are a number of environmental concerns associated with bioenergy centering on potential ecosystem damage, especially in the developing countries, and the level of climate change benefits of some bioenergies, particularly first generation biofuels (Börjesson, 2009; Escobar et al., 2009; Smyth et al., 2010; Thamsiriroj and Murphy, 2009). Arising from these concerns and those linked to impacts for food prices, the EU Renewable Energy Directive (Directive 2009/28/EC) (EC, 2009c) establishes that biofuels must meet certain s*ustainability criteria* in order for them to be counted towards national biofuels targets. The main criteria are: i) from January 2017, the greenhouse gas emissions saving from the use of biofuels and bioliquids compared with the fossil fuels they displace shall be at least 50%. From 2018 that saving shall be at least 60%; ii) biofuels from peatlands and land with high biodiversity value or high carbon stock may not be used; iii) impact of biofuel policy on social sustainability, food prices and other development issues is to be assessed. Separate studies for Ireland (Clancy et al., 2012; Murphy et al., 2013; Smyth et al., 2010) and UK (Howes et al., 2011) show these s*ustainability criteria* beyond 2017 may affect the availability of bioenergy (especially biodiesel) for international trade limiting *de facto* the capacity of single countries of achieving emissions reduction targets. This paper assesses how limited availability of bioenergy imports impacts on the energy system attempts to achieve deep GHG emissions reductions.

4.3. Methodology

This paper builds and compares different pathway scenarios for GHG emissions reduction in the period to 2050 for Ireland using the Irish TIMES Energy Systems Model. The Irish TIMES model provides a range of energy system configurations for Ireland that each delivers projected energy service demand requirements optimised to least cost (over the entire time horizon) and subject to a range of technical and policy constraints. It provides a means of testing energy policy choices and scenarios, and assessing the implications i) for the Irish economy (technology choices, prices, output, etc.), ii) for Ireland’s energy mix and energy dependence, and iii) for the environment, with a particular focus on greenhouse gas emissions. It is used both to examine baseline projections, and to assess the implications of emerging technologies and of mobilising alternative policy choices such as meeting renewable energy targets and carbon mitigation strategies.

The Irish TIMES model was developed with the TIMES (The Integrated Markal-Efom System) energy systems modelling tool; developed and supported by the Energy Technology Systems Analysis Program (ETSAP), an Implementing Agreement of the International Energy Agency (IEA) [30]. TIMES is a bottom-up model generator for local, national or multi-regional energy systems, which combines two different, but complementary, systematic approaches to modelling energy: a technical engineering approach and an economic approach (Gargiulo and Ó Gallachóir, 2013). The technical documentation and a number of studies involving TIMES (and its predecessor MARKAL) models may be found in (IEA-ETSAP, 2011; Loulou et al., 2005).

The Irish TIMES model was originally extracted from the Pan European TIMES (PET) model and then updated updated with improved data based on much extensive local knowledge. The Irish energy system is characterized and modelled in terms of its supply sectors, its power generation sector, and its demand sectors. Extensive description and details on modelling structure and approach may be found in (Chiodi et al., 2013a; Chiodi et al., 2013b; Ó Gallachóir et al., 2012).

The Irish TIMES model used in this analysis has a base year calibrated to 2005 national energy balance (Howley et al., 2006), a time horizon of 45 years (to 2050) and a time resolution of four seasons with day-night time resolution, the latter comprising day, night and peak time-slices. Energy demands are driven by a macroeconomic scenario, which is based on the ESRI HERMES macroeconomic model of the economy (FitzGerald et al., 2013), with key drivers extended to the period 2050. On the supply side, fossil fuel prices are based on IEA's current policy scenario in World Energy Outlook 2012 Report (IEA, 2012d).

Given the importance of renewable energy for the achievement of mitigation targets, Ireland's energy potentials and costs are based on the most recently available data. The domestic bioenergy resources are represented by 12 different commodities. The total resource capacity limit for domestic bioenergy – considering both available and technical potential – has been set at 2887 ktoe for the year 2030 and at 3805 ktoe by 2050, based on the estimates from (Clancy et al., 2012; Howley et al., 2012; Phillips, 2011; SEAI, 2010a; Smyth et al., 2010) (see Table A-4 of Appendix A for details). The upper capacity limit for other renewable resources such as onshore and offshore wind energy, ocean, hydro, solar and geothermal energy are summarized in Chiodi et al. (2013b).

The cost assumptions for domestic bioenergy commodities are based on McEniry et al. (2011) for biogas from grass, Kent et al. (2011) for forestry, Clancy et al. (2008) for willow and miscanthus crops and delivery costs, and Clancy et al. (2012) for wheat crops, oil seed rape (OSR) and recycled vegetable oil (RVO). For the remaining commodities, the cost assumptions used in the PET model within the RES2020 project (RES2020) were used. Cost estimates for bioenergy imports are based on

[30]See <http://iea-etsap.org/> for more information

(Clancy et al., 2012) international trends. Details are included in Table A-5 of Appendix A. Cost assumptions for bulk renewable energy technologies were recently updated based on Parsons Brinckerhoff (2011), VGB Powertech (2011) (for wind energy) and Parsons Brinckerhoff (2012) (for solar). Other model reviews focused on conventional generation technologies are based on the values form Parsons Brinckerhoff (2011).

Based on work undertaken by Ireland's transmission system operator EirGrid (2010)[31], the level of variable (non-dispatchable) renewable generation – namely wind, solar and ocean energy – is limited here to a maximum share of 70% of electricity generation within each timeslice and to 50% at annual level to account for operational issues associated with such high levels of variable generation in the power system. Regarding policies, investment subsidies and feed-in-tariffs for renewables based on policies currently in practice are assumed here to continue until 2030 and no trading of green certificates is assumed. The installation of new coal power plant capacities are limited to the replacement of current capacity levels, while for wind a maximum installation rate is set at 750 MW per year.

4.4. Scenario definition

Six scenarios are built in this paper, a business as usual (*BaU*) scenario and five distinct mitigation scenarios reflecting the ambition to move towards a low carbon economy combined with contextual considerations as outlined in Section 4.2.1. The *BaU* scenario delivers energy service demands in the absence of efficiency improvements and emissions reduction targets. This scenario is used as a reference case against which to compare the mitigation scenarios. All the mitigation scenarios assume that Ireland's 2020 targets for emissions reduction are met[32] and that the energy system is required to deliver an 80% reduction in CO_2 emissions by 2050 relative to 1990 levels (equivalent to a 52% target for GHG). The key differences in the scenarios are the targets chosen for intermediate emissions reduction in 2030 and the availability of bioenergy for international trade (imports).

For the scenarios named *Trg-20*, *Trg-30* and *Trg-40*, the key driver is the GHG target for the year 2030 and total GHG emissions reductions of 20%, 30% and 40% are required respectively relative to 1990 levels. Agricultural non-energy emissions (not covered by the model) are implicitly assumed to be aligned with national GHG projections in the period to 2020 and remain constant over the period 2020-2050. Therefore the energy system is required to achieve CO_2 reductions by 2030 of 29% (49.4%), 44.8% (60.6%) and 60.5% (71.8%) below 1990 (2005) levels.

[31] Ireland's Transmission System Operator (TSO).

[32] Although not with the ETS / non-ETS split

The two additional scenarios entitled *Trg-20 SC* and *Trg-20 DR* deliver the same emissions reduction pathway as the *Trg-20* scenario, but differ in terms of availability for bioenergy imports. The *Trg-20 SC* scenario simulates how shortages on imported bioenergy commodities consequent with the introduction of the *sustainability criteria* (SC) of the EU Renewable Energy Directive may affect the energy system choices. To simulate the maximum levels of available imported bioenergy, which meet SC requirements, we refer to analysis in Clancy et al. (2012). Assuming a global context of high bioenergy demand driven by the introduction of mitigation targets in several countries, the *Medium supply/High demand* scenario has been used as main reference for the period 2010-2030, as shown in Table 4-1[33].

Description	2010	2020	2030	2040	2050	Unit
Bio Ethanol	781.3	409.4	1404.1	1460.8	1519.9	ktoe
Biodiesel	101.5	0.0	109.9	114.4	119.0	ktoe
Wood Pellets	22.9	0.0	427.1	444.4	462.4	ktoe
Wood Chip	7.6	0.0	142.4	148.1	154.1	ktoe

Table 4-1. Imported bioenergy potential

The *Trg-20 DR* simulates an energy scenario where, given the growing concerns over sustainability and impacts in terms of *Direct and Indirect Land Use Change* (DLUC and ILUC) of most of the imported bioenergy crops, the mitigation targets may be achieved only by mean of domestic resources (DR), meaning that no bioenergy imports are allowed beyond 2020.

The main scenarios assumptions are summarized in Table 4-2.

Scenario	Mitigation Target			Bioenergy Imports		
	2020	2030	2050	2020	2030	2050
BaU	No	No	No	Yes	Yes	Yes
Trg-20	-20.4% GHG (-28.2% CO_2) rel. 2005	-20% GHG (-29.0% CO_2) rel. 1990	-52.4% GHG (-80% CO_2) rel. 1990	Yes	Yes	Yes
Trg-30	-20.4% GHG (-28.2% CO_2) rel. 2005	-30% GHG (-44.7% CO_2) rel. 1990	-52.4% GHG (-80% CO_2) rel. 1990	Yes	Yes	Yes
Trg-40	-20.4% GHG (-28.2% CO_2) rel. 2005	-40% GHG (-60.4% CO_2) rel. 1990	-52.4% GHG (-80% CO_2) rel. 1990	Yes	Yes	Yes
Trg-20 SC	-20.4% GHG (-28.2% CO_2) rel. 2005	-20% GHG (-29.0% CO_2) rel. 1990	-52.4% GHG (-80% CO_2) rel. 1990	Limited	Limited	Limited
Trg-20 DR	-20.4% GHG (-28.2% CO_2) rel. 2005	-20% GHG (-29.0% CO_2) rel. 1990	-52.4% GHG (-80% CO_2) rel. 1990	No	No	No

Table 4-2. Scenarios assumptions

[33] Beyond 2030 we assumed a 2% increase every 5 years.

4.5. Results

This section provides a range of energy system configurations for Ireland that each deliver projected energy service demand requirements optimised to least cost and subject to different policy constraints for the time period out to 2050. The analysis of results focuses on the differences in the energy systems configurations, in order to inform policy decisions regarding energy efficiency, renewable energy and climate change mitigation. Economic considerations and the implications for energy security and for land usage are also assessed. The results firstly (Section 4.5.1) explores implications of introducing different 2030 emissions targets, comparing results for the *BaU*, the *Trg-20* and the *Trg-40* energy futures. Results from the intermediate scenario *Trg-30* are included in certain cases for sensitivity. Section 4.5.2 discusses implications of possible biofuels imports shortages given the introduction of *sustainability criteria* of the EU Renewable Energy Directive, assessing how this results in terms of capacity of delivering emissions reductions. This is followed by a discussion on how these future low carbon economies may result on Irelands import dependency (Section 4.5.3). Section 4.5.4 investigates implications of results in terms of land usage. Lastly Section 4.5.5 discusses economics of energy futures.

4.5.1. Implications of different low carbon pathways for energy efficiency and renewable energy

This section discusses the implication of delivering deep emissions reduction for the year 2030. In particular model results are compared for three distinct energy scenarios: the business as usual, where energy system delivers energy demands without efficiency improvement and emissions targets; the *Trg-20* where the emissions targets is *aligned* to the EU Low Carbon Roadmap; the *Trg-40* where the EU target is *applied* directly to Ireland's energy system.

The results show radically different futures. In the absence of emissions mitigation (see Figure 4-3), the *BaU* scenario shows the energy system emissions at approximately 51 Mt CO_2 in 2030, representing a growth of 20% relative to 2010 (43 Mt). This increasing trend continues further to 2050 reaching 53 Mt. To illustrate the scale of the challenge in 2030, a 20% GHG reduction target hence means effectively halving the projected *BaU* emissions, while for a 40% target is equivalent to a 75% reduction. The breakdown of CO_2 reductions shows that by 2030 to achieve reductions between 20% and 40% relative to 1990 levels, emissions should decrease in all sectors. In the *Trg-20* scenario, 86% of the overall emissions reduction is delivered within the power, transport and industry sectors. In the *Trg-40* scenario the model points to further reductions mostly in the transport sector. Compared to 2010 emissions levels, the mitigation scenarios therefore show reductions of 69% and 79% in the in *Trg-20* and *Trg-40* in the power sector respectively; by 57% and 74% in the residential sector, by 53% and 82% in the industry and services sectors and by 8% and 52% in transport.

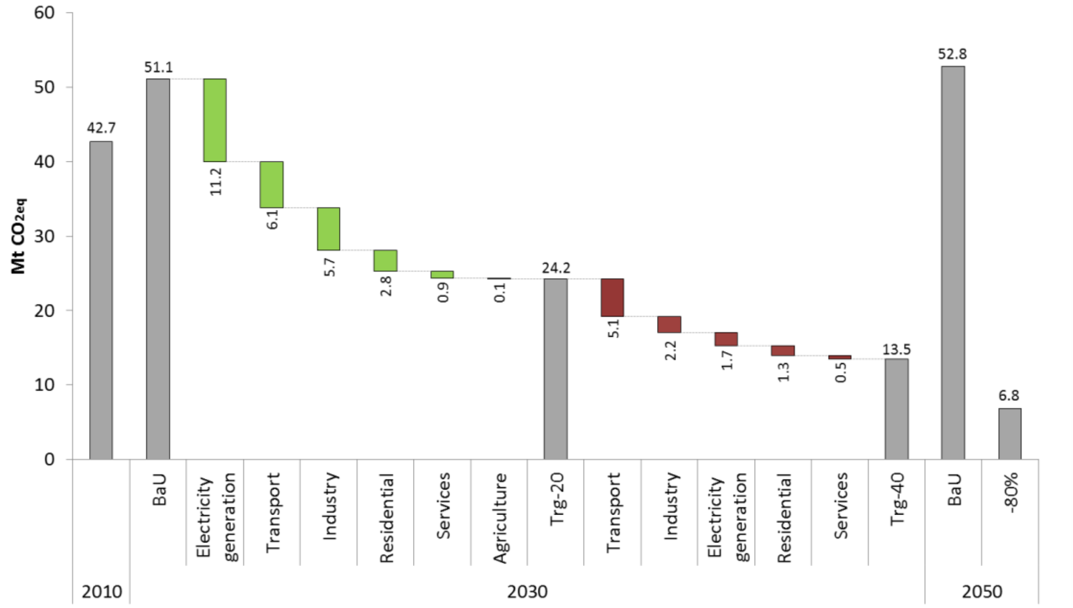

Figure 4-3. Incremental changes in CO_2 emission required by each sector to reach 20% and 40% reduction targets relative to BaU scenario by 2030

Very different energy trends drive these emissions trajectories. Table 4-3 summarizes primary energy requirements by fuel in these alternative energy futures. The Table 4-4 provides indications of how energy is consumed in the end-use sectors. The projected primary energy consumption in the *BaU* suggests future trends very similar to the current, i.e. substantial reliance on oil and gas with a small share for renewables.

The *Trg-20* scenario shows a drop in reliance on oil from 2030, coupled with a bioenergy expansion. Liquid biofuels (mostly ethanol) nearly triples in transport, with significant growth of biomass in industry (from 8% to 42% of TFC) and in buildings (from 5% to 9%). In electricity generation, there is a significant expansion of wind energy which displaces coal and some natural gas in the generation mix. Although there is no significant electrification of heat or transport by 2030, the electricity share of energy use rises due to improved end-use efficiency (Table 4-4). Coal has all but disappeared from the domestic energy system except for use in industry in combination with CCS technology.

Under the *Trg-40* scenario, the trends in the *Trg-20* scenario are strengthened into the medium term. By 2030, fossil fuels consumption shrinks further (by 40% relative to 2010); while bioenergy surpasses oil consumption, with biofuels used in transport (a mix of ethanol, biogas and biodiesel), accounting for 39% of transport TFC, and biomass used for the heating sectors reaching 63% of industry TFC and 18% of buildings TFC. Natural gas accounts for 43.5% of electricity generation and about half of this is used in combination with CCS technology.

By the year 2050 the *Trg-20* and the *Trg-40* scenarios show very similar results with few small differences driven by different allocation of investments in the year 2030. These energy systems show a dramatic drop in oil and coal consumption, while renewables (wind and bioenergy) rapidly increase. Liquid biofuels are extensively used in transport (51%-55% of transport TFC), while biomass is largely used in industry (63% of industry TFC) and buildings (26% of buildings TFC). Wind energy and natural gas in combination with CCS technology provide an impetus for the electrification of private cars and rail in the transport sector.

		BaU			Trg-20			Trg-40		
Unit: Mtoe	**2010**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Fossil Fuels (Total)	**14.4**	**17.2**	**18.4**	**19.4**	**13.5**	**11.2**	**7.9**	**13.2**	**8.6**	**7.4**
Coal and Peat	2.03	2.33	2.01	1.44	0.71	0.46	0.51	0.93	0.49	0.51
Oil (incl. Int Aviation)	7.71	9.81	10.5	11.4	7.92	6.46	3.05	8.29	4.58	2.81
Oil (excl. Int Aviation)	6.94	8.48	9.08	9.87	6.59	5.05	1.53	6.97	3.16	1.29
Natural Gas	4.69	5.08	5.88	6.57	4.88	4.3	4.3	3.98	3.53	4.1
Renewables (Total)	**0.8**	**1.4**	**1.5**	**1.9**	**1.5**	**4.5**	**11.3**	**2.0**	**9.1**	**12.0**
Hydro	0.05	0.05	0.05	0.04	0.09	0.09	0.1	0.09	0.09	0.1
Wind	0.24	0.55	0.55	0.55	0.66	1.33	1.65	0.71	1.41	1.58
Biomass	0.21	0.55	0.64	0.83	0.42	1.49	3.07	0.46	2.27	3.3
of which imported	0.01	0	0.04	0.12	0.06	0.88	1.87	0.07	1.4	2.1
Bioliquids	0.09	0.07	0.12	0.1	0.1	0.35	1.75	0.31	1.42	1.85
of which imported	0.07	0.07	0.08	0.09	0.07	0.31	1.62	0.28	1.38	1.71
Biogas	0.06	0.06	0.06	0.06	0.06	0.06	1.19	0.06	1.13	1.19
Other Renewables	0.02	0	0.01	0.08	0.01	0.01	0.03	0.01	0.02	0.13
Electricity Imports (Net)	**0.04**	**0.00**	**0.05**	**0.12**	**0.17**	**0.17**	**0.17**	**0.17**	**0.17**	**0.17**
Total	**15.2**	**18.6**	**20.0**	**21.4**	**15.1**	**15.9**	**19.3**	**15.4**	**17.9**	**19.6**

Table 4-3. Primary energy trends for BaU, Trg-20 and Trg-40 (Mtoe)

	BaU		Trg-20		Trg-40	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**
Fossil Fuels/TFC	78.5%	78.8%	64.3%	30.5%	41.1%	28.6%
Renewables/TFC	4.0%	5.1%	14.9%	44.5%	37.2%	46.7%
of Thermal TFC	*5.7%*	*8.1%*	*21.6%*	*39.6%*	*35.7%*	*40.0%*
of Transport TFC	*1.9%*	*1.9%*	*6.5%*	*51.0%*	*39.1%*	*55.5%*
Electricity/TFC	17.5%	16.0%	20.8%	25.0%	21.7%	24.6%
of Thermal TFC	*31.9%*	*30.3%*	*33.3%*	*35.5%*	*35.8%*	*35.0%*
of Transport TFC	*0.2%*	*0.3%*	*4.9%*	*11.0%*	*4.9%*	*11.0%*

Table 4-4. Fuel shares of energy use for BaU, Trg-20 and Trg-40

The European Commission, with the 2020 Energy Climate Package Framework, established both climate mitigation targets and energy targets for renewable energy and energy efficiency. Current policy discussions (EC, 2013) centre on whether or not similar sets of targets should be established in the 2030 policy framework. If this is the case, the cost optimal results from this paper may provide some useful insights into the levels of ambition that might be appropriate in future. Table 4-5 summarizes the scenario results for renewable shares and for energy savings for the years 2030 and 2050. The intermediate scenario *Trg-30* was included for sensitivity. The calculation of the renewable shares was carried out in accordance with Article 5 of Directive 2009/28/EC (EC, 2009c), namely the share of energy from renewable sources was evaluated as a percentage of gross final consumption (GFC). Energy savings are quantified in the model as a reduction in final energy consumption as compared to the *BaU* scenario. The *BaU* scenario does not assume any technology improvements over the time horizon to 2050 and is therefore a counterfactual against which the other scenarios can be compared.

The results show a strong correlation between renewable shares in 2030 the emissions reduction target, while this is not the case for energy savings. This is due to the intrinsic nature of the tool used, based on a least cost approach. Most of the efficiency measures are cost effective and are selected in all scenarios.

Ireland's National Renewable Energy Action Plan (NREAP) (DCENR, 2010) stipulates that by 2020 the 16% renewable energy share of GFC target will be achieved through sectoral targets comprising 42.5% of electricity generation (RES-E), 10% of transport consumption (RES-T) and 12% of heating (RES-H); equivalent to 8.5% of GFC from RES-E, 4.2% from RES-H and 3.4% from RES-T. The least cost analysis here shows that by 2030, a significant growth in renewable heat is anticipated in the three scenarios and, growth also in renewable transport although only for the *Trg-30* and Trg-40 scenarios. Renewable energy for electricity generation does not vary considerably across the policy scenarios, since the maximum share of non-dispatchable renewable electricity is already achieved in the *Trg-20* scenario allowing very little scope for growth. It is worth noting that while Ireland is on track (though not without challenge) to achieve its ambitions for renewable electricity in its NREAP, there is considerably uncertainty regarding the ambitions for renewable transport and renewable heat. Based on current trends, the most difficult element of the scenarios will be achieving the growth of renewable heat.

	Trg-20		**Trg-30**		**Trg-40**	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**
Renewable Share	25.4%	54.8%	37.7%	54.8%	47.5%	56.7%
of which RES-H	*11.7%*	*21.2%*	*16.8%*	*21.0%*	*18.8%*	*21.3%*
of which RES-E	*11.0%*	*13.0%*	*10.8%*	*13.2%*	*11.5%*	*12.9%*
of which RES-T	*2.9%*	*20.9%*	*10.4%*	*21.0%*	*17.6%*	*22.9%*
Energy savings	-21.3%	-28.7%	-21.6%	-28.7%	-21.2%	-28.9%

Table 4-5. Renewable share of GFC and energy efficiency savings for Trg-20, Trg-30 and Trg-40

4.5.2. How sustainable is the low carbon future?

This section discusses the sustainability of low carbon future pathways, in particular how the ability of the energy system of delivering deep reductions in emissions levels given the sustainability implications of bioenergy imports. In this case a pathway with 20% GHG target for the year 2030 is selected as the one most aligned with the EU Low Carbon Roadmap (see Section 4.2.1). The *Trg-20* results are compared with results from the *Trg-20 SC* scenario (which limits imported bioenergy commodities due to the *sustainability criteria* (SC) of the EU Renewable Energy Directive) and the

Trg-20 DR scenario (in which mitigation targets may be achieved only by mean of domestic resources (DR)).

Figure 4-4, which compare bioenergy and other renewables consumption by sector, indicates that limited import capability causes reductions in bioenergy consumption. The two bioenergy scenarios (*Trg-20 SC* and *Trg-20 DR*) show that restrictions in biofuels and biomass imports have only limited impact on the short term (2020) but may have a larger impact on over the longer term. Reductions in bioenergy levels are only partially replaced with domestic bioenergy resources and other renewable sources (mostly from the power sector). Results for the *Trg-20 SC* scenario indicate that bioenergy consumption will reduce by about 6% in 2030 and by 19% in 2050 relative to the *Trg-20* scenario. These reductions by 2030 largely affect the industry sector, where limitations in biomass availability causes a reduction of 11% in biomass consumption, only partially counterbalanced by higher consumption levels in transport (+3.2% for ethanol) and residential (+7% in biogas and geothermal). On the longer term bioenergy shrinks in all sectors while renewable electricity from wind and solar grows (+36% relative to *Trg-20*), as shown in Figure 4-4. In the transport sector the drop in biodiesel and biomass imports are therefore only partially balanced by higher domestic biogas production (from grass) (+21%) and increased imports of ethanol (+32%). With respect to heating, electricity displaces biomass and biogas (-23%) in the heating sectors. The *Trg-20 DR* shows a similar pattern, but with steeper reduction trends in bioenergy consumption. By 2030 the reduction in bioenergy consumption is 36% relative to the unconstrained case and passes to 53% in 2050. The heating sectors moves further from bioenergy (-42% in 2030 and -45% in 2050) to electricity (+2.5% in 2030 and 76% in 2050) which shows increased levels of renewable generation (+2.4% in 2030 and +70% in 2050 from onshore and offshore wind, solar and some ocean). The transport sector (freight and public transport) from 2030 transitions from bioliquids to biogas, while in 2050 about 40% of freight fleet consumes hydrogen (from gasification of coal with CCS).

The other main consequences of introducing import constraints are: i) a reduced overall renewable share; ii) a higher end-use efficiency; iii) an increased electrification of the end-use sectors. As indicated in Table 4-6, the total renewable share reduces in the sustainable bioenergy policy scenarios due to the lower shares transport and heat sectors, where biomass and biofuels are the dominant renewable sources. These limitations do not influence the RES-E sector, where the share indeed grows. The reduced bioenergy availability forces the model to adopt deeper efficiency measures with further reductions compared to the *Trg-20* which take place in transport, residential and services sectors. As third consequence, the results highlight an increase in electricity importance for the end-use sectors (Table 4-7): i) in absolute terms electricity will grow in 2050 by 35% (*Trg-20 SC*) and 67% (*Trg-20 DR)* relative to the *Trg-20* case; ii) in relative terms (see Table 4-7) electricity becomes the most important energy vector for thermal energy and, in some cases, for all end-use sectors. The electricity generation fuel mix to provide this increased demand is summarized in Figure 4-5.

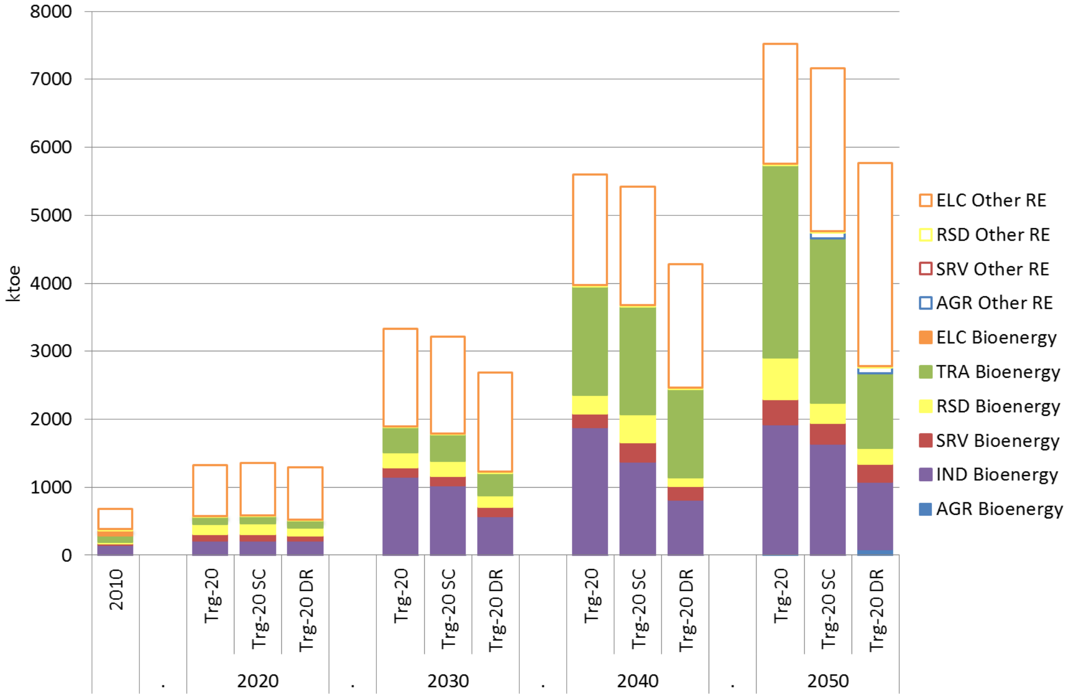

Figure 4-4. Bioenergy and other renewables consumption by sector in Trg-20, Trg-20 SC and Trg-20 DR (ktoe)

	Trg-20		Trg-20 SC		Trg-20 DR	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**
Renewable Share	25.4%	54.8%	24.7%	52.2%	21.1%	43.6%
of which RES-H	*11.7%*	*21.2%*	*10.9%*	*17.3%*	*7.0%*	*12.7%*
of which RES-E	*11.0%*	*13.0%*	*10.9%*	*17.6%*	*11.4%*	*22.6%*
of which RES-T	*2.9%*	*20.9%*	*3.0%*	*17.8%*	*2.6%*	*8.3%*
Energy savings	-21.3%	-28.7%	-22.0%	-29.2%	-23.3%	-32.9%

Table 4-6. Renewable share and energy efficiency for Trg-20, Trg-20 SC and Trg-20 DR

	Trg-20		Trg-20 SC		Trg-20 DR	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**
Fossil Fuels/TFC	64.3%	30.5%	65.0%	28.6%	68.3%	33.1%
Renewables/TFC	14.9%	44.5%	14.2%	37.4%	9.9%	23.1%
Electricity/TFC	20.8%	25.0%	20.8%	34.0%	21.8%	43.8%
of Thermal TFC	*33.3%*	*35.5%*	*33.2%*	*52.2%*	*35.1%*	*65.9%*
of Transport TFC	*4.9%*	*11.0%*	*5.2%*	*11.0%*	*5.3%*	*12.3%*

Table 4-7. Share of energy use in end-use sectors for Trg-20, Trg-20 SC and Trg-20 DR

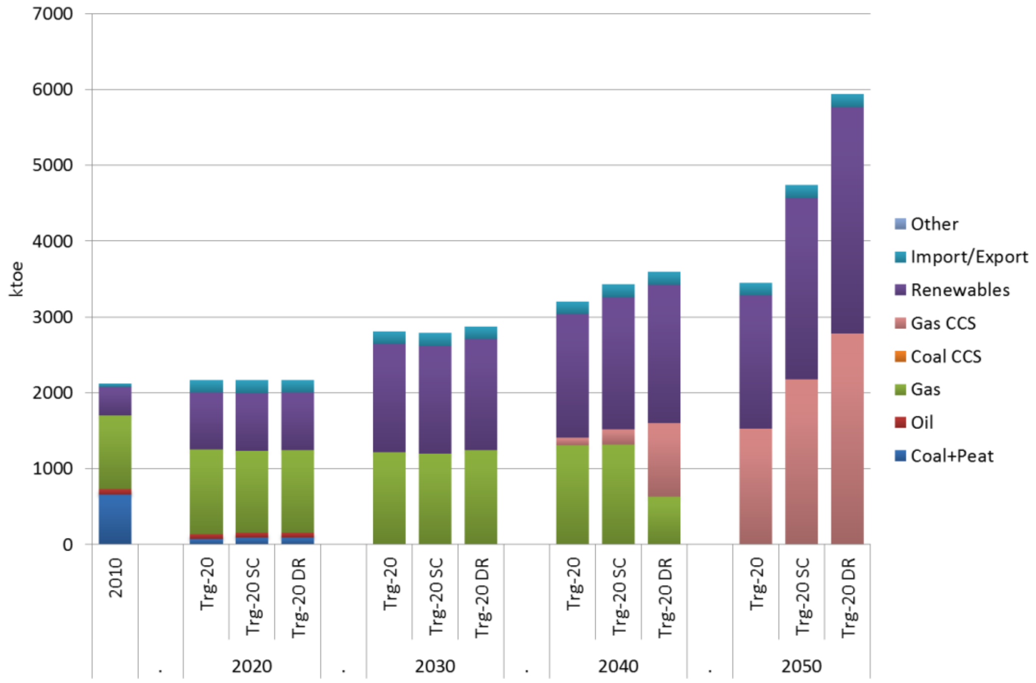

Figure 4-5. Electricity generation by fuel in Trg-20, Trg-20 SC and Trg-20 DR

4.5.3. Implications for energy security

Table 4-8 highlights the implications of these different mitigation scenarios on another key policy issue, energy security. The analysis here is limited to import dependency, which is a crude and limited metric by which to assess energy security. Focussing first on primary energy import dependency, the results show that the import dependency in the business as usual scenario grows to approximately 93% in 2050, while across the mitigation scenarios reducing trends are shown. The *Trg-40* scenario shows interestingly that the steeper reduction in emissions levels drives a more radical reduction in energy dependency by 2030, but then aligns to the *Trg-20* case over the longer term. Bioenergy contributes in this reduction resulting in all scenarios with lower import dependency indices compared to overall primary energy levels.

	Scenario	2010	2020	2030	2040	2050
Primary Energy	**BaU**	86.0%	86.8%	87.9%	91.4%	92.9%
	Trg-20	86.0%	85.9%	81.3%	78.3%	72.4%
	Trg-40	86.0%	84.0%	72.5%	70.7%	72.1%
	Trg-20 SC	86.0%	85.1%	79.6%	71.4%	67.5%
	Trg-20 DR	86.0%	84.9%	76.9%	68.9%	65.0%
Bioenergy	**BaU**	32.6%	10.9%	14.1%	16.6%	21.5%
	Trg-20	32.6%	22.4%	62.5%	68.6%	58.0%
	Trg-40	32.6%	42.2%	57.7%	56.0%	60.2%
	Trg-20 SC	32.6%	13.7%	47.3%	41.9%	41.3%
	Trg-20 DR	32.6%	0.0%	0.0%	0.0%	0.0%

Table 4-8. Primary energy and bioenergy import dependency

4.5.4. Implications for land usage

The potential growth of bioenergy raises a number of concerns relating to land depletion and implications with one of Ireland's most important economic sectors: the agri-food sector. These concerns have also been highlighted recently in (Murphy et al., 2013) which shows that the EU Agricultural Policy (Cross Compliance) (EC, 2009a, b) does not accept that pasture (currently 4 Mha in Ireland) can be ploughed to generate arable land for biofuel production. Ireland is not self-sufficient in grains (Smyth et al., 2010) and as such there would be intense competition for a grain ethanol industry with the likelihood that ethanol production in Ireland would be based on imported grains or at least necessitate import of more grain (Murphy et al., 2013).

This section therefore presents a first attempt on quantifying this impact, presenting modelling results, not only in terms of energy flows or emissions, but also in terms of land consumption. The conversion factors of each individual commodity (Table 4-9) are drawn from (Murphy et al., 2013; SEAI; Smyth et al., 2009). Crop rotation levels determine the ratio between required and contracted land.

Commodity	Conversion factor ha/ktoe	Rotation	Reference
Willow	253.0	1 in 2	(SEAI)
Miscanthus	268.3	1 in 1	(SEAI)
Rape Seed Biodiesel	910.2	1 in 5	(Smyth et al., 2009)
Palm Oil Biodiesel	348.9	1 in 1	(Smyth et al., 2009)
Wheat Ethanol	634.4	2 in 3	(Smyth et al., 2009)
Optimized Wheat Ethanol	498.4	2 in 3	(Smyth et al., 2009)
Grass Biomethane	263.4	1 in 1	(Murphy et al., 2013)

Table 4-9. Bioenergy conversion factors

Table 4-10 summarizes energy crops (including grass) consumptions in the different scenarios converted into land units, namely hectares. Regarding imported commodities, the model does not distinguish between different import locations nor different feedstock crops and hence the following assumptions were made to complete this analysis: i) imported bioethanol is assumed to originate from optimized wheat crops; ii) biodiesel originates from palm oil; iii) woody biomass originates from miscanthus crops. Given the total of Ireland's agriculture land is 4.3 Mha (Smyth et al., 2009), the required land for domestic energy crops in 2030 ranges from 1.4% (in *BaU*) to 8.9% (in *Trg-40*) and by 2050 between 0.7% (in *BaU*) and 11.9% (in *Trg-20 DR*) of total agriculture land. Given crop rotation this translates into values shown in Table 4-10. Equally bioenergy imports require the equivalent of 1.2% (*BaU* by 2030) to 30.5% (*Trg-40* by 2050) of current agricultural land (between 1.6% and 35.9% contracted).

Currently tillage accounts only for about 0.4 Mha, while the remaining 3.9 Mha are under pasture grassland. Future scenarios therefore indicate that by 2030 to produce methane from grass in the *Trg-*

40 scenario would require the equivalent of 7.2 % of current grassland area. However research in (McEniry et al., 2013) has highlighted that practices such as increasing nitrogen (N) fertiliser input (to the limit permitted by the EU Nitrates Directive) combined with increasing the grazed grass utilisation rate has the potential to significantly increase the average available grass resource by a factor of 7 over currently available grassland resources (from 1.7 million t of dry matter (DM)) available in excess of livestock requirements to 12.2 million t DM/annum). It is also suggested that under this scenario alternative uses for grassland biomass such as anaerobic digestion and green bio-refining would not compete with traditional dairy, beef and lamb production systems, but could provide an alternative enterprise and income to farmers. Energy crops in total in the *Trg-40* scenario would require an equivalent of 66% of today's arable land contracted.

By 2050 the situation are even more challenging with (in the *Trg-20 DR* scenario) approximately 8% of current grassland used to produce methane and the equivalent of 113% of today's arable land under contract to produce willow, miscanthus, wheat and rapeseed for energy purposes.

		BaU		Trg-20		Trg-40		Trg-20 SC		Trg-20 DR	
Unit: kha		**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Domestic	Willow	0	0	40	44	50	44	50	160	73	160
	Miscanthus	30	30	43	95	43	95	43	95	43	95
	Grass Biomethane	0	0	0	299	283	299	0	299	63	299
	Wheat Ethanol	0	0	0	0	0	0	0	0	0	8
	Rape seed Biodiesel	148	0	148	148	148	148	148	148	148	148
	TOTAL	**178**	**30**	**231**	**586**	**523**	**586**	**241**	**702**	**326**	**710**
Imported	Wheat Ethanol	58	70	213	677	677	677	222	894	0	0
	Biodiesel[34]	0	0	8	247	165	282	8	42	0	0
	Wood Chip[35]	10	31	229	229	229	229	36	40	0	0
	Wood Pellets[36]	0	0	0	260	137	319	102	121	0	0
	TOTAL	**68**	**100**	**450**	**1413**	**1208**	**1507**	**368**	**1096**	**0**	**0**
% of AGR Land	**Domestic (%)**	4.2	0.7	5.4	13.7	12.3	13.7	5.7	16.5	7.6	16.7
	Imported (%)	1.6	2.4	10.7	33.6	28.8	35.9	8.8	26.1	0	0

Table 4-10. Land required (contracted) for domestic and imported energy crops in 2030 and 2050

4.5.5. Implications for the economy

One of the main insights that can be gained from the use of energy systems models such as TIMES is from quantifying the impact of different mitigation targets on marginal CO_2 abatement costs, which provide an indication of the costs of abating the last tonne of CO_2 and can be used as a proxy for indicating the level of carbon tax that may be required to reach a certain level of mitigation.

[34] From Palm Oil

[35] From Miscanthus

[36] From Miscanthus

Table 4-11 summarises the marginal CO_2 abatement costs for the mitigation scenarios presented in this paper. Interestingly the earlier investments required to achieve a 40% rather than 20% GHG emissions target in 2030 appear less cost effective in terms of the CO_2 marginal price, which remains higher in *Trg-40* compared with *Trg-20* over the whole period 2030-2050. The *Trg-20 SC* scenario indicates as early as 2030, higher CO_2 abatement prices due to insufficient availability of bioenergy resources. By 2050 this difference becomes steeper, illustrating how bioenergy imports influences the achievement of this challenging mitigation targets. Similarly the *Trg-20 DR* scenario shows that limitations in import options may forces the energy system to invest in expensive abatement technologies (e.g. hydrogen) which drives the marginal abatement costs at values even higher than the *Trg-20 SC* case

Scenario	**2020**	**2030**	**2040**	**2050**	
Trg-20	74	98	312	395	€/tonne
Trg-30	74	220	322	400	€/tonne
Trg-40	74	363	389	410	€/tonne
Trg-20 SC	74	110	380	1389	€/tonne
Trg-20 DR	74	259	387	1747	€/tonne

Table 4-11. CO_2 shadow prices (€$_{2010}$/tonne of $CO_{2,eq}$)

Other interesting insights are also provided by analysing the system costs components. Figure 6 gives a breakdown of total energy system costs expressed here as a percentage of GDP for 3 scenarios (*BaU*, *Trg-20* and *Trg-40)*. Cost components have been divided between investments, which include investment in power generation plants, transport vehicles, heating, as well as machines and equipment; fuel costs and other system costs (largely operational and maintenance costs). In all scenarios we assume the same GDP level, conscious that in reality the movement to a low carbon energy system will impact on the structure and level of economic growth. This simplification is due to the current modelling framework, which does not incorporate a feedback mechanism between the developments in the energy system and the wider economy.

The results show (Figure 4-6) that to move from *BaU* to a 20% emissions target the investments levels should grow by 18%, but also fuel costs reduce by approximately 30%. This results in an overall system cost reduction of 0.4% in terms of GDP. Conversely the achievement of a more stringent emissions target (the *Trg-40*) may drive a further increase in investments that are only partially balanced by lower fuel costs. The overall energy system cost hence results with an increase of 0.9 % of GDP.

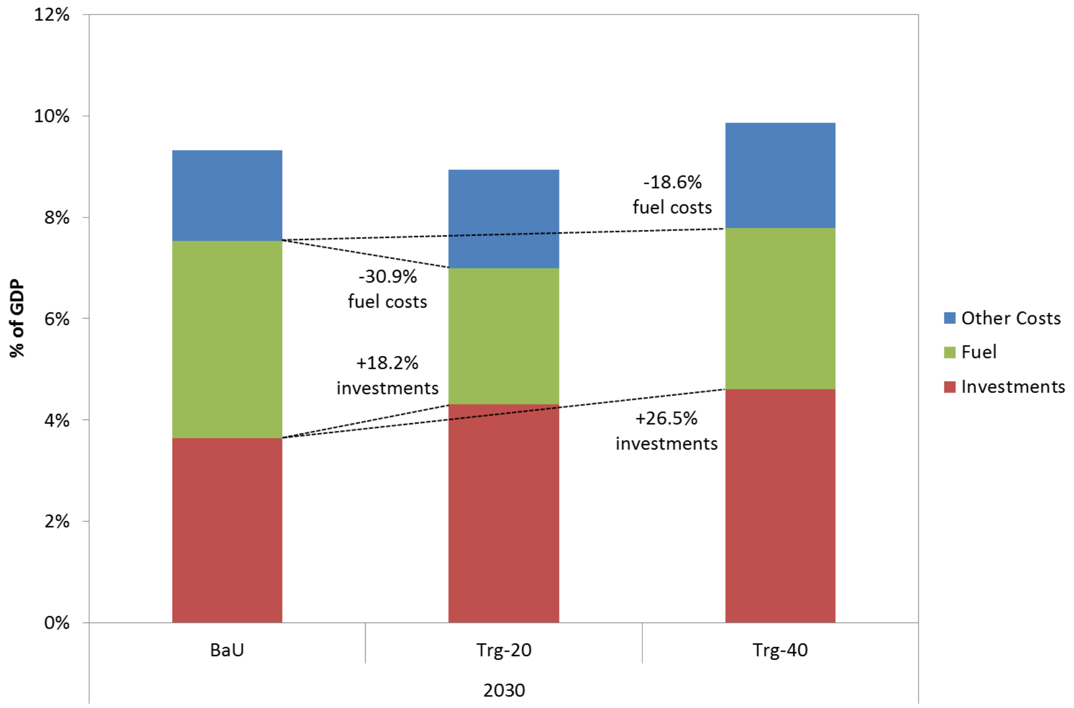

Figure 4-6. Breakdown of 2030 system cost as % of GDP for BAU and Trg-20 and Trg-40 scenario

4.6. Discussion and Conclusion

Transitioning to a low carbon economy to mitigate climate change represents globally one of the most challenging policy targets for the future years. The EU has set this ambition implementing policy targets for the year 2020 and now is reflecting on a new 2030 framework for climate and energy policies. This paper focuses on 2030 climate mitigation scenarios for Ireland, which is unique among MS for its recent emissions trends and the amount of GHG emissions from agriculture. The purpose of this paper is to provide evidence for energy policy makers in Ireland to enable them to engage with the European Commission regarding what targets might be appropriate. This paper also highlighted a number of implications that, in authors' opinion, should be carefully assessed in the development of a new policy framework, notably relating to bioenergy sustainability, energy security, land-use and costs.

The paper showed how different GHG emissions targets may influence the energy system in transitioning to a low carbon economy by 2050. The energy system arrived at in 2050 does not differ significantly across the scenarios but the pathways to get there are different. Moving from a pathway in which the EU Low Carbon Roadmap is aligned to Ireland's current trajectory – namely applying a 35-38% target relative to 2005 levels (approx. 20% relative to 1990) – to a target which simply applies the roadmap (a 40% target relative to 1990 levels), require significant changes for the energy system. The 20% reduction target showed a smoother transition, while in the 40% reduction target bioenergy consumption in 2030 surpasses fossil fuel consumption. Also in the 40%

reduction target the renewable energy share will pass from the current 16% target for the year 2020 to approximately 48% only 10 years later. Marginal CO_2 price increases from €$_{2010}$98/t to €$_{2010}$363/t. Moreover the earlier investments required to achieve a 40% rather than 20% GHG emissions target in 2030 are less cost effective in terms of CO_2 marginal price, which remain higher in the whole period 2030-2050.

The paper has a specific focus on bioenergy, which the results suggest are likely to be the most significant fuel source for the future economy. There are several concerns however regarding sustainability of these energy sources. The paper shown that application of sustainability criteria in international markets – for example as in the EU Renewable Energy Directive – may cause restrictions in bioenergy supply (mostly biodiesel), which can strongly influence the ability of Ireland energy system to deliver GHG emissions reductions. With constraints on imports, bioenergy contributions are significantly reduced, mainly within the transport sector, with consequent increases in electrification – based on gas CCS and renewables (wind, solar and also ocean), – end-use efficiency and hydrogen. Marginal CO_2 abatement costs rise sharply in accordance with the level of import restrictions.

This paper also sheds light on the implications for energy security. The energy import dependency in Ireland is anticipated to be reduced significantly in all the mitigation scenarios considered. Variable renewable energies – namely wind, solar and ocean – are the main drivers of this reduction, but also bioenergy positively contributes with at least 40% domestic consumption.

Finally the results point to the implications of bioenergy in terms of land usage. Domestically bioenergy passes from approximately 5,000 ha of land contracted in 2010, to about 710,000 ha by 2050 (in the *Trg-20 DR* scenario), equivalent to 17% of total agricultural land area. This may have serious implications for the food supply which should be addressed in future. Further research work is required to improve the integrated modelling of both the energy and agriculture systems in order to provide richer insights to the strategy between energy, food and climate mitigation.

Part II – Developing new methodologies for energy and climate modelling

5. Soft-Linking of a power systems model and energy systems model

Abstract

In this paper we present a soft-linking methodology that employs detailed simulation outputs from a dedicated power systems model to gain insights and understanding of the generation electricity plant portfolio results for the electricity sector from a separate energy systems model. We apply the methodology and present and discuss the results. The motivation for this soft-linking is to provide a transfer of information from the power systems model strong points to the energy systems model and use this information to improve and develop understanding of energy systems model results. Part of this motivation is derived from a view that one specific energy modelling tool cannot address all aspects of the full energy system in great detail and greater insights and progress can be gained by drawing on the strengths of multiple modelling tools rather than trying to incorporate them all into one comprehensive model. The methodology takes an optimized generation portfolio for a specific year from an energy systems model and undertakes a detailed high resolution chronological simulation of the same portfolio in the power systems model with added degrees of technical detail. Results presented here show that in the absence of key technical constraints, an energy systems model can potentially undervalue flexible resources, underestimate wind curtailment and overestimate the use of base load plant.

5.1. Introduction

Motivated by the need to reduce CO_2 emissions many European and Global governments have developed or are developing roadmaps and strategies to low carbon economies by the year 2050 (DECC, 2011; EC, 2011c; Jiang et al., 2010). The year 2050 is seen as a key year and much work has been undertaken on techno-economic modelling of entire energy systems out to this year. Energy systems modelling helps to identify technologies capable of having the greatest impact on CO_2 emissions and highlights technologies which potentially offer the lowest technical and financial risk in the face of a range of possible future demand scenarios. While a large range of dedicated energy systems models exist (Connolly et al., 2010) they generally concur that relative to today's levels, increased levels of renewable energy along with other low carbon measures will be required by 2050 in order to meet stringent emission reductions (Chen et al., 2011; EC, 2011c; Lior, 2012). Global wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand and that contribution could grow to in excess of

20% by 2050 (IPCC, 2011). The power system challenges surrounding the stochastic nature of wind, predictability and integration into electrical grids have been well documented (Ibrahim et al., 2011; IPCC, 2011; Lund, 2005; Rosen et al., 2007). Greater integration of variable renewables will require power systems to be increasingly flexible. In order to assess how suitable power systems are to levels of fluctuating renewable energy, high resolution chronological modelling is required to model the highly temporal variation of wind power output in association with the sometimes intertemporally constrained thermal plant. Many detailed assessments of wind power integration in various regions around the world have been undertaken and are summarized in (Holttinen et al., 2006). In general dedicated power systems models, run at hourly or sub-hourly resolutions, are used to undertake these types of studies as these models are capable of capturing the temporal variation of wind and its effect on the entire power system on a short time scale. Load flow modelling (both D.C. and A.C.) are also utilized to analyse network impacts of wind power integration but these are not the focus of this paper.

While power systems and energy systems models both address the modelling of complex systems, they are fundamentally different in their focus and application. Power systems models focus solely on the electrical power system and sometimes the gas network but do not consider the rest of the energy system. The primary inputs are generally exogenous in nature, including electricity load, fuel prices and power plant technical limits. Energy systems models examine the full energy system however the electrical power system is by contrast completely endogenous and driven by the combined behaviour of supply sectors that provide primary fuels and end-use sectors driven by exogenous energy service demands. The focus is typically to provide a technology rich basis for estimating energy dynamics over a medium and long-term, multiple period time horizon. Because of the exclusive focus on electricity generation within power systems models, the problem description can be at a higher resolution when compared to full energy systems model, which have to handle a much broader range of problems and sub-systems. Typically a power systems model can model from hourly to 5-minute or higher resolution while energy systems models may have a limited number of temporally-independent timeslices which can be a disadvantage when looking at power systems with levels of fluctuating renewable energy.

The benefit of higher resolution within power systems and energy systems modelling has been recognized where it was shown that optimal investment decisions derived from models can vary significantly depending on the timeslice selection used (Ludig et al., 2011; Nicolosi et al., 2011). In Ramachandran (2011) the author has developed a temporal UK MARKAL model to investigate the role of electricity storage. The UK temporal MARKAL model has 20 annual timeslices compared to six in most standard MARKAL databases. In Pina et al. (2011) the authors have developed a high resolution temporal TIMES model by dividing each year into 4 seasons, with 3 days per season and 24 hours per day. The results show that the increase in temporal resolution allows for more constraints to be taken into account, such as renewable resource availability, operational constraints, electricity demand dynamics and others.

The work presented in this paper is different as it is intended to present a methodology to soft-link a power systems model to an energy systems model. The motivation for this soft-linking is to provide a transfer of information from the power systems model strong points and use this information to improve and develop model results within an energy systems model. Part of this motivation is also derived from accepting the situation that perhaps one specific modelling tool cannot model everything and greater insights and progress can be gained by drawing on the strengths of other modelling tools rather than trying to incorporate them all into one comprehensive model. Power systems models are better suited to high resolution modelling of the electrical power system while energy systems models provide a more comprehensive overview of the entire energy sector including the long term resource mix problem and electrical demand elasticities. While some power systems models are capable of long-term capacity expansion the demand and growth for electricity is generally exogenous, as are fuel prices. The focus of this current methodology therefore is to use the high resolution economic unit commitment and dispatch capability of a power systems model to examine results from an energy systems model and gain insight into important features of power system design and operation, with a particular focus on how variable renewable generation impacts on the system. These insights can then be used to better interpret or improve results from the energy systems model. Such features of interest are system reliability, system flexibility, CO_2 emissions modelling and curtailment of renewable resources.

In this methodology one specific year is chosen from the energy systems model results and examined in greater detail in a power systems model. The energy systems model used in this analysis is the Irish TIMES model which is developed using the TIMES modelling tool. The power systems modelling tool used is *PLEXOS for Power Systems* (Energy Exemplar) and a model of the Irish power system in PLEXOS is presented in this analysis. These tools and models are explained in greater detail in Section 3. Both models are tested on the Republic of Ireland energy system and focus on the electrical power system within the full energy system.

While electricity generation in Ireland in 2005 accounted for approximately 18% of total final consumption, results for the year 2050 under a mitigation 80% carbon reduction target (relative to 1990 levels)[37] show this increasing to approximately 33% of total final consumption with a greater electrification in the heating sectors and transport on the pathway to 2050 (Chiodi et al., 2013b). This is coupled with a projected marked increase in wind generation as shown in Figure 5-1.

[37] -86.5% relative to 2005 levels

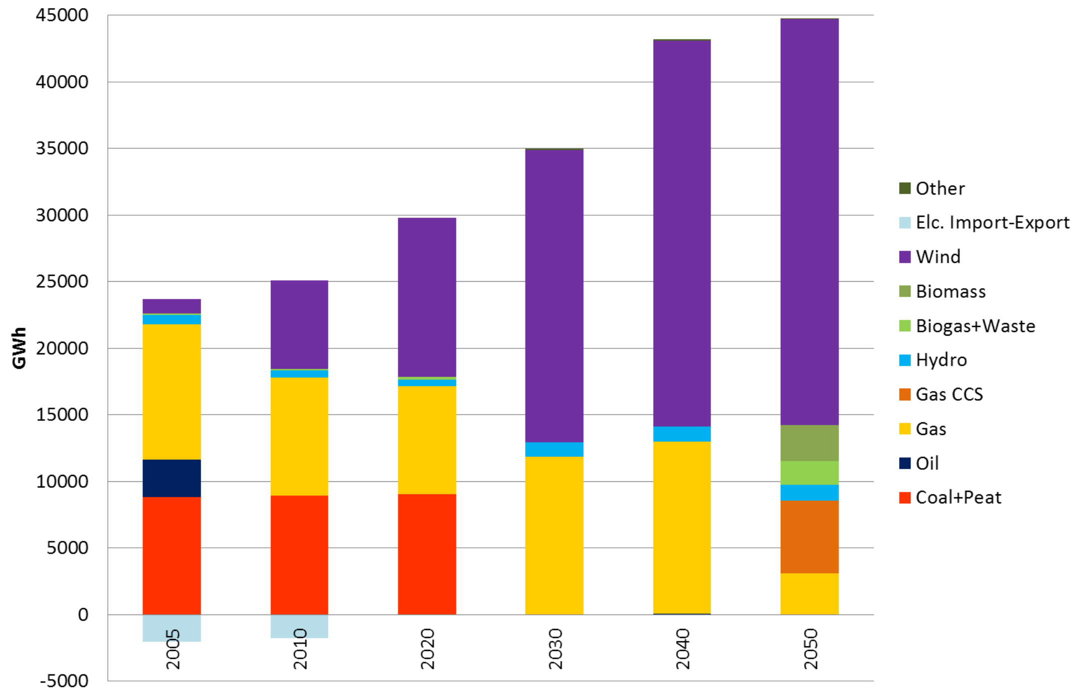

Figure 5-1. Electricity production under an 80% (rel. to 1990) carbon reduction scenario for Republic of Ireland (Chiodi et al., 2013b)

This increase in electrification and increase in wind generation may pose significant challenges for the power system. The research in this paper is can therefore be considered relevant as it aims to determine whether the electrical portfolios generated in the Irish-TIMES model are technically feasible and aims to gain insight into the appropriateness of the derived generation portfolio. Note that while this methodology is presented here for the Irish TIMES model it could also be applied to other countries and models which may have high projected levels of variable renewable generation in future power systems.

This paper is thus structured as follows. Section 2 introduces important aspects of the power and energy system features and discusses the common ground between the two, and how one can improve on the other. Section 3 discusses the soft-linking methodology and introduces the two models used in this analysis. Section 4 presents results of the analysis.

5.2. Research focus and issues addressed

This section introduces important aspects of electrical power systems modelling that, due to their broader focus, energy systems models are unable to directly address. These aspects fall under the headings of reliability, flexibility and unit commitment and dispatch.

5.2.1. Reliability

Fluctuating renewable power such as wind, solar and ocean energy bring more variability and uncertainty to power system planning and operations and this can have an impact on power system reliability. Power system reliability is fundamentally composed of security and adequacy. A power system can be considered secure if it can withstand a loss (or potentially multiple losses) of key power supply components such as generators or transmission links. A power system is adequate if there is a sufficient installed capacity to meet demand. In general a number of key metrics are used to assess reliability. An overview of these can be found in (Holttinen et al., 2006). Briefly these are Loss of Load Probability (LOLP) which is a measure of the probability that demand will exceed the capacity of the system in a given period and the Loss of Load Expectation (LOLE) which is number of times in a given period that the load will be greater than the demand. LOLE can be used to set a security standard, generally given as a number of hours per year. If this is exceeded in, it indicates the system has a higher than acceptable level of risk. Expected Unserved Energy (EUE) is also a useful metric as it takes account of the extent of the shortages.

Power systems models are capable of explicitly calculating these metrics as they can process detailed temporal information on maintenance outages, forced outages rates, mean time to repair modes and load information. They can iterate through all units in the system, accumulating the unit outages and calculating their respective probabilities of outages. Power systems model are also capable of detailed modelling of ancillary services for system reserves and can optimize the provision of reserves for each period of the simulation. Simply put, system reserve modelling means that units must hold spare generation capacity online in order to meet an unforeseen outage of largest in feed, this type of quick response reserve is generally called spinning reserve as it is provided by units that are already online. Replacement reserve is also required which can be provided by both online and offline units as long as the units offline can start up with the required timeframe. And further, critical to the accurate valuation of renewable generation integration is the modelling of downward type reserves i.e. the ability of thermal generation to unload in the event that the variable renewable generation suddenly spikes upward. It is this lack of downward reserves that has proven to be the key limiting constraint for renewables integration for some regions (California Independent System Operator, 2010). Energy systems models do not explicitly derive these indices and instead use heuristic rules for capacity margins, and do not address the downward reserve requirements at all.

5.2.2. Unit Commitment and Dispatch

The security-constrained unit commitment and dispatch problem involves deciding the correct combination and power output of units for the economic and reliable operation of the power system, taking into account fuel and carbon costs, and reserve requirements required in case of forced outages of power plants or transmission lines and against demand uncertainty. Unit commitment being the decision of which units to turn on or off and dispatch being the decision of what level to run units at once they are on. A large number of commercial and non-commercial models are available for modelling the power system and power markets and are summarized in (Foley et al., 2010). The value of detailed unit commitment and dispatch modelling is that it captures many of the technical constraints and limitations of thermal power plant and quantifies the implications for variable renewable generation in terms of its impact on the probability of the system running short of generation and/or reserve requirements. This feeds back into the determination of the technical suitability and flexibility of the power system. While power systems models can model the unit commitment and dispatch problem at high resolutions (1 minute to 1 hour), energy systems model generally assume a lower timely resolution for which the problem is solved. This is done so as to keep the problem computationally manageable. The unit commitment and dispatch problem can be relatively complicated to solve because the physical delivery of electricity is subject to the technical and economic constraints on generation. Some of these technical constraints may introduce integer variables into the linear programming formulation in order to track the on/off state of generation plant in time and to enforce important technical constraints minimum stable generation, minimum up and down times and start costs as a function of unit temperature.

5.2.3. Flexibility

Electrical Power systems must also be adequately flexible and contain flexible resources to manage variability in the residual load. Flexibility, in power system terms, is traditionally associated with quickly dispatchable generators. Balancing however is not simply about power plants, it must also consider other resources such as storage, demand-side management or response, and interconnection to adjacent power systems for trade (IEA, 2011). Within actual power system operation, technical constraints such as minimum stable generation, ramps rates and minimum up and down times restrict the flexibility of power plant and can affect renewable energy curtailment and emissions outputs. Modelling in the absence of these technical constraints can lead to very heavy cycling of baseload plants (as shown in results section), give a false impression of the capability of the system to integrate renewables and specifically an incorrect evaluation of wind curtailment.

The assessment of power system reliability and flexibility is important in the context of energy model results because while the model may correctly derive a least cost generation portfolio with consideration to broad technical and emission constraints, the resultant portfolio may not be technically suitable when examined in the context of higher resolution temporal modelling.

5.3. Soft-Linking Methodology

A methodology is presented that employs detailed modelling of the unit commitment and dispatch of the electrical power system, derived from an energy systems model, in a dedicated power systems model to provide insight and feedback to the energy systems model. The power systems model is populated with an electrical portfolio, fuel prices and demand from the energy systems model while the energy systems model is enhanced with output from the power systems model. The goal of the methodology is ultimately to have an improved understanding of the energy systems model's results in relation to the electrical power sector and to understand what elements of the power system are important.

The power systems and energy systems modelling tools used in this analysis and the energy systems model are presented below before a detailed description of the soft-linking methodology.

5.3.1. Power Systems Modelling Tool: PLEXOS for Power Systems

In this analysis the PLEXOS modelling tool is used to build and solve a model of the Irish power system. PLEXOS is a power systems modelling tool used for electricity market modelling and planning worldwide. PLEXOS is a commercial modelling tool but is provided by Energy Exemplar free for non-commercial research to academic institutions. Modelling is generally carried out using deterministic or stochastic programming techniques that aim to minimize an objective function or expected value subject to the modelled cost of electricity dispatch and to a number of constraints including availability and operational characteristics of generating plants, licensing environmental limits, and fuel costs, operator and transmission constraints. The model solves using linear or mixed integer linear programming. Importantly from a research perspective PLEXOS is a transparent model, with the mathematical formulations available to the user via diagnostics.

In this analysis we are concerned with short–term deterministic modelling. This means that the model assumes perfect foresight in relation to wind production and forced outages of plant. When modelling in short term mode (typically a full year of daily half-hourly optimizations of the power system) PLEXOS models every trading period and maintains chronological consistency across the full optimization horizon. The tool models generator start-ups and shutdowns and tracks the status of units across time. Within the modelling unit commitment process on/off decisions for each unit must be made. This is necessary to correctly model technical parameters for generators such as minimum stable generation, minimum up and down times. The inclusion of these technical constraints introduces integer decision variables. The presence of the integer variables means that the problem cannot be solved as a linear model. PLEXOS uses mixed integer programming (MIP) to solve these problems. MIP means the modelling tool can realistically replicate the actual operation of generator in the physical market as all technical constraints can be modelled and obeyed. To avoid issues with intertemporal constraints at the simulation step boundaries a '*look ahead'* period is used. Look ahead means that the optimiser is given information about what happens ahead of the period of optimisation and solves for this full period (i.e. simulation period + look ahead period) however only results for the simulation period are kept. Within the model maintenance schedules for generation units can be fixed exogenously if a known maintenance schedule is available, otherwise the model can determine an optimal maintenance schedule based on the annual maintenance rate and mean time to repair for each unit. The objective function of the maintenance scheduling formulation to equalize the capacity reserves across all peak periods. Random outages for units are calculated based on Monte Carlo simulations. Outages occur at random times throughout the year with frequency and severity defined by forced outage rate, mean time to repair and repair time distribution. At simulation run time PLEXOS dynamically constructs the linear equations for the problem using AMMO[38] software and uses a solver to solve the equation. In this work Xpress MP (Xpress Optimizer) with a duality gap set to 0.1%. Within the PLEXOS modelling tool, wind and other renewables are essentially treated as 'free' generation (i.e. the marginal cost is zero) although this can be changed by the user, therefore PLEXOS will use as much renewable generation as possible to reduce overall system costs subject to the technical constraints applied to the system. In PLEXOS, demand is represented as a chronological time series at 30 minutes resolution. The PLEXOS modelling tool is used by the Commission for Energy Regulation (CER) in Ireland to validate Ireland's Single Electricity market and thus has a history of use in Ireland (CER, 2010).

5.3.2. Energy Systems Modelling Tool: TIMES

TIMES (The Integrated MARKAL-EFOM System) is one of the tools developed and used by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA). It combines all the advanced features of MARKAL (Market Allocation) models, and to a lesser extent of EFOM (Energy Flow Model Optimization) models. The equations of the initial MARKAL model appear in Fishbone and Abilock (1981) and numerous improvements on the model have been developed since then for various applications (Kanudia et al., 2005; Kanudia and Loulou, 1999; Labriet et al., 2005). The full technical documentation of the

[38] AMMO performs a similar role in PLEXOS as other mathematical languages such as AIMMS, AMPL, or GAMS but is written exclusively for PLEXOS

TIMES model is available in Loulou et al. (2005). TIMES is a technical economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but may also applied to study in detail single sectors (e.g. the electricity sector). TIMES is a deterministic linear programming model generator that computes a dynamic inter-temporal partial equilibrium on integrated energy markets. The objective function to maximize is the total surplus. In the simplest case this is equivalent to minimizing the total discounted energy system cost while respecting environmental and many technical constraints.

The key inputs to TIMES are the demand component (energy service demands), the supply component (resource potential and costs), the policy component (scenarios) and the techno-economic component (technologies and associated costs to choose from). The model is driven by exogenous demand specified by the list of each energy service demanded (disaggregation), actual values in the base year (calibration) and values for all milestone years till 2050 (projection).

Figure 5-2 shows an overview of a TIMES model. Each economic sector is described by technologies, each of which is characterized by its economic, technological and environmental parameters.

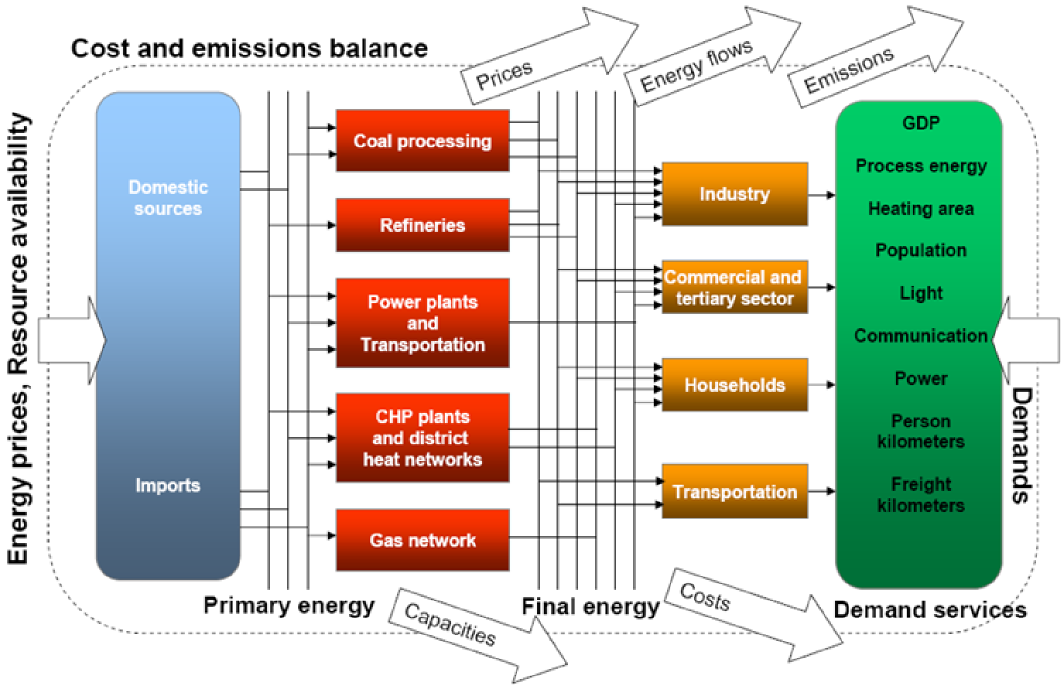

Figure 5-2. Overview of TIMES Modelling Tool (Remme, 2007)

TIMES is mainly used for medium and long term modelling, but it is theoretically possible to use this tool also for shorter term analysis. Each time period is usually divided by sub-period, commonly called timeslice. The timeslice represent the “mesh” of each period and the definition depends strongly to the computing capacity and the time-scale. Long-medium term optimizations

(20-50 years of time horizon) rarely use more than 12 timeslices. For example the model used in this paper work, the Irish TIMES model, has a 2005-2050 time horizon while each period is sub-divided by 12 timeslices, commonly defined by day, night and peak hours for four season.

In the TIMES model net electricity demand profiles are not imposed exogenously, but rather are endogenously evaluated to optimally provide the energy service demand for each sector. The electricity generation sector is commonly characterized by various voltage levels (commonly three or four) in which each voltage level of the network is modelled by an equivalent simplified system composed of lines, transformers, infrastructure for electricity transport and distribution Power plants are described by processes grouped as base year or post-base year capacities. Each plant is moreover characterized by input and output commodities that fit into the energy system composing the whole energy chain from primary energy supply to the final energy service demand. Several parameters and constraints can be defined for each process of the chain. They can be commonly grouped as technical, economic and environmental parameters. Table 5-1 details the main technical parameters that describe power plant in both the selected energy systems model and power systems model.

	PLEXOS modelling tool	**TIMES modelling tool**
Technical parameters of Generation Plant	Installed Capacity (MW)	Capacities (MW),
	Min. stable generation (MW)	No equivalent
	Max. Generation (MW),	No equivalent
	Up/Down Ramp Rates (MW/min)	No equivalent
	Heat rates, (GJ/MWh)	Efficiencies, (%)
	Min. up and down times (hrs)	No equivalent
	Maintenance rates, repair time and failure rates (%)	Availability factors (%)
Economic parameters	Fuel and emission costs (€/GJ)	Fuel and emission costs (€/GJ)
	Variable O&M	O&M costs (fix and variable),
	Start costs (€)	No equivalent
Environmental parameters	Emissions (CO_2 Only)	Emissions (CO_2 Only)

Table 5-1. Main parameters that characterize each power plant in each modelling tool

Within TIMES most of renewable technologies (e.g. wind energy or solar PV) are commonly treated with efficiencies of 100% while the availability of the resource is inserted as capacity or activity constraint. The load fluctuation due to the resource variability (that represents the fuel for the process) is modelled by a timeslice dependent definition of average availability factors generating different generation profiles.

5.3.3. Soft-Linking Methodology

The soft-linking methodology is described using a number of steps listed below and illustrated in Figure 5-3. It is assumed that the energy systems model is already developed and available. Note that before the soft-linking approach can be correctly employed it is important that both models share certain common inputs. Depending on how the energy systems model is developed these inputs may already be the same. These particular inputs are electricity profile shape and renewable generation profiles. This aspect is discussed in more detail in Section 5.3.4.

The steps in the soft-linking methodology are as follows:

1. Select the model, the scenario and the target year of the analysis for the energy systems model and execute the model.
2. Extract results from the energy systems model for the target year of interest for the electricity generation portfolio and populate the power systems model with this generation portfolio. Additional technical detail and data such as minimum stable generation, ramp rates and start costs, failure and maintenance rates are included in the power systems model. Fuel prices and carbon prices from the energy systems model are also provided to the power systems model.
3. Convert the annual electricity demand profile for the target year from the energy systems model into a half hourly chronological profile. This is done by taking an existing actual electricity half hourly demand for the region of interest and scaling it using quadratic optimisation so that the annual demand for electricity and peak demand for electricity are equal to the demand from the energy systems model, a function that is provided by PLEXOS. In this way a detailed chronological demand profile is developed and input into the power systems model. In this current use of the methodology it is assumed that the historic electricity demand profile is representative of a future demand profile. This may not always be the case as outlined in Section 3.4.2
4. Initially run the power systems model for the target year using this data at half-hourly resolution without any additional technical constraints such as minimum stable generation, ramp rates and start costs. This is done to investigate the impact of increasing the chronological resolution of model.
5. Subsequently run the power system model with increasing level of technical constraints in order to determine the impact these technical parameters on model results.
6. Compare results between the two models, determine the differences and examine the reliability and flexibility of the power system. Detailed information from the power systems model solving of the unit commitment and dispatch problem can shed light on the role each plant type provides in relation to system operation.

7. Determine the implications of low wind production years on the reliability of the derived portfolio from the energy system model by running the power systems model with a number of different years of wind production profiles.

Figure 5-3 details a graphical representation of the methodology. Depending on differences that arise and insights that are gained, the energy systems model inputs or technical parameters can be adjusted to aim for improvement of results.

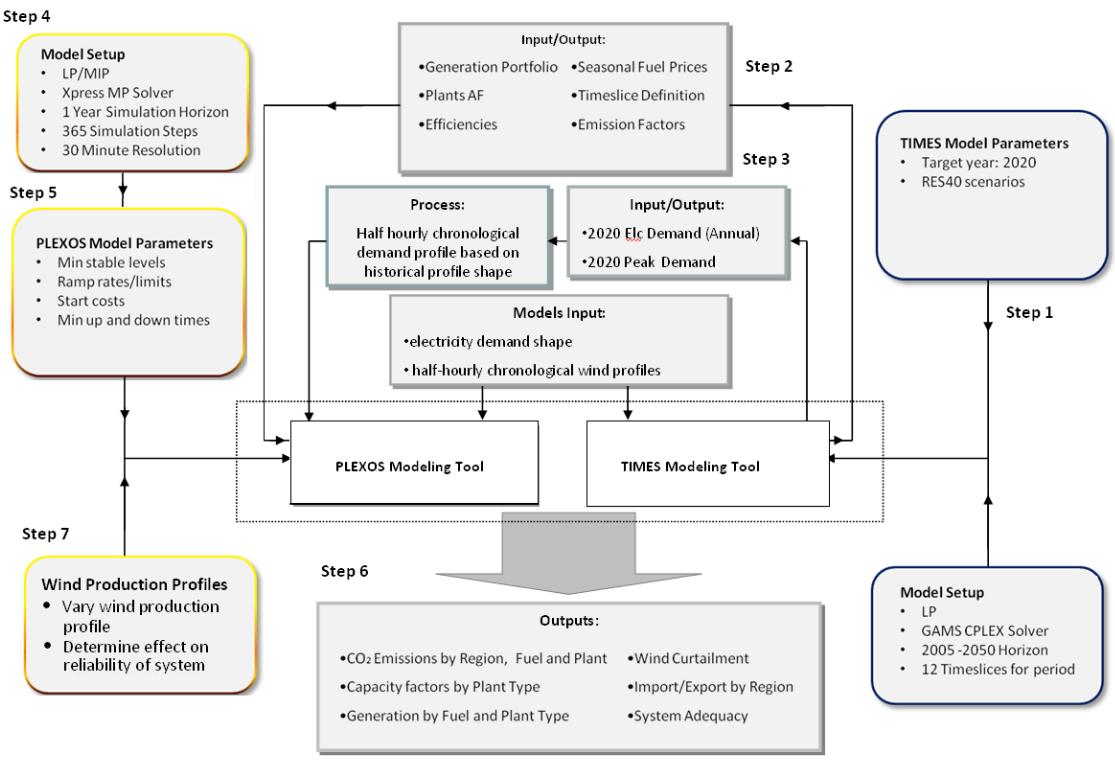

Figure 5-3. Flow chart of soft-linking methodology

5.3.4. Application of Methodology

To demonstrate the soft-linking methodology as outlined above, we applied soft-linking in Ireland to an energy systems model, Irish TIMES and an equivalent power systems model. This section describes the model and how the soft-linking methodology was applied.

The Irish TIMES model: details and configuration

The Irish TIMES model (UCC) is an energy systems model for the Republic of Ireland developed by University College Cork (UCC), Energy Policy and Modelling Group in collaboration with the ESRI (Economic and Social Research Institute). The Irish TIMES model has been developed to build a range of medium (to 2020) (Ó Gallachóir et al., 2010b) and long term (to 2050) energy and

emissions policy scenarios in order to inform policy decisions. Irish TIMES was originally extracted from the Pan European TIMES model that includes EU27, Iceland, Norway, Switzerland and Balkans countries and then updated with local and more detailed data and assumptions (Ó Gallachóir et al., 2010c). The time horizon used here is the period 2005 – 2020 and the model has a time resolution of four seasons with day-night time (divided into day, night and peak time-slices).
The scenario used in this paper is *RES40*, which assumes that the Ireland's energy system delivers by 2020 at least 16% renewable energy penetration (in compliance with Directive 2009/28/EC) and is consistent with Ireland's White Paper on Energy, which specifies an individual target for electricity sector of 40% of renewable generation.
The year 2020 was chosen as a test year (and not 2050 for example) because there will be relatively high amounts of wind generation in this portfolio and more importantly the electricity demand profile will be similar to the electricity demand profile of the base year. It is expected that with the introduction of electric vehicles and greater electrification of heating this demand profile will change. The development of these new demand profiles is a target for future research and this point is discussed further in Section 6.

Model inputs and configuration

To produce consistent outputs in both models certain common inputs have been imposed. Firstly in both models the same electricity demand shape profile is used and is based in this instance on pre-economic recession 2007 electricity demand profile for Ireland. This assumption defines the likely chronological demand shape for the year 2020 under the *RES40* scenario. This specific scenario indicates that electrification between end-use sectors will not affect largely the load curve given the limited impact of electricity for heating purposes and for transportation. Within the Irish TIMES model the load curves for energy service demands, indicated as commodity fraction (COM_FR), have been recalibrated to follow globally the expected profile. Furthermore given the importance of accurate wind resource assessment estimation, both models initially use wind production data from the same year. In this analysis wind production data from the year 2008 was used. The average capacity factor for wind generation for the year was 31.7%. The long term time weighted annual average from 2002 to 2009 was 32.2% with a range of 34.7% to 29.1% (EirGrid, 2010). The Irish TIMES model used this data segregated into 12 timeslices. This was done by summing up the half hourly production of each time period within each timeslice definition. The power systems model used a half-hourly chronological profile of the same data, both giving the same total energy production. This analysis does not consider detailed modelling of transmission issues, frequency and inertia issues of voltage stability however to reproduce operational constraints within the Irish power system the instantaneous level of wind generation is limited to 70% (EirGrid). Table 5-2 details the optimized generation portfolio from the Irish-TIMES model for the year 2020 subject to demand and energy constraints. This generation portfolio was input into the PLEXOS model along with detailed technical parameters as set out in Table 5-2.

Category	Description	From Irish TIMES						PLEXOS Additional Parameters				
		Capacity (MW)	Efficiency (%)	Max Availability Factors (%)	O&M Costs (€/Mwh)	Fuel Cost (€/GJ)	$C0_2$ Emission Factor (kg/GJ)	Number of Plant	Heat Rates (GJ/MWh)	Min Stable Generation (MW)	Ramp Rates (MW/min)	Min up/down times (hrs)
Gas	Combine Cycle	1422	47.5	57	0.04	4.4	56.1	4	7.5	150	12	4
	Combine Cycle-new	1664	55.1	85	1.53	4.4	56.1	4	6.5	220	30	4
	Gas Turbine	200	40	55	2.05	4.4	56.1	1	9	110	15	4
Coal	Steam Turb. Hard Coal	840	39.5	87	0.04	2.9	95	3	9.1	180	4	8
Peat	Steam Turb. Lignite	347	41.5	87	0.04	1.1	110.6	3	8.6	80	2	8
Distillate	Gas Turb. Dist. Oil	496	38	55	2.05	4	77.4	8	9.4	10	10	1
Biogas	Int. Comb. Biogas Plant	22	33.5	57	0.04	4.7	56.1	1	10.7	5	5	8
Waste	CHP: Municipal waste	21	25	60	2.56	0.3	85.9	1	14.4	5	5	8
Wind	On-Shore wind	4305	100	31.7	NA	0	0	1	3.6	NA	NA	NA
Hydro	Hydro Dam Plant	215	100	25.5	NA	0	0	15	3.6	2	10	NA
	Run of River Plant	19	100	25.5	NA	0	0	1	3.6	0	NA	NA
Storage	Storage Hydro Plant	292	70	13.8	NA	-	0	4		5	50	NA
Total		9843										

Table 5-2. Generation portfolio from Irish TIMES model for the year 2020 and equivalent PLEXOS model input.

According to the Irish TIMES model the total electricity requirement[39] for the year was 29.8 TWh with a peak electricity demand of 4.9 GW. For the PLEXOS model technical information and characteristic of plants not available in TIMES (i.e. number of individual units, ramp rates, and minimum stable generation) are based on actual performance of plants within the current Irish power system (CER). Within the PLEXOS model pump storage is modelled as having 3 distinct phases and is modelled on the current pumped storage station in Ireland. These phases are: 1) Pumping mode: the plant has 4 fixed speed pumps which draw a load of 71.5 MW each and can provide this full quantity to all reserve. 2) In spin mode each unit can provide 5 MW of power but no more than 2 units can be in spin mode at any one time. In this mode the efficiency of the generation units is 50%. 3) In generation mode each unit can provide a minimum of 40 MW and up to a maximum of 73 MW. As all units share a common penstock they are not allowed to generate

[39] All the electricity sent out of power plants. This value is equivalent to the sum of final electricity consumption and grid losses.

and pump at the same time. The pumped storage system is closed loop with no inflow. The reservoirs have capacity for approximately 1.24 GWh of energy storage and so the system can generate at full load for 4.2 hours. Water in the storage has no ‘value’ other than the value of the thermal generation it can replace. Thus the optimization will use all the water possible to minimize thermal costs. In this model set up, the upper reservoir is forced to refill by the end of each trading day (06:00). In TIMES, electricity storage is modelled as a single process technology. This process is characterized by the capacity that describes the volume of the storage, and the activity, i.e. the storage content. In Irish TIMES, pumped storage is set as timeslice storage, which means its operation is optimized between timeslices. The maximum capacity of the reservoir is the same as the PLEXOS model 2020 is 292 MW with the same overall efficiency of 70%.

To assess the methodology a series of yearly model runs (scenarios) were undertaken in the power systems model with added degrees of technical complexity. This was done to assess and quantify the added benefit of each of these parameters to the modelling process. The first of these scenarios (*Scenario Simple*) was a simple unit commitment and dispatch simulation with no technical constraints other than maximum generation capacity of each individual plant. A second scenario (*Scenario Start Costs*) added the start costs of each plant to the problem formulation. A third model scenario (*Scenario MSG*) also added minimum stable generation, a fourth added ramp rates (*Scenario Ramp Rates*) for each plant while a final scenario (*Scenario Reserve*) added full modelling of upward reserve requirement. This final scenario can be interpreted as the most complete model of the power system and the one that provides the most realistic results in terms of power system operation. Therefore the differences between this scenario and the results from the energy systems model are the most important. These scenarios are summarized in Table 5-3 while Table 5-1 gives an overview of both model parameters and their equivalence for both models. A series of simulations were also undertaken in the power systems model to determine the effect of low wind production years to investigate the robustness of the derived power system. This was done by using actual historic wind power production data from the year 2010 which historically was a low wind production year in Ireland with an annual capacity factor of 24%.

Scenario	Description
“Simple”	Simple case with only maximum capacity of generators
“Start Costs”	Added start costs for each plant
“MSG”	Added minimum stable generation for each plant
“Ramp rates”	Added ramp rates limits for each plant
“Reserve”	Added spinning and replacement reserve requirements

Table 5-3. Summary of Individual Model Scenarios for power systems model simulations

5.4. Results

This section presents and discusses a selection of results in two main sections, where firstly the impact on generation reliability is discussed and then the differences between both model outputs for the electricity sector are presented. As the focus of this work is on the soft-linking methodology, the results are used only to show how this methodology can be employed and should not be taken as definitive. All simulations were undertaken on a Dell laptop with two 2.39 GHz processors. The longest TIMES simulation took 40 seconds. The longest PLEXOS simulation was the 'Reserve' scenario and took approximately 5.5 hours of run time

5.4.1. Reliability

The power systems model PLEXOS is able to assess generation adequacy of any modelled power system by the evaluation of PASA (Projected Assessment of System Adequacy) reliability indices. Table 5-4 details results of this assessment and shows the generation portfolio developed in the Irish TIMES model to be reliable as the loss of load expectation and expected unserved energy are very low. Note that the parameter Firm Generation Capacity takes account of the capacity credit of wind rather than it full nameplate capacity. The portfolio was also tested under a low wind production year. It was found that the portfolio was reliable with only a marginal increase in expected unserved energy.

Property	Value
Peak Load (MW)	4947
Generation Capacity (MW)	9843
Firm Generation Capacity (MW)	6399
Capacity Reserves (MW)	1452
Capacity Reserve Margin (%)	29
Expected Unserved Energy (MWh)	84.3
Loss of Load Expectation (days)	0.02

Table 5-4. Result of reliability and security analysis for the given portfolio

5.4.2. Unit Commitment and Dispatch

Table 5-5 details the annual capacity factors for both model runs and each scenario simulation. The result presented here are for the 'typical' wind year and not the low wind year. Looking firstly at the results from the energy systems model and the 'Simple' scenario from the power systems model, it can be seen that results are broadly similar. However as more technical detail is added to the power systems model the results for certain plant diverge indicating the significance and importance of technical portrayal in modelling the electrical power system.

	Irish-TIMES Results	PLEXOS Results				
		Scenario “Simple”	Scenario “Start Costs”	Scenario “MSG”	Scenario “Ramp rates”	Scenario “Reserve”
Gas-CC	0%	16%	15%	16%	16%	21%
Gas-New	55%	54%	57%	58%	59%	58%
Gas- Turbine	0%	1%	1%	1%	1%	1%
Coal	87%	84%	73%	69%	69%	67%
Peat	87%	87%	83%	81%	81%	75%
Distillate	0%	2%	16%	17%	17%	12%
Biogas	57%	57%	57%	57%	57%	57%
Waste	60%	60%	60%	60%	60%	60%
Wind	32%	28%	28%	28%	28%	27%
Hydro	26%	23%	23%	23%	23%	23%
Hydro-ROR	26%	26%	26%	26%	26%	26%
Storage	0%	0%	4%	7%	7%	10%

Table 5-5. Annual capacity factors (%) for target year (2020) for both models and each power system model scenario

Results of the detailed unit commitment and dispatch show that the power systems model commits more of the less efficient CCGT units (CC-00) than the energy systems model across all technical scenarios examined. This is because these units come online when the newer CCGT units (CC-01) are out for maintenance or forced outages and are an important source of flexibility for the system. The energy model exploits the coal powered plant to its full capacity whereas in the power systems model these units are used less particularly with the inclusion of more technical parameters as the start cost gets incorporated into the objective function and coal generation is a ‘pulled back’ to allow gas and other generation to come online and run above their minimum stable level. As shown in Figure 5-4 the distillate fuelled plants, while having a low capacity factor in the energy systems model run are shown to provide an import peaking ability and this value is only seen when higher levels of technical detail are modelled in the power systems model. Also pumped storage is an important contributor to spinning reserve and is brought online more often to provide this service. Likewise the value of the pumped storage plant only becomes apparent when this level of detail is included in the power systems model. In relation to wind energy it can be seen that wind production is lower in the power systems model scenarios than the energy system model run indicating that wind curtailment occurring. Results of the power systems model show annual wind curtailment to rise from 7% for the simple scenario to 8% for the ‘Reserve’ scenario whereas the Irish TIMES model shows no wind curtailment. This stresses the importance of the correct modelling of flexible resources such as storage in the determination of system flexibility and suitability for renewable energy integration. Results for the low wind year simulations were broadly similar however as annual wind generation was lower an increase in thermal generation was seen.

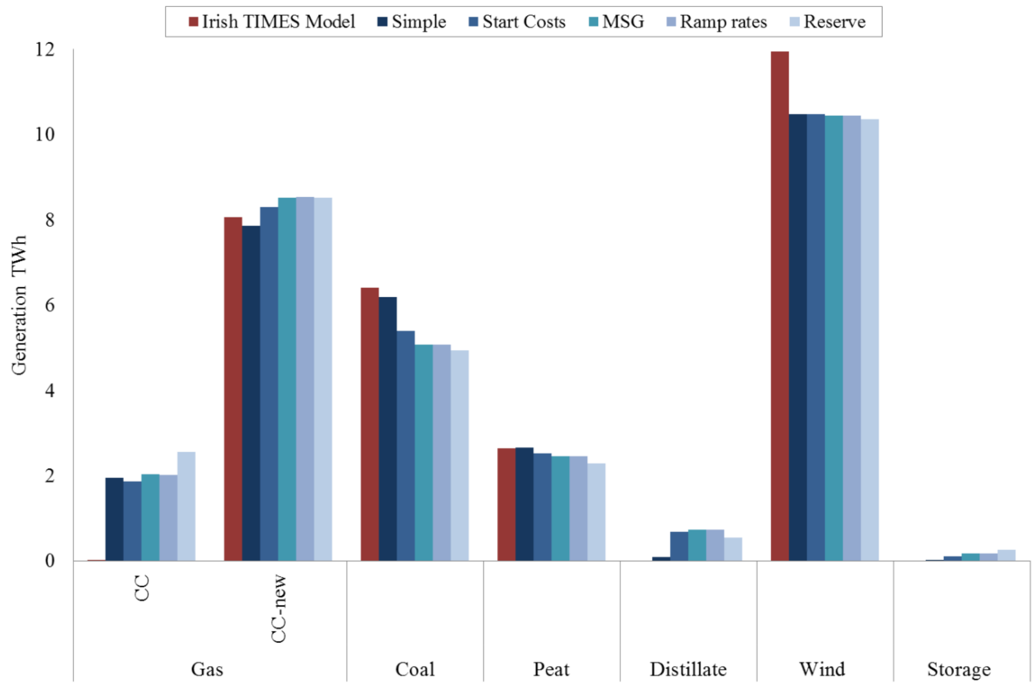

Figure 5-4. Annual generation (TWh) for target year for both models and each power system model scenario

5.4.3. Flexibility

Results of the detailed unit commitment and dispatch of the power system were also used to assess the flexibility of the generation portfolio developed by the Irish TIMES model and understand what technical details are important when modelling an electrical power system. Insights gained from this type of analysis can be useful in understanding why results differ between the two models. Table 5-6 firstly looks at the number of 'start ups' for each category of unit under each scenario of added technical detail. This is a useful metric as it gives an overview as to what units are cycling to meet variable demand and changes in wind power production and informs on what units are important for delivering system flexibility. Note that the TIMES model cannot report the number of start-ups of units throughout the year so only results for the power systems model are shown.

The total number of starts changes significantly as more technical detail is added to the model, particularly for the less efficient gas CCGT units (CC-00) which the model cycles very heavily in the absence of either a start cost constraint or minimum stable generation constraint. The number of starts for the open-cycle gas (GT-00) units also changes significantly. In the absence of detailed technical constraints these units are brought on and off line at very low generation levels and at frequent intervals.

In general, all thermal units decrease their cycling as more technical detail is added to the model. In place, flexible resources like pumped storage become more important as they are cycled more often to deal with changing demand while thermal units stay online longer. In the power systems model, the introduction of more detailed technical constraints also has a marked effect on the number of starts and usage of the older Gas Turbine (GT-01) which is almost put out of merit due to it relatively high start cost and minimum stable generation constraint.

The inclusion of reserve services has an effect, particularly on CCGT units. Gas CC-01 are required to be online longer to provide spinning reserve and operate at slightly lower output, this also has the effect of bringing more of the older (CC-00) CCGT units. Pumped storage is also an important contributor to spinning reserve both in generation and pumping mode.

Category	**Scenario "Simple"**	**Scenario "Start Costs"**	**Scenario "MSG"**	**Scenario "Ramp rates"**	**Scenario "Reserve"**
Gas-CC	1246	191	188	190	309
Gas-New	601	282	296	284	244
Gas- Turbine	363	6	6	6	8
Coal	153	114	112	114	117
Peat	141	120	117	116	123
Distillate	1817	742	756	765	828
Storage	3246	3990	4966	4873	4131
Total	**7567**	**5445**	**6441**	**6348**	**5760**

Table 5-6. Detailed number of start-ups for each thermal generation and storage for each power system model scenario

Examining Table 5-6 and Table 5-5 in detail, it can be seen that the most important technical constraint (i.e. the constraint that causes a marked change in results from one scenario to another) is start costs as this has the effect of reducing the cycling of mid-merit gas units plant and forces the use of more flexible units. The issue of starting up and turning off plant frequently is more so an important issue for mid-merit plant (i.e. gas CCGT units) rather than baseload plant as the lower fuel cost of coal and peat generally means that the model will schedule them at their maximum capacity. The introduction of the minimum stable generation constraint has less impact although it does force some coal units offline to allow for gas units to come online above their minimum stable level. A test scenario was undertaken enforcing only the minimum stable level constraint in the absence of start costs and it was seen that the start cost constraint had a more marked effect on results and did not reduce the number of start-ups to the same degree as the start cost. The introduction of ramp rates has a limited consequence for results. Most plants in the model are able to ramp from minimum stable level to max generation within a half hour so it has little effect. However it is planned to look at a 10 minute unit commitment and dispatch as part of further research to determine the impact of ramp rates. The introduction of reserve requirements force units contributing to spinning reserve to hold spare generating capacity to contribute to the specified requirement for this service. This has important consequences for pumped storage plant.

5.4.4. CO_2 Emissions

Table 5-7 shows the annual CO_2 emissions for both model runs and each scenario simulation. Looking at the power system scenario with full technical and reserve requirements (scenario 'Reserve') it is seen that the Irish-TIMES model has a greater estimation of total annual emissions. This is because it has a higher level of coal and peat generation compared to the power systems model. The power systems model has higher emissions from gas plant but is offset by higher reduction in emissions from the coal and peat plant. In the absence of technical constraints the power systems model produces higher emissions as the baseload peat and coal plants are allowed to run longer.

	Irish-TIMES results	PLEXOS results				
		Scenario "Simple"	Scenario "Start Costs"	Scenario "MSG"	Scenario "Ramp rates"	Scenario "Reserve"
Gas-CC	0.01	0.83	0.8	0.87	0.86	1.1
Gas-New	2.95	2.88	3.05	3.13	3.13	3.12
Gas- Turbine	0	0.01	0.01	0.01	0.01	0.01
Distillate	0	0.06	0.48	0.51	0.52	0.38
Coal	5.77	5.36	4.74	4.46	4.46	4.35
Peat	2.48	2.54	2.42	2.37	2.36	2.2
Waste	0.14	0.14	0.14	0.14	0.14	0.14
Total	**11.35**	**11.81**	**11.63**	**11.47**	**11.47**	**11.29**

Table 5-7. Annual CO_2 emissions (Mt) for target year for both models and each power system model scenario

5.5. Conclusions and Discussion

A soft-linking methodology that can be used to verify and gain insight into electricity sector results from energy systems models using a power systems model has been presented and detailed. Results for one specific year have been presented. The work in this paper shows that the soft-linking methodology provides important insights into results and provides a useful method to crosschecking the technical appropriateness of the optimized power system results arising from an energy systems model. In this particular analysis it was shown that while the optimized portfolio from the Irish TIMES model was a reliable and adequate power system, the value of key flexible elements namely storage were undervalued. It was also shown while the energy systems model does not use the older CCGT gas units (CC-00) or distillate fired units they are an important element in the system. Wind curtailment was approximately 8% higher than expected and emissions were higher than reported when compared to detailed results from the power systems model. These insights could only be gained by the addition of key technical criteria to the modelling process such as imposing start costs, minimum stable generation levels and reserve requirements on the model. In relation to these constraints it was shown in this analysis that start costs have a marked effect on the modelling of the power system and has important implication on the modelling of CO_2 emissions.

5.6. Future Work

Future work will involve applying the soft linking methodology to other target years with significant amounts of installed wind capacity such as 2050 and determining the best method of feeding insights from the results of the soft-linking methodology back into the energy system model to improve results. An important element of this work will involve the development of accurate chronological electricity demand profiles which will consider the changes that may occur to the demand profile over coming years. These include changes in demand and electricity usage due to the introduction of electric vehicles and the electrification of heating. Higher resolution power systems modelling (current resolution is 30 minutes) will also be investigated to determine the effect this has on ramp rates of thermal power plant. A further important modelling challenge will be the modelling of interconnection to other regions such as Great Britain and Northern Ireland. It is expected that these extra loads and generation centres coupled with wind and renewable energy variability will pose further significant modelling challenges and increase the value of this soft linking methodology particularly in the determination of imports and export of electricity from one region to another.

6. Integrating agriculture and energy to assess GHG emissions reduction - a Methodological approach

Abstract

Agriculture is responsible for approximately 25% of anthropogenic global greenhouse gas (GHG) emissions. This significant share highlights the fundamental importance of the agricultural sector in the global greenhouse gas emissions reduction challenge. This paper develops and tests a methodology for the integration of agricultural and energy systems modelling. The goal of the research is to extend an energy systems modelling approach to agriculture in order to provide richer insights into the dynamics and interactions between the two (for example in competition for land-use). We build an agricultural systems module using the TIMES energy systems modelling framework to model the effect of livestock emissions and explore emissions reduction options. The paper focuses on Ireland, which is an interesting test case for two reasons: agriculture currently accounts for about 30% of Ireland's GHG emissions, significantly higher than other industrialised countries yet comparable with global levels (here including emissions associated with other land use change and forestation); secondly Ireland is both a complete and reasonably sized agricultural system to act as a test case for this new approach. This paper describes the methodology used, the data requirements and technical assumption made to facilitate the modelling. It also presents results to illustrate the approach and provide associated initial insights.

Policy relevance

Most of the policy focus to regarding climate mitigation targets has been on reducing energy-related CO_2 emissions, which is understandable as they represent by far the largest source of emissions. Non-energy-related GHG emissions – largely from agriculture, industrial processes and waste – have received significantly less attention in policy discourse. Going forward however, if significant cuts are made in energy-related CO_2 emissions, the role of non-energy related GHG emissions will grow in importance. It is therefore crucial that climate mitigation analyses and strategies are not limited to the energy system. This paper shows the value of using integrated energy and agriculture techno-economic modelling techniques to draw evidence for new comprehensive climate policy strategies able to discern between the full range of technical solutions available. It enables the production of economy wide least cost climate mitigation pathways.

6.1. Introduction

Combating climate change and achieving food security are two of the most important and interlinked global policy challenges at the start of the 21st century. The growth in world population – projected to reach 9.6 billion by 2050 and 10.9 billion by 2100[40] (UN, 2013) – will drive an increase in food demand[41] (Alexandratos and Bruinsma, 2012). Much of the growth in global agriculture output is expected to come from the developing world with food security concerns, increased income levels and shifts in diet as the main drivers for increased production. This future growth poses challenges to achieving climate mitigation targets[42] (IPCC, 2007b) and in turn generates pressure for agriculture in the developed world to reduce its emissions. Such pressure may be particularly felt in developed countries with high shares of agricultural emissions in total GHG emissions, such as Ireland and New Zealand, countries which both are considerable net exporters of food commodities. This has recently been reconfirmed at European Union (EU) level in the laying out of a pathway for an 80% GHG reduction by 2050 relative to 1990 levels (EC, 2011a, b, c). According to Table 1 of COM/2011/112 (EC, 2011c) GHG emissions from agriculture are anticipated to be reduced relative to 1990 levels amongst Member States (MS) by 20% by 2020, by 36%-37% by 2030 and between 42% and 49% by 2050. The other (primarily energy) sectors of the economy are anticipated to achieve more significant reductions than agriculture, suggesting that at EU level, the share of GHG emissions from agriculture will grow in time, while the role of the energy sector will reduce.

To date most climate mitigation modelling studies have tended to focus only on energy, despite the need for improved understanding of the interactions between climate mitigation and food security, and between the energy sector and agriculture. A proper functioning integrated model could track feedbacks and interactions in terms of emissions, energy flows and land use between the agricultural and energy sectors. Such a model could also provide insights into the effects of emission mitigations policies across the whole economy.

This paper takes the TIMES energy systems modelling framework as a starting point and develops a methodology to build an agricultural systems model using this framework as an initial step towards an integrated energy/agricultural systems model. The methodology presented here uses Ireland as a test case – which is of sufficient scale to be relevant and small enough to be manageable. The model used is the Irish TIMES energy systems model but this work and methodology could also be applied to other countries and models.

[40] Was 7.2 billion in mid-2013

[41] 60% of 2005/2007 levels in 2050

[42] IPCC indicates that to hold the increase in global temperature below 2 degrees Celsius global GHG emissions must peak by 2020 and reduce by at least 50 % below their 1990 levels by 2050.

The paper is structured as follows. Section 6.2 introduces the reasons why Ireland was chosen as a case study. Section 6.3 describes the methodological approach, introducing TIMES and the Irish TIMES model. Section 6.3 also presents the newly developed agriculture module along with the data requirements and technical assumption made. Section 6.4 discusses results of the scenario analysis, while Section 6.5 concludes with an overview of results and summary points. Lastly Section 6.6 presents some research ideas for future developments.

6.2. Context

6.2.1. GHG emission in Agriculture

Ireland is unique among EU member states and other OECD countries in terms of the proportion of its greenhouse gas emissions which originate from agriculture. In 2010 Irish agriculture was responsible for 30.6% of total GHG emissions while energy (including energy supply and direct energy use in transport, residential sector, industry and services) accounted for 66% of total GHG emissions (EEA, 2013). Amongst other developed economies, only New Zealand has a higher proportion of national GHG emissions associated with agriculture (MoE, 2013). In the EU for example agriculture accounts only for 11.5% of total GHG emissions and energy accounts for 80% (EEA, 2013). At a global level the agriculture, forestry, and other land use (AFOLU) sector is responsible for just under a quarter (~10─12 GtCO2eq/yr) of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management (IPCC, 2014). This analogy in terms of emissions share makes Ireland a good test case for this new approach. Globally agriculture accounted for an estimated 5.0 to 5.8 $GtCO_{2,eq}$/yr from 2000 to 2010 (IPCC, 2014). Conversely Irish agriculture contributed 18.6 $MtCO_{2,eq}$/yr in 2012 (EPA, 2012). Methane emissions sourced from livestock enteric fermentation is the primary source of GHG in Ireland, accounting for about 45% of total emissions. The two other major sources are methane emissions from manure management (11%) and nitrogen oxide emissions arising as a result of chemical/organic fertilizer application and animal deposition (37%).

6.2.2. Agriculture in Ireland

Agriculture in Ireland is predominantly based on milk and meat production from ruminant animals, currently accounting for around 61% of agricultural output (Donnellan et al., 2013). Over 80% of this output is exported, representing almost 10% share of total exports, contributing approximately 7% to Ireland's economy (in terms of GDP) (Breen et al., 2010b; Teagasc). Livestock activities are largely based on extensive, grass-based farming. Approximately 82% (3.36 million ha) of total agricultural area in 2011 is devoted to grass (silage, hay and pasture), while the remainder is allocated to rough grazing (11%) and crop production (7%). In terms of the total land area of Ireland, agriculture accounts for about 60% as shown in Figure 6-1.

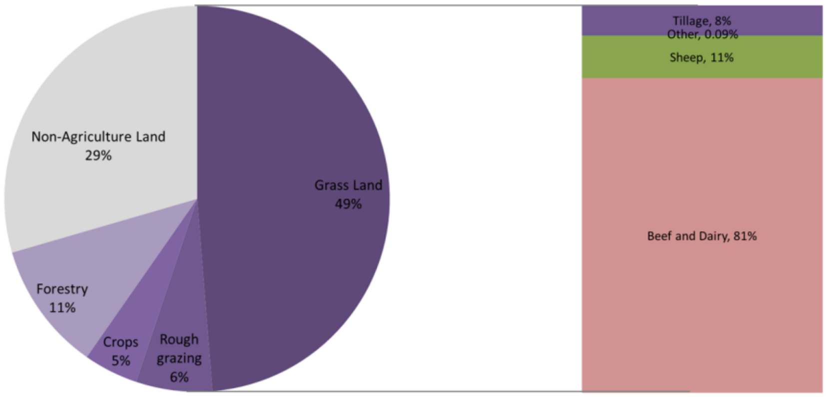

Figure 6-1. Breakdown of land use in Ireland in 2010

In 2010 the Department of Agriculture, Fisheries and Food (DAFF) in collaboration with food industry stakeholders produced the Food Harvest 2020 (FH2020) report (DAFF, 2010). Food Harvest 2020 is a strategy for the medium-term development of the agricultural production for the period to 2020. The report outlined a series of strategic targets for the different sub-sectors of Irish agriculture envisaged for the year 2020, namely; i) increased primary output of 33% compared to the 2007-2009 average; ii) increased value-added by 40% compared to 2008; iii) an increase of exports by 42% compared to the 2007-2009 average. The policy objective of facilitating and encouraging strong growth in agricultural production contrasts with national policy relating to climate change.

The Environmental Protection Agency (EPA) estimates in its national emissions projections, that agriculture GHG emissions will grow by 4% in the period 2005-2020 and will retain its 30% share of total GHG emissions (EPA, 2013). This contrasts with Ireland’s current climate GHG 2020 commitments, which seek a 20% reduction (below 2005 levels) in GHG levels for sectors not engaged in the EU Emissions Trading Scheme, i.e. non-ETS sectors (agriculture accounts for 42% of non-ETS GHG emissions) (EU, 2009a). Over the longer term horizon, no official projections for agriculture GHG are available for Ireland. Initial modelling analysis has been carried out by Teagasc using the FAPRI-Ireland model (Donnellan et al., 2013) suggesting that GHG emissions from agriculture may reach 20.6 Mt by 2050 in a Business as Usual scenario, namely 5.3% higher than 1990 levels.

6.3. Methodology

In recent years a number of studies have focused on the need to identify solutions for reducing GHG emissions from agriculture. Some analysis focused on determining cost-effective policy instruments to deliver reductions (Bakam et al., 2012; Neufeldt and Schäfer, 2008), others focussed on the abatement potential of a range of abatement measures (Erda et al., 1997; Li et al., 2013; O'Mara et al., 2007; Van Middelaar et al., 2013; Xiaohong et al., 2011) or on prioritising GHG mitigation measures (Kulshreshtha et al., 2000). Other work has been undertaken to develop marginal abatement cost curves (Breen and Donnellan, 2009; MacLeod et al., 2010; Schulte et al., 2012) in order to assess the cost and potential for mitigation.

Current modelling of agriculture and associated emissions in Ireland is carried out using the top-down sector/market based FAPRI-Ireland model and the bottom-up Farm-level Agricultural Greenhouse Gases Simulation (FLAGGS) model. FAPRI-Ireland is a dynamic partial equilibrium model of the Irish agriculture sector which generates activity projections for most agriculture commodities. Further details on FAPRI-Ireland and the methodology adopted for the projections may be found in (Donnellan and Hanrahan, 2006; Donnellan et al., 2013). The FLAGGS model maximises sectoral gross margins, subject to farm and sector constraints (Breen et al., 2010a).

The purpose of this paper is to test a different approach: it uses an energy system modelling tool (TIMES) to develop a module for the agriculture system to be used in conjunction with a full energy system model (Irish TIMES). This approach aims i) to assess the emissions reduction potential via technological abatement options of the agriculture sector, ii) and to gain insights into the dynamics between the energy and non-energy systems in response to GHG emissions reduction targets. This approach models agriculture in a much simpler manner to either FAPRI-Ireland model or the FLAGGs model and does not have the same level of detail.

This section describes the methodology used for the integration of agriculture into the TIMES modelling framework along with the data requirements and technical assumptions made to facilitate the modelling. The module is designed to work in conjunction with the Irish TIMES model, an energy system model of Ireland, moving towards an integrated modelling approach where the agriculture and energy systems are modelled together to provide an overall least cost pathways to climate mitigation. The ultimate goal of this paper is to test the new methodology and to establish whether it can provide new insights into the relationship between the energy and agricultural systems. The system is tested in a context of a low carbon economy and identifies the elements (techniques and technologies) for emissions reduction in the agricultural sector. The primary inputs for the module have been provided by the dedicated agriculture tool FAPRI-Ireland. The TIMES modelling tool and in particular the Irish TIMES model used in this analysis are presented below before a detailed description of the methodology used to describe the agriculture sector.

6.3.1. TIMES Modelling tool

TIMES (The Integrated Markal-Efom System) is one of a modelling framework developed and supported by ETSAP (Energy Technology Systems Analysis Program), an implementing agreement of the International Energy Agency (IEA)[43]. TIMES is a technical economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon (Loulou et al., 2005). The objective function to maximize is the total surplus. This is equivalent to minimizing the total discounted energy system cost while respecting environmental and many technical constraints. This cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon. The key inputs to TIMES are the demand component (energy service demands), the supply component (resource potential and costs), the policy component (scenarios) and the techno-economic component (technologies and associated costs to choose from). The model is driven by exogenous demand specified by the list of each energy service demanded (disaggregation), actual values in the base year (calibration) and values for all milestone years till 2050 (projection). The full technical documentation of the TIMES model is available in Loulou et al. (2005). There is a considerable body of on-going international research involving TIMES (and its predecessor MARKAL) models. A selection of case studies covering the period 2008–2010 are summarized in the recent IEA-ETSAP report (IEA-ETSAP, 2011).

6.3.2. The Irish TIMES model

The Irish TIMES model is the energy system model for Ireland developed by UCC under the Climate Change Research Programme 2007-2013. It has been developed to build a range of medium (to 2020) to long term (to 2050) energy and emissions policy scenarios in order to inform policy decisions. The Irish TIMES model was originally extracted from the Pan European TIMES (PET) model – a 36 regions (EU27, Iceland, Norway, Switzerland, and six Balkan countries) model of Europe (Gargiulo and Ó Gallachóir, 2013) – and then updated with local and more detailed data and assumptions (Ó Gallachóir et al., 2012). The model represents the Irish energy system and its possible long term evolution through a network of processes which transform, transport, distribute and convert energy from its supply sector (fuel mining, primary and secondary production, exogenous import and export), to its power generation sector (including also the combined heat and power description), and to its demand sectors (residential, commercial and public services,

[43]See <http://iea-etsap.org/> for more details.

agricultural, transport and industry). Extensive description and details on modelling structure and approach may be found in (Chiodi et al., 2013a; Chiodi et al., 2013b; Ó Gallachóir et al., 2012).

The Irish TIMES model version used in this analysis has the years 2005-2012 calibrated to the national energy balances (Howley et al., 2012; Howley et al., 2006), a time horizon of 45 years (to 2050) and a time resolution of four seasons with day-night time resolution, the latter comprising day, night and peak time-slices. Energy demands are driven by a macroeconomic scenario covering the period to 2050, which is based on the ESRI HERMES macroeconomic model of the economy. HERMES is used for medium-term forecasting and scenario analysis of the Irish economy and most recently the model has been used to generate the scenarios underpinning the 2013 edition of the ESRI's Medium-Term Review (FitzGerald et al., 2013). On the supply side, fossil fuel prices are based on IEA's current policy scenario in World Energy Outlook 2012 Report (IEA, 2012d). Additional details on model assumptions are presented in Appendix A.

6.3.3. The Agriculture TIMES module

6.3.3.1. Model structure

In the case of the Irish agriculture sector we chose to follow a flow-based approach in which averaged technical and economical attributes are defined for each of the macro processes. The conceptual model structure of the agriculture module is presented in the flowchart of Figure 6-2. The white boxes with coloured borders represent the new elements of the new module, while grey boxes represent components that already exist in Irish TIMES.

The complexity of the Irish agriculture system has been characterised and modelled in a simplified way in terms of 1) its supply component commodities; 2) its production macro-sectors (technology component) and 3) its service demands, i.e. the required output for dairy, livestock and crops. In this schema, the energy sector supplies the energy requirements of the agriculture requirements, but at the same time agriculture could potentially become the supplier of bioenergy commodities to the energy sectors. The following sections describe details of each of these components.

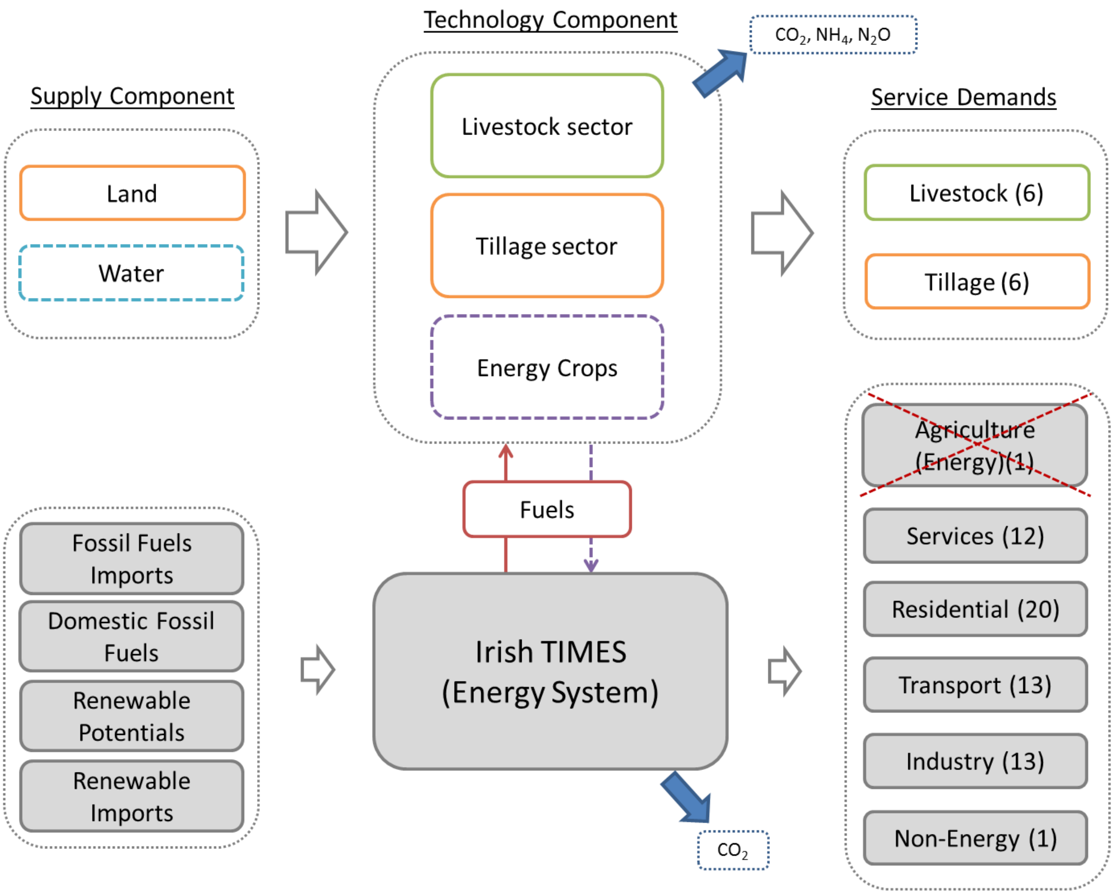

Figure 6-2. Flow chart of the agricultural system module and interactions with Irish TIMES

6.3.3.2. *Demand component*

Similarly to all other TIMES models, the Agriculture TIMES module is driven by exogenous demands specified by a list of service demands (SD), actual values in the base year (calibration) and values for all milestone years (projections). In the new agriculture module we identified 12 relevant demand categories, which adds to the existing (59[44]) Irish TIMES energy related service demands. Six of these SD belong to the livestock sector, the remaining six to tillage. Base year (2005), 2006 and 2010 demands were calibrated to values in the National Inventory Report (EPA, 2012), while projections over a time horizon of 40 years (to 2050) are based on FAPRI-Ireland's model stock projections. For the estimates of the dairy demand stock, an average milk yield is taken from (Teagasc, 2011b). Table 6-1 presents the list of SD, the projection trends and the units used to represent each demand driver.

[44] Agricultural energy demand was removed because energy consumption is now endogenously evaluated within the new module.

Sector	Process	Code	2005	2010	2020	2030	2040	2050	Unit
Livestock	Dairy Cattle	ADCAT	5,302	5,494	6,412	7,374	7,572	7,461	Mlitre
	Non-Dairy Cattle	ANDCAT	5.93	5.59	5.60	5.47	5.24	5.11	Mhead
	Sheep	ASHE	6.43	4.70	5.88	6.09	6.57	7.01	Mhead
	Pigs	APIG	1.67	1.53	1.97	2.43	2.88	3.29	Mhead
	Poultry	APOU	16.04	16.43	18.91	25.58	32.48	39.76	Mhead
	Other Animals	AOTH	0.09	0.12	0.12	0.12	0.12	0.12	Mhead
Tillage	Pulses	APUL	0.02	0.02	0.02	0.02	0.02	0.02	Mtonne
	Potatoes	APOT	0.41	0.36	0.39	0.28	0.32	0.32	Mtonne
	Sugarbeet	ASUG	1.40	0.00	0.00	0.00	0.00	0.00	Mtonne
	Barley	ABAR	1.02	1.25	1.44	1.52	1.49	1.43	Mtonne
	Oats	AOAT	0.11	0.16	0.19	0.20	0.19	0.17	Mtonne
	Wheat	AWHE	0.80	0.78	0.93	0.82	0.67	0.54	Mtonne

Table 6-1. Agricultural Services Demand drivers

Even though the approach and methodology presented here can be applied elsewhere to different geographic areas, it is worth noting that the number of the SD is highly country dependant. In the Irish case, the policy interest is mainly on the livestock sector, which accounts for the vast majority of agricultural activity and accounts (directly or indirectly) for most of the GHG emissions from the sector.

6.3.3.3. Supply component

We also identified two new supply commodities relevant for the agriculture sector, namely 1) land and 2) water. Land availability is incorporated through a dedicated land commodity and is associated to each process. A cap on land availability can be imposed to investigate land use and land-use competition issues between agri-food sectors and bioenergy. A water commodity is introduced to quantify the water consumption for each process and again a cap could be imposed here if necessary. For the purposes of this paper values are not assigned to these commodities, but they may be introduced in the next steps of model development.

Conversely energy commodities are provided by the Irish TIMES supply sector, which is inherited from the previous model version.

6.3.3.4. Technology component

The technology component represents the core of the model. A network of processes transforms supply commodities, converting them into service demands. For each of these processes technical data (e.g. efficiency, capacity), environmental data (e.g. emission coefficients) and economic data (e.g. capital costs, O&M costs) can be defined.

The module network distinguishes between three sub-sectors, the *livestock* sector, the *tillage* sector and the *energy crops* sector. In each of these two distinct types of processes are defined; namely the *base-year* (or *standard*) (BY) processes, which describes the current system, and the *alternative* (or *abatement*) processes which incorporates abatement options for reducing emissions. With this approach the standard processes are set as free technologies which will be used by the model to deliver demands in the absence of emissions limits. When emissions constraints are introduced (e.g. due to policy targets) the model optimizes the combined energy and agriculture systems in order to deliver emissions reductions at least cost, where reductions in the agriculture sector may be delivered by the abatement options. Figure 6-3 details the model structure of the module. The green boxes represent the livestock sector, the orange the tillage, the purple the energy conversion (energy technologies), while the violet represents energy crops. The coloured boxes represent the BY processes, the blank boxes the alternative options. The number of processes is indicated in square brackets.

In the livestock sector, a distinction is drawn in the BY technologies between *pasture land* and *animal production* processes, which are linked to each other. The *pasture* technologies were created to represent the land consumed for grazing by each livestock category. The *animal production* process represents (in a simplified way) the animal's storage, processing and production. These two groups of processes are kept separately to distinguish between emissions directly or indirectly related to the pasture land and to the animal[45]. This was done to ensure the flexibility of the model for the utilization of abatement options (further details are provided later in the text). Standard technologies were also established in the tillage sector for each of the relevant production categories and for the energy technologies (one for each production category).

The capital, operation & maintenance (O&M) costs are set to 0. Data from the National Inventory Report 2012 (EPA, 2012) has been used to calibrate stocks and emissions factors arising from each subsector. The GHG emissions factors allocation for each process are based on the IPCC source categories definition as used by EPA in its inventory report (EPA, 2012).

[45] For modelling simplicity emissions from soils which originate from animal activity (e.g. amount of excretion deposition) are associated to the so called *animal production* processes despite are in the reality emitted by soils.

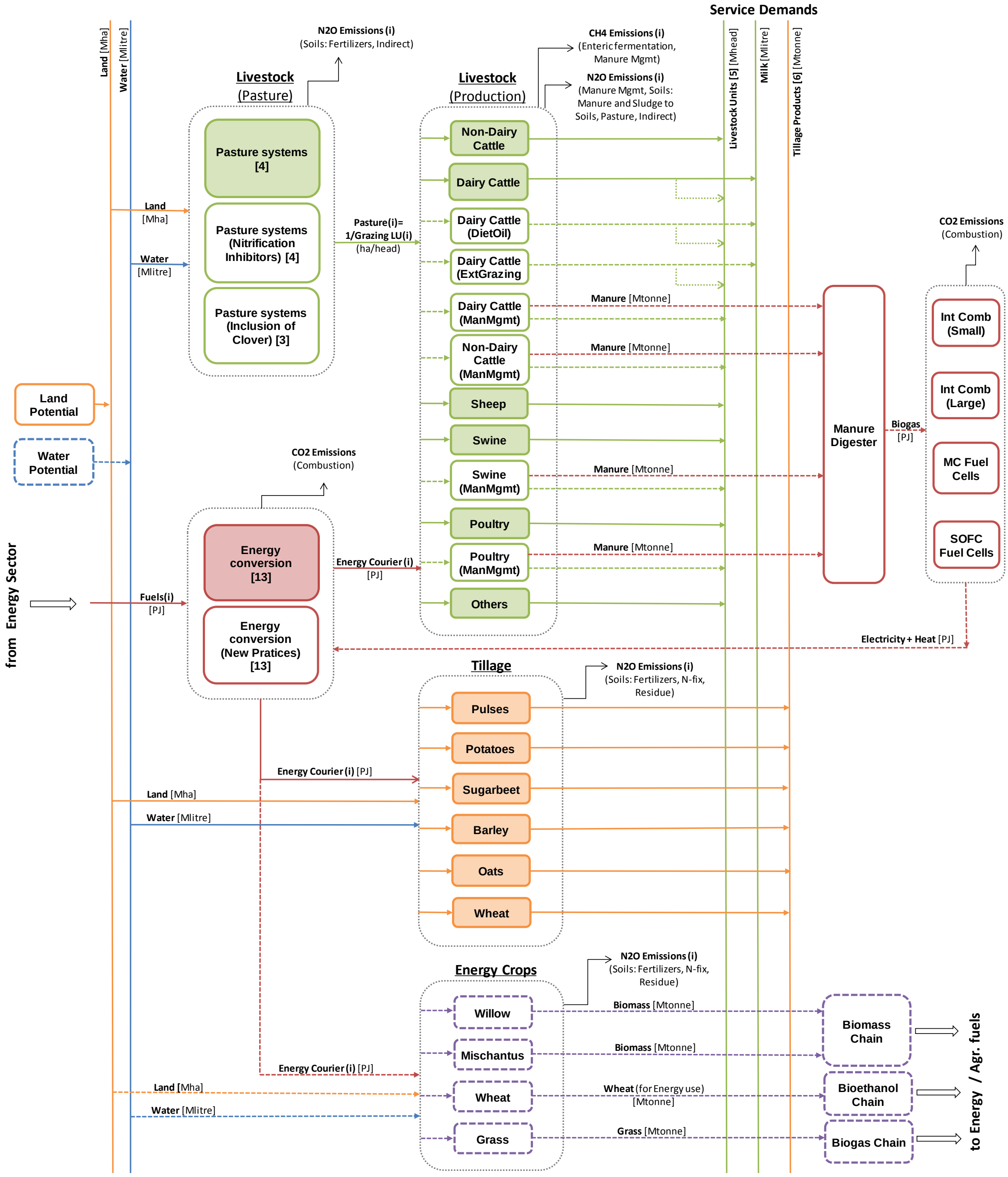

Figure 6-3. Reference Energy System (RES) of the agriculture module

Table 6-2 shows how emissions were allocated between processes. The emissions factors evolution along the model horizon is set according to the assumptions made by the FAPRI-Ireland model. Information from (Teagasc, 2011a) and (Teagasc, 2012) have been used to improve energy consumption figures from the 2005-2011 energy balances (Howley et al., 2012) which supplies information for single sectors. The model uses also National Farm Survey (NFS) data (Hennessy et al., 2011) to estimate average fertiliser application rates.

Sector	Process Type	Emission Type	Emission Source
Livestock	**Animal production**	CH_4	Enteric fermentation (4.A) and manure management (4.B)
		N_2O	Manure management (4.B), direct soil emissions (4.D.1) (manure and sludge nitrogen applied directly to soils), pasture range and paddock manure (4.D.2) (slurry, solid, pasture) and indirect emissions (4.D.3) (deposition and leaching related to animals)
	Pasture Land	N_2O	Direct soil emissions (4.D.1) (fertilizers) and indirect (4.D.3) (deposition and leaching due to fertilizers).
Tillage		N_2O	Direct soil emissions (4.D.1) (fertilizers, nitrogen fixed, residues) and indirect (4.D.3) (deposition and leaching due to fertilizers)

Table 6-2. Allocation of GHG emissions

Regarding abatement technologies a large number of options may be defined. For this methodology we focus primarily on the livestock sector, which represent the primary contributor to GHG emissions. Abatement options have hence been introduced for the livestock sector and for energy conversion, but not for the tillage sector. Energy crops may represent an interesting test case for energy-agriculture integration, but this is outside the scope of this current paper.

In this paper, non-energy emissions abatement technologies have been selected based on the most likely (yet limited) techniques and options available in the future. These techniques are drawn mainly from (Breen et al., 2010a). The assumed cost represents the additional cost (relative to the related BY technology) in terms of technology costs and labour, etc. required for the implementation of these techniques. An initial estimate of the range of applicability and the emissions abatement potential of these measures have been drawn from the findings gained from NFS (Hennessy et al., 2011). The challenge is that agriculture is a complex sector where production levels and techniques vary considerably from farm to farm. More accurate estimates of have been left to further analysis.

The option of introducing (manure) anaerobic digesters was also included. The techno-economic attributes for the digester and the CHP plants were inherited from equivalent technologies that already exist in Irish TIMES. The evaluation of the emission reduction potential was calculated assuming an average rate for fugitive emissions of 10%, as indicated in (IPCC, 2006). Table 6-3 describes the options designed for the livestock sector.

For the energy side, a similar approach to one previously used in the Irish TIMES model has been used. Energy processes in agriculture are divided between *standard processes* with fixed consumption shares between diesel and electricity (which reproduce the current energy mix) and *new practices* with flexible fuel shares. The costs and the bound for these shares have been calibrated from previous assumptions made in Irish TIMES and updated with more recent findings.

Abatement technology	Description
Nitrification Inhibitors	70% reduction in N_2O emissions from pasture systems. Two applications per hectare at a cost of €60 per application. Suitable for all livestock enterprises.
Inclusion of Clover in the Grassland Sward	Clover fixes nitrogen from the atmosphere resulting in a reduction in nitrogen fertilizer use and direct N_2O emissions from nitrogen fertilizer application. Reduce nitrogen use to 90 kg/ha. Limited to farms of intermediate stocking density with organic nitrogen of 140-190 kg/ha Cost of clover seed is 10 €/ha. Suitable for all livestock enterprises.
Dietary Oil Supplement	Feeding 4% oil results in a reduction in CH_4 of 23.6% per cow. Oil supplement cost is 1,400 €/tonne or 283 €/cow. Increase in milk production of 434.95 litre/cow. Suitable for the dairy enterprise.
Extending the Grazing Season	Extended grazing season length to 285 days for farms with good soil conditions and 255 days for farms with poor soil conditions. Emissions reduction of 0.14% per cow per extra grazing day. Increased profitability of €2.70 per cow per extra grazing day. Suitable for the dairy enterprise.
Manure Digester	Fugitive CH4 emissions 10% of produced biogas Cost of manure digester is 2777.8 €/kW Suitable for the dairy, non-dairy, pigs and poultry enterprise

Table 6-3. Livestock abatement technology options

6.3.3.5. Scenario component

To illustrate insights of this new approach, we apply three alternative scenarios up to the year 2050: i) one reference (*REF*) scenario (which delivers the least cost optimal pathway in the absence of emissions reductions targets); and ii) two mitigation policy scenarios. The mitigation scenarios presented in this paper use a different approach than those used for previous analysis (Chiodi et al., 2013a; Chiodi et al., 2013b), where agriculture GHG emissions trajectories were imposed exogenously. In this methodology we impose targets on overall GHG emissions (no single targets are imposed on individual sectors) and the model optimally allocates GHG reductions to the agricultural and the energy sectors. The chosen GHG reduction targets for 2050 are 50% and 60% relative to 1990 levels. These are not aligned with the EU perspective (EC, 2011c) which points to reductions of between 80 to 95%. However, in the case of Ireland, for the motivation outlined in Section 6.2.1 (high emissions share rising from agriculture) these targets seem more appropriate. The findings gained from the results (section 6.4.2) reconfirm the appropriateness of this assumption.

The assumed GHG targets for each scenario are summarized in Table 6-4.

Scenario\Target	2020	2030	2040	2050
Reference (REF)	No	No	No	No
GHG-50	-20.4% GHG rel. 2005 (-1.1% rel. 1990)	-16.5% GHG rel. 1990	-33% GHG rel. 1990	-50% GHG rel. 1990
GHG-60	-20.4% GHG rel. 2005 (-1.1% rel. 1990)	-20% GHG rel. 1990	-40% GHG rel. 1990	-60% GHG rel. 1990

Table 6-4. GHG mitigation targets in REF, GHG-50 and GHG-60

6.4. Results

This section presents and discusses a selection of results in three main sections. Section 6.4.1 compares agriculture emissions pathways under the *REF*, *GHG-50* and *GHG-60* scenarios, and identifies the measures which contribute to GHG reduction. Section 6.4.2 focuses on integrated agriculture and energy trends, while section 6.4.3 discusses economics. As the focus of this work is on the methodology, the results are used only to show how this methodology can be employed and should not be taken as definitive.

6.4.1. Agriculture pathways

This section analyses how the agriculture sector responds to the introduction of a number of emissions targets in the system. As explained in section 6.3.3.5, emissions targets have been applied to the overall GHG emissions and therefore agriculture trends are a result of a least cost optimization between the energy and the agriculture sectors.

The results show (Figure 6-4) that in the reference scenario – which reproduces FAPRI-Ireland projections – agriculture-related emissions in 2050 will grow by approximately 5% (15%) relative to 1990 (2010) values, driven by increased demand levels. Different emissions trends are therefore shown in the mitigation scenarios. The *GHG-50* indicates an increase in emissions in the period 2010-2030, which stabilize in 2040 and are overall reduced by 6.5% (2.3%) relative to 1990 (2010) in 2050. Under the *GHG-60* scenario, the reduction trends start earlier. From the year 2040 the agricultural sector delivers reductions of 5% (0.7%) relative to 1990 (2010) which then results in an overall reduction of 16.2% (12.4%) in 2050. Comparing these results against the *REF* scenario – where no GHG abatement measures are developed – it is therefore possible to detail (Figure 6-5) the contribution of single measures to these GHG emissions reductions by 2050. The scenario *GHG-50* suggests that the introduction of dietary oils in the dairy cattle diet is (in absolute terms) the measure which makes the largest contribution, followed by the inclusion of clover in the pasture land, the introduction of anaerobic digesters in poultry farms and some fuel switching (from diesel to biodiesel and to gas). Under the scenario *GHG-60*, steeper reduction trends are delivered with the application of nitrification inhibitors in place of the clover to the pasture land, the introduction of additional anaerobic digesters (in the pig sector) and further fuel switching where diesel is replaced by biodiesel.

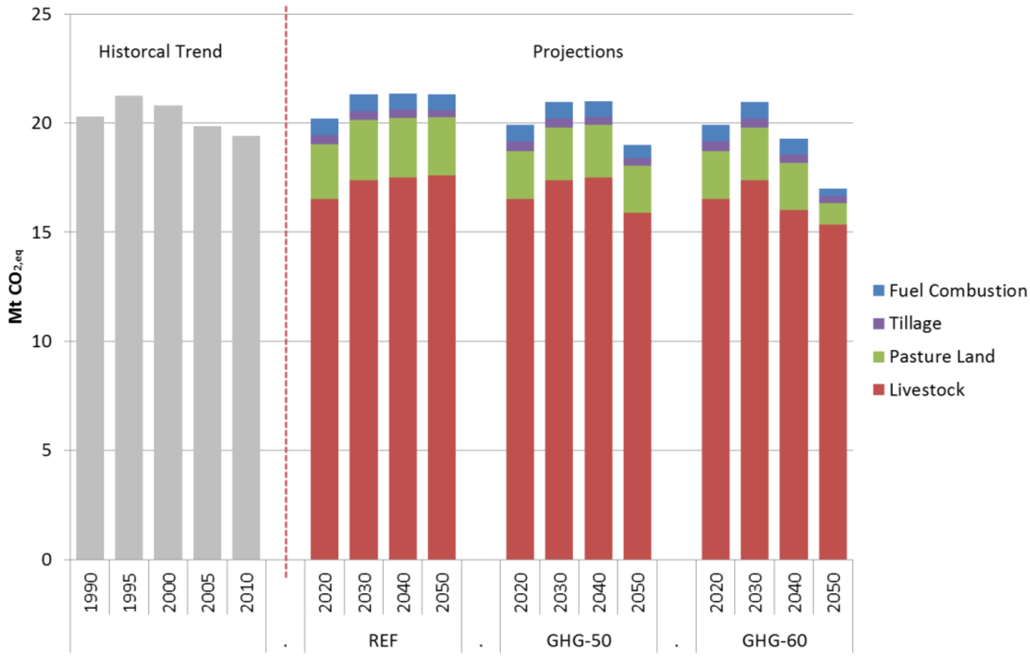

Figure 6-4. GHG emissions pathways for agriculture in REF, GHG-50 and GHG-60 ($CO_{2,eq}$)

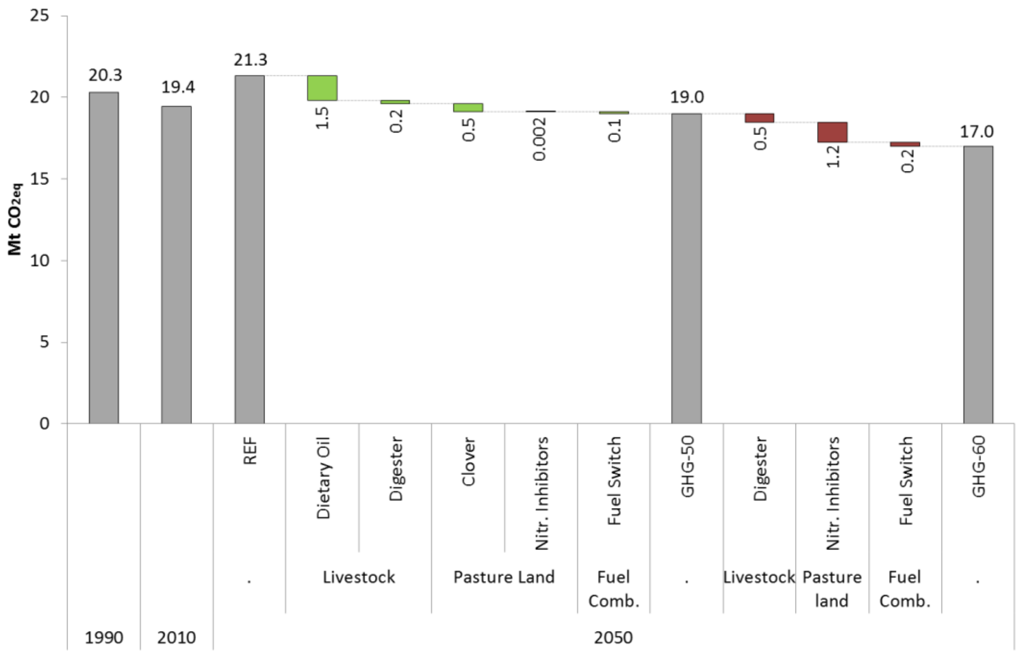

Figure 6-5. Contribution of single measures to GHG emissions reduction in 2050

6.4.2. Integrated pathways

The results from the integrated model are also used to examine how emissions targets impact on interactions between energy and agriculture. Figure 6-6 details the evolution of emissions shares for 2010 and 2050. As outlined in Section 6.2.1, in 2010 agriculture had an important role in the emissions balance accounting for approximately 31% of total emissions. The results suggest that this share of GHG emissions from agriculture will grow in time and the share from the energy sector will reduce. The extent of this reduction however varies depending on the scenario. By 2050, the *REF* scenario indicates that agriculture is responsible for approximately 34.3% (33.1% non-energy) of emissions, while energy is responsible for 61.1%, hence showing no radical changes in the relationship between the two sectors. A very different situation is shown in the mitigation scenarios where agriculture surpasses energy related emissions representing more than two thirds of total emissions in *GHG-50* and three-quarters in *GHG-60*.

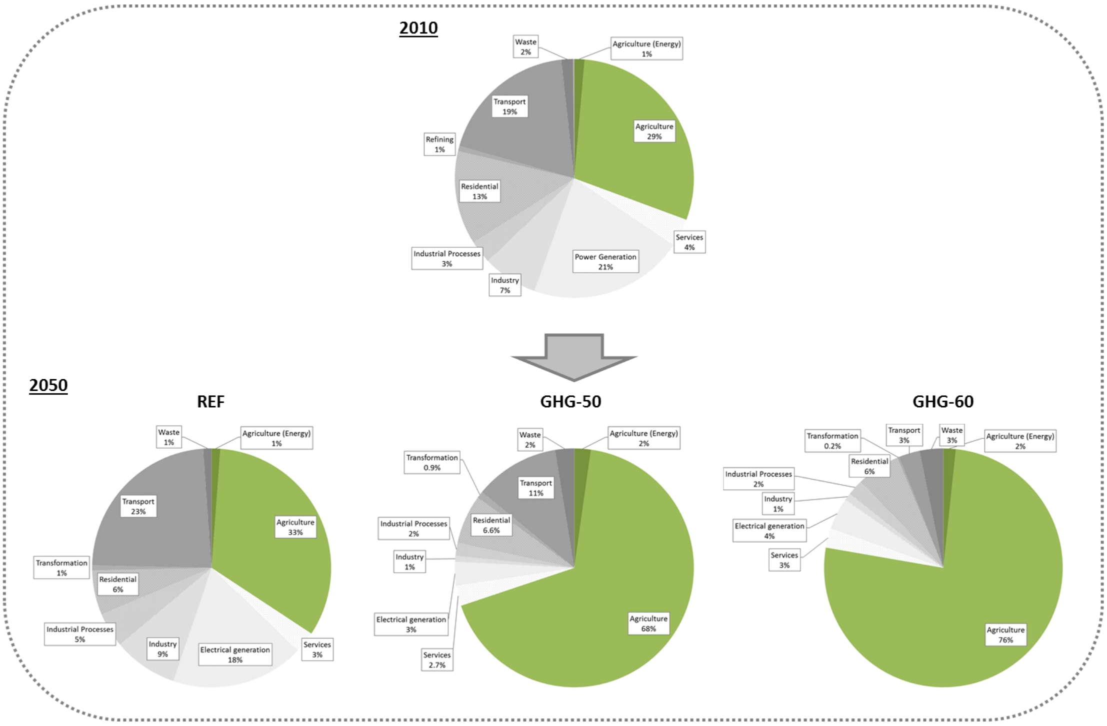

Figure 6-6. GHG emissions shares in 2010 (source: (EEA, 2013)) and 2050

The European Commission's Roadmap for moving to a competitive low carbon economy in 2050 (EC, 2011c) outlined how the mitigation target may be distributed amongst sectors at EU level, highlighting that certain sectors (notably electricity generation and energy in buildings) can achieve deep emissions cuts more readily than others (notably agriculture and transport). Similarly the cost optimal results from this model may provide some useful insights into the levels of ambition that might be appropriate for Ireland. Table 6-5 shows the cost optimal GHG reductions for the *GHG-50* and *GHG-60* scenarios. The results indicate that to achieve GHG emissions targets between

50% and 60% below 1990 the energy system is subject to steep reductions in emissions (between 75% and 87%), while non-energy sectors (notably agriculture) contribute partially (between 17% and 25%). Compared to the values presented in the EU roadmap this paper shows that energy results are in line with the EU context. Contrariwise in agriculture a reduction target between 42% and 49% relative to 1990 levels seems – according with this modelling results – not applicable to Ireland (at least without affecting activity levels).

	2005	2030		2050	
Sectors		**GHG-50**	**GHG-60**	**GHG-50**	**GHG-60**
Power Generation	37%	-58%	-59%	-92%	-91%
Industry (incl. process)	26%	-61%	-67%	-90%	-90%
Transport (incl. int. aviation)	149%	108%	93%	-39%	-88%
Residential and services	1%	-51%	-56%	-74%	-81%
Agriculture (CO_2, non-CO_2)	-3%	3%	3%	-6%	-16%
Transformation	62%	55%	55%	-10%	-81%
Energy	44%	-25%	-29%	-75%	-87%
Non-Energy	-3%	-8%	-10%	-17%	-25%
Total	**26%**	**-16%**	**-20%**	**-50%**	**-60%**

Table 6-5. GHG sectoral reductions (relative to 1990) in GHG-50 and GHG-60

6.4.3. GHG Shadow Prices

Table 6-6 show the trend in GHG shadow price for both mitigation scenarios analysed in this paper. The shadow price quantifies the impact of different mitigation targets on marginal abatement costs and provides an indication of the costs of abating the last tonne of $CO_{2,eq}$. It can be used as a proxy for indicating the level of carbon tax that may be required to reach a certain level of mitigation. In this case the results show that the cost of mitigation rises to €335/tonne by 2050 under the *GHG-50* scenario and doubles to €683/tonne when moving from a 50% to a 60% reduction target.

Scenario	2020	2030	2040	2050	
GHG-50	74	89	308	341	€/tonne
GHG-60	74	161	317	683	€/tonne

Table 6-6. GHG shadow prices (€$_{2010}$/tonne of $CO_{2,eq}$)

6.5. Conclusion

This paper has explored a case for the integration of the agricultural sector into an energy system model. This was done not only to assess the extent for emissions reduction potential in the agricultural sector (for which more detailed modelling tools are already available) but also to gain insights into the (cost optimal) dynamics between the energy and non-energy systems in the context of GHG emissions mitigation. This paper described the methodology used to build an agriculture module using the TIMES energy systems modelling framework, along with the data requirements and the technical assumptions made to assess emissions reduction options. For each modelling component – namely the demand, the supply and the technology components – a detailed description of the modelling details were provided.

The paper also presents results for the period 2010 to 2050. The work in this paper showed that an integrated modelling approach provides important insights into the most cost effective mitigation pathways and draws evidence for new comprehensive policy strategies able to discern between the full range of technical solutions available. In this particular analysis it was shown that technical solutions in agriculture may contribute with some emissions reductions – however these reductions represent less than a 20% reduction relative to 1990 levels – while the bulk of cost optimal emissions reductions remain in the energy related sectors. Comparing with the findings of the EU roadmap (EC, 2011c) the results indicated that in the case of Ireland an 80% to 95% GHG emissions reduction by 2050 would be very challenging without also reducing activity levels of the agriculture. This solution seems very unlikely given the implications that this decision would have for the Irish economy and in some extent also for food security. Therefore the authors' initial viewpoint is that an appropriate effort sharing decision for Ireland should range between 50% and 60% reduction by 2050 relative to 1990 levels, in the context of an EU goal of 80%-95% reduction.

6.6. Future work

The analysis points to further work to improve a number of areas in the module in order to provide a more robust assessment of agricultural mitigation potential. Future work should focus on the abatement measures, namely identifying new possible measures and assessing their levels of applicability. The challenge is that agriculture is a complex sector, where production levels and techniques vary considerably from farm to farm. In this context estimating the applicability and the abatement potential of measures is not simple. Moreover new elements of the tool should be implemented to describe energy crops. Bioenergy is likely to be the most significant fuel source for the future economy and therefore a detailed assessment of the dynamics between energy crops and other agriculture areas is of primal importance for the development of new food and energy policy strategies. A further important modelling challenge will be the improvement of the existing sectors, with the identification and disaggregation of processes (e.g. tractors, heaters, etc.) in each production chain.

7. Conclusions

This thesis has investigated the implications of the key challenges and decisions facing Ireland in energy and climate policy; providing indications, which could be not readily addressed when this work commenced, to the following key research objectives:

1. Assess technical-economic impacts of key energy and climate mitigation policies for Ireland's energy system.
2. Provide insight and identify gaps on current energy trends and policies in light of a low carbon economy by 2050.
3. Evaluate the implications of different mitigation pathways and policy targets on transitioning to a low carbon economy by 2050.
4. Identify emerging technologies and new commodity trends in the end-use sectors.
5. Quantify the role of renewable energies and energy efficiency on future energy systems.
6. Analyse the consequences for energy security, sustainability and land usage of future energy systems.
7. Asses the implications of high shares of intermittent electricity generation in a low carbon power generation sectors.
8. Examine the role of agriculture in delivering climate mitigation targets.

To address these research objectives the research work has been divided into two parts. The Part I answered the following research question: *What technology choices and emission reduction targets are cost-optimal for Ireland in the context of a low carbon economy to 2050?* To do so, this research contributed to the development and employed an energy system model (the Irish TIMES model); and has investigated via scenario analysis the implications for energy systems of delivering mitigation trajectories with three specific time scale perspectives, aligning with key policy target time horizons: 2020 (chapter 2), 2050 (chapter 3) and 2030 (chapter 4).

Chapter 2 has explored the techno-economic implications for Ireland's energy system in delivering the 2020 EU climate framework. The analysis raised a number of questions regarding Ireland's obligations under the Effort Sharing Decision 2009/406/EC and pointed to the need of a significant reassessment of renewable energy policy; i.e. the current dominant policy focus on wind-generated electricity is misplaced, while more ambition on renewable energy in transport and renewable thermal energy is required. Non-ETS emissions reductions may be achieved within the residential, transport and services sector through two key pathways, namely electrification of heating in buildings – i.e. shifting CO_2 emissions from the non-ETS sectors to the ETS sectors (namely electricity generation) – and significantly increasing the amount biofuels used in transport. The high abatement costs (€$_{2000}$158/tonne in 2020) also shown that the target set for Ireland is far from a cost optimal target. This challenges the findings of analysis for EU using the PRIMES model which found that Non-ETS emissions reduction of 17% below 2005 levels could be achieved at a marginal abatement cost of €40-€50/tonne. Results moreover underlined the importance of agriculture emissions that, even not directly modelled, represents nearly half of Non-ETS emissions in Ireland, and has few mitigation options. The chapter quantified the costs associated with imposing a 31.5% non-ETS emissions reduction target on Ireland's energy system (€$_{2000}$213/tonne) to compensate for the fact that agriculture delivers a reduction of 4% by 2020 relative to 2005 levels.

Chapter 3 therefore has focussed on 2050 energy system, presenting the vision for a near zero emissions energy system, namely delivering CO_2 reductions between 80% and 95% relative to 1990 levels. Results have shown that, although with considerable effort, reductions of this magnitude are technically achievable. It implies a transition where fossil fuels are incompatible with a low carbon economy; significant investments involve energy efficiency and renewable energy technologies – which will deliver between 71.7% and 90.1% of gross energy consumption by 2050 –; and significant changes are required in energy infrastructure to enable the electrification of heat and transport, to accommodate carbon capture and storage facilities (CCS) and for biofuels. The cost of achieving this mitigation targets represents between 1% and 2% of GDP in 2050 while marginal CO_2 abatement costs reaches between €$_{2000}$273/tonne and €$_{2000}$1308/tonne CO_2 by 2050, considerably higher than current levels, but comparable with similar analysis. This chapter also investigated the impacts of short term targets and policies on the longer term mitigation pathway. It found that extending current policies beyond 2020 i.e. separate 80% CO_2 emissions reduction targets for ETS and non-ETS sectors, results in greater electrification and efficiency measures (already important in the previous cases), but also results in the short term with higher emissions from the electricity generation sector. The marginal abatement cost in 2050 in this scenario reaches levels similar to an 85% CO_2 emissions reduction scenario with no ETS/non-ETS distinction.

An assessment of implications for a range of emissions pathways for 2030 has been hence developed in Chapter 4 of this thesis. These results provided evidence for energy policy makers in Ireland to enable them to engage with the European Commission in the definition of appropriate climate and energy targets for 2030. The chapter has compared techno-economic results of alternative emissions trajectories in the context of a single longer term (2050) target. Moving from a pathway in which the EU Low Carbon Roadmap is aligned to Ireland's current trajectory – namely applying a 36% target relative to 2005 levels (approx. 20% relative to 1990) – to a target which simply applies the roadmap (a 40% target relative to 1990 levels), require significant changes for the energy system. The 20% reduction target showed a smoother transition, while to deliver a 40% reduction target larger investments are required across the energy system in the decade 2020-2030. Earlier investments drives and increase in the renewable energy share, which passes from the current 16% target by 2020 to approximately 25% in 2030 in the 20% reduction scenario, and to 48% in the 40% reduction target. They although result less cost effective in a long term perspective, as reflected by CO_2 marginal prices, which remain higher in the whole period 2030-2050. For these reasons a 20% reduction target seems the more appropriate. The chapter moreover had a specific focus on bioenergy, which according to modelling results is intended to become the most important fuel source of low carbon economies. It has been explored the implications for the energy system of reduced availability of sustainable bioenergy in the international market. This contingency has not been scrutinized in the current (EU, 2009a, b) and future (EC, 2014) EU policy packages, but as shown in literature may represent an issue in the near term. The results have shown that with constrained imports, bioenergy contributions are significantly reduced, mainly in the transport sector, with consequent increase in electrification – based on gas CCS and renewables (wind, solar and also ocean), – end-use efficiency and hydrogen. Marginal CO_2 abatement costs rise sharply in accordance with the level of import restrictions. Moreover the chapter quantified implications of low carbon economies for import dependency, which has been anticipated to be reduced significantly in all the mitigation scenarios considered contributing positively to energy security. The reduction is driven by increased generation form renewable energy sources – wind, solar and ocean – and (partially) by bioenergy. The results also indicated that land usage for bioenergy production may have serious implication for the food supply. The 'consumed' land for energy purposes is anticipated to pass from the current 5,000 ha to approximately 710,000 ha of contracted land, thus equivalent to 17% of current agricultural land area.

Part II of this research work has therefore looked to address the following research question: *How can techno-economic modelling techniques be improved and developed to represent better the Irish policy context?* To do so this thesis has developed new methodologies which improve existing modelling techniques and provide new instruments to address technical and policy questions which could not be readily answered before: assess the implications of high shares of intermittent electricity generation in a low carbon power sector and examine mitigation trade-offs between energy system and agriculture sector.

Chapter 5 has presented a soft-linking methodology to improve the interpretation of results for the electricity sector from an energy system model by using high resolution chronological simulations from a power system model. Results for one specific year, 2020, have demonstrated that the soft-linking methodology provides important insights into results and provides a useful method to crosschecking/validating the technical appropriateness of the optimized power system results arising from an energy systems model. It was shown that for the system examined, the optimized portfolio was a reliable and adequate power system, although the role of base-load plants were overestimates and the value of key flexible elements namely storage were undervalued. This modelling approach have been used to introduce new elements to the energy system model, i.e. introducing additional constraints of the maximum amount of intermittent electricity generation in the system and implementing a limit on the penetration of electric heating systems (namely radiators and heat pumps) in the end use sectors.

Chapter 6 has developed and tested a methodology for the integration of agricultural systems modelling and energy systems modelling. This has been done to examine the role of agriculture in delivering climate mitigation targets, but even more to gain insights into the cost-optimal dynamics between the energy and non-energy systems in transitioning to a low emission economy. Results for the period 2010 to 2050 have demonstrated that this modelling approach provides valuable insights into the most cost effective mitigation pathways and draws evidence for new comprehensive policy strategies able to discern between the full range of technical solutions available. Results from the scenario analysed, provided useful indications of what emissions target may be more appropriate for Ireland in a context of long term (2050) effort sharing decision. It was shown that the Irish agriculture may contribute with some emissions reductions (however these reductions represent less than a 20% reduction relative to 1990 levels); but the bulk of emissions reductions remains in the energy sectors, with reductions which ranges between 75% and 85% below 1990 levels. In terms of total emissions this would mean for Ireland delivering in 2050 reductions between 50% and 60% relative to 1990 levels.

7.1. Recommendations

A key objective of the technical economic modelling works is to assist decision makers in assessing policies related to energy technologies. This thesis has been able to quantify the impacts of a number of key policy questions for Ireland from which the following policy recommendations are made.

1. Ireland's renewable energy policies need to be urgently reassessed in light of the non-ETS emissions reduction target.
2. There is a need for a focus on renewable heat, renewable transport and electrification of heat, in contrast to the current dominant focus on wind-generated electricity.
3. Biomass and biofuels are likely to be the most significant fuel source for the future economy. There is a need of detailed assessments of possible implications for sustainability and competition with the agri-food sectors.
4. Significant changes need to be done in infrastructure to deliver deep emissions reductions. Investments are foreseen for electrification of heat and transport, for gas and biogas networks, for carbon capture and storage facilities (CCS) and for biofuels.
5. The impacts of imposing a higher emissions reduction target on Ireland's energy system to compensate for limited mitigation options in agriculture should carefully considered in future.
6. The applicability of abatement measures in agriculture should be carefully scrutinized.

7. Renewable energies contribute positively to energy security, delivering reduced energy dependency.
8. Energy efficiency is one of the most cost effective measures to deliver emissions reduction.

Moreover this thesis has also contributed to the development of new modelling techniques and practices. These are underpinned by the fact that energy systems models cannot address all aspects of energy (and non-energy) systems with great detail. From these research experiences the following modelling recommendations are also made:

1. The use of complementary modelling tools should be considered to address individual modelling limitations, to gain additional insights, and to increase the robustness of the results.
2. The impact of intermittent renewable generation and the required responses (including storage, system flexibility, etc.) are generally under valuated in energy system models.
3. The trade-off between energy and non-energy (including agriculture) systems requires careful scrutiny in long term climate mitigation analysis.

7.2. Use of models to support policy

The modelling instruments which this thesis has contributed to implement may have a key role on supporting climate and energy policy in Ireland. Since October 2013 the outputs of the Irish TIMES model, some techniques and analysis developed in this thesis work formed the basis for the development of roadmaps for the Irish Department of Environment, Community and Local Government (DECLG) (Cahill et al., 2014; Deane et al., 2013), and the Department of Communications Energy and Natural Resources (DCENR), providing evidence for new policy measures and for negotiation with the European Commission regarding the 2030 effort sharing agreement. The use of models to support policy is well documented across EU countries and larger contexts, e.g. the IEA ETP-Model (IEA), the PRIMES model (NTUA, 2011), the UK-MARKAL model (UCL). In Ireland however no similar experiences were available.

Ensuring transparency in the model assumptions is one of the key elements for supporting policy. Producing accessible and complete documentation of the model structure and all the key assumptions of the model represent a key challenge given the richness of these modelling instruments. Efforts therefore should be made to provide correct and useful metrics which respond to policy needs. For the Irish TIMES model, substantial efforts have been made in respect of the transparency and completeness of the model structure and assumptions, through stakeholder events and the online publication of model documentation and main input assumptions[46]. Moreover

[46] Available online at <http://www.ucc.ie/en/energypolicy/irishtimes/>

stakeholders contributed directly to the development of the model, proving information and data inputs which have been used to update the model database, i.e. the techno-economic assumptions of the electricity generation portfolio and bioenergy resource potentials and costs. This may constitute a complication for the model development; however it represents an enormous added value in terms of transparency and consistency. In alignment with this goal, this thesis provides in Appendix A an overview of the key inputs used to perform these analysis. In addition, links to websites with additional details have been provided, when available.

7.3. Applicability of the methodologies

The methods used in this thesis work focuses primarily on Ireland and its implications within the EU context. It's worth noting that these techniques therefore can be applied elsewhere to different geographic areas, regions or sectors. The TIMES energy system modelling paradigm is in fact widely used internationally and therefore has the significant advantage that the results and techniques can be applied and compared with other countries. The same applies to the new methods developed in this thesis. A practical example of this is shown in Deane et al. (2012b) where the soft-linking methodology drawn in Chapter 5 has been applied to the Italy's power system. Similarly, the methodology outlined in Chapter 6 of this thesis has shown a number of analogies with the global context. This finding made Ireland a good test case for this new approach that could be potentially applied at a larger scale in future.

7.4. Further research

Based on the research presented in this thesis there is a number of areas with potential for further research developments, as outlined in the follows:

1. *Incorporating land-use into TIMES:* There is a need for the identification of interactions between the agri-food activities and the energy crops. Further development of the TIMES agriculture module could focus on the implementation of the energy crops sector, as outlined in the Chapter 6. This development would enable a more comprehensive evaluation of the land competition between the two types of activity.
2. *Introducing feedback to the economy:* The movement to a low carbon energy system will impact the economy. The modelling framework developed in this thesis does not incorporate a feedback mechanism between the developments in the energy system and the wider economy. Further research could involve the development of new methodologies able to generate such feedbacks via interactions between energy system models and macro-economic models.

3. *Improving the soft-linking analysis*: There is a need of improving the representation of residential electrical heating loads, smart metering technologies and electrical vehicles in power system models in order to better inform the results from energy system models. Further research could focus on the implementation of new soft-linking cases to respond directly to such policy questions and feedback to the energy system model.

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Appendix

A. Irish TIMES model input assumptions

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 Irish TIMES and which are used in the final calculations for the model outputs. Some of relevant model inputs are presented in the following sections.

A.1. Technologies

In the Irish TIMES model, there are more than 1350 technologies for the supply-side and demand-side sectors of the economy. 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 inherited from the databases of the Pan European TIMES (PET) model developed by NEEDS and RES2020 EU projects, from which a detailed description is provided in (RES2020, 2008). For Irish TIMES, the technologies parameters were all reviewed and revised, as appropriate, for Irish conditions. A summary of input assumptions for a selection of relevant technologies is available from: <http://www.ucc.ie/en/energypolicy/irishtimes/>. Specific data assumptions on single or groups of technologies not yet available online may be provided on request.

A.2. Resource potential and prices

The commodity supply curves and renewable resource for Irish TIMES have been carefully scrutinized and updated based on most recently available data, local knowledge or known technical limits.

Fossil fuels

The Irish TIMES model in the analysis of chapters 2, 3 and 5 has used for future fuel prices for key fuel commodities (e.g. coal, oil and gas) projections from IEA's reference scenario in the world energy outlook 2008 (IEA, 2008).

Fossil fuel commodities projections has been hence updated in chapters 4 and 6, where fuel prices are taken from IEA's Current Policy Scenario in the world energy outlook 2012 (IEA, 2012d), as summarized in Figure A-1.

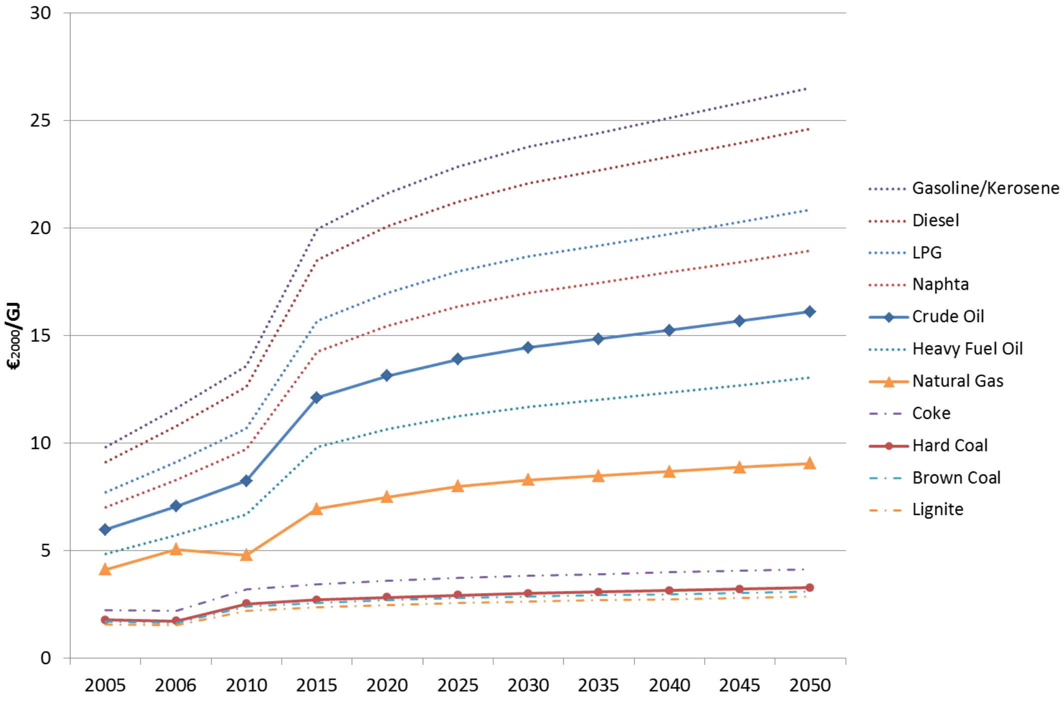

Figure A-1. Fossil fuels prices in Irish TIMES

Wind energy

The upper capacity limit for onshore and offshore wind energy is summarized in Table A-1 based on (Chiodi, 2010; DETI & DCENR, 2008; SEI, 2004).

Technology	Unit	2006	2010	2015	2020	2025	2030	2050
Wind onshore	GW	0.3	2.1	3.1	5.3	5.6	5.9	6.9
Wind offshore	GW	0.0	0.1	0.6	1.0	2.7	3.8	7.5

Table A-1. Wind resource potential in Irish TIMES

Ocean energy

The ocean energy resource potential is aligned with the ocean energy roadmap (SEAI, 2010b) and set at 29 GW in 2050.

Hydro

The maximum capacity for hydro energy has been set at 224 MW for large plants and at 250 MW for run of river plants. The existing 292 MW pumped hydro storage plant is also modelled.

Bioenergy

The Irish TIMES model used for the analysis of chapters 2, 3 and 5 the bioenergy potentials and costs are summarized in Table A-2 and Table A-3.

Potentials (ktoe)

Commodity	Unit	2005	2010	2020	2030	2040	2050
Agricultural waste[1]	ktoe	25.0	153.1	188.0	188.0	188.0	188.0
Starch crop[1]	ktoe	0.0	31.6	47.4	79.0	79.0	79.0
Grassy crop (Miscanthus)[1]	ktoe	2.7	4.0	28.0	211.3	394.7	910.3
Woody crop (Willow)[1]	ktoe	13.1	19.7	137.6	284.4	431.2	722.0
Forestry residues[1]	ktoe	62.3	93.5	109.1	109.1	109.1	109.1
Biogas[1,2]	ktoe	30.8	38.4	284.9	382.6	480.3	578.0
Municipal waste[1]	ktoe	71.1	142.2	155.5	155.5	155.5	155.5
Rape seed[2]	ktoe	1.7	7.2	14.3	14.3	14.3	14.3
Industrial waste[1]	ktoe	0.0	2.3	7.0	7.0	7.0	7.0
Wood processing residues[1]	ktoe	258.9	258.9	258.9	258.9	258.9	258.9

[1] Assumptions based on BSG (2004)

[2] Assumption based on Smyth et al. (2010)

Table A-2. Bioenergy potential in Irish TIMES (chapters 2, 3 and 5)

Costs (€$_{2000}$/GJ)

Commodity	2005	2010	2020	2030	2040	2050
Agricultural waste	4.10	4.60	5.20	5.20	5.20	5.20
Starch crop	8.16	7.73	7.06	6.59	6.59	6.59
Sugar crop	7.57	7.39	7.15	7.03	7.03	7.03
Grassy crop	4.48	4.30	4.20	4.20	4.20	4.20
Woody crop	2.57	2.41	2.21	2.10	2.10	2.10
Forestry residues	2.74	2.63	2.53	2.53	2.53	2.53
Biogas (from Grass)	4.50	4.10	3.70	3.70	3.70	3.70
Municipal waste	0.80	0.40	0.20	0.20	0.20	0.20
Rape seed	2.74	2.67	2.54	2.43	2.43	2.43
Industrial waste	0.01	0.01	0.01	0.01	0.01	0.01
Wood processing residues	3.25	3.35	3.45	3.45	3.45	3.45

Table A-3.Bioenergy cost assumption in Irish TIMES (€2000/GJ) (chapters 2, 3 and 5)

By contrast, in the Irish TIMES model used for the analysis of chapters 4 and 6 the domestic bioenergy resources has been represented by 12 different commodities. The total resource capacity limit for domestic bioenergy – considering both available and technical potential – has been set at 2887 ktoe for the year 2030 and at 3805 ktoe by 2050, based on the estimates from (Clancy et al., 2012; Howley et al., 2012; Phillips, 2011; SEAI, 2010a; Smyth et al., 2010). The cost assumptions for domestic bioenergy commodities are based on (McEniry et al., 2011) for biogas from grass, (Kent et al., 2011) for forestry, (Clancy et al., 2008) for willow and miscanthus crops and delivery costs, and (Clancy et al., 2012) for wheat crops, oil seed rape (OSR) and recycled vegetable oil (RVO). For the remaining commodities, the cost assumptions used in the PET model within the RES2020 project (RES2020) were used. Assumptions are summarized in Table A-4 and Table A-5. It is worth noting that information on resource potentials and prices used in the Irish TIMES model are updated on a regular basis in the online database available from: <http://www.ucc.ie/en/energypolicy/irishtimes/>.

Potentials (ktoe)

Commodity	**2010**	**2020**	**2030**	**2040**	**2050**	**Unit**
Agricultural residues-dry	153	188	188	188	188	ktoe
Maize/Wheat	0	42	45	45	45	ktoe
Sugar beet	0	0	0	0	0	ktoe
Miscanthus Crop (Total)	6	36	160	285	353	Ktoe
- Miscanthus crop - RSV 1	*6*	*36*	*89*	*89*	*89*	*ktoe*
- Miscanthus crop - RSV 2	*0*	*0*	*22*	*22*	*22*	*ktoe*
- Miscanthus crop - RSV 3	*0*	*0*	*0.2*	*0.2*	*0.2*	*ktoe*
- Miscanthus crop - RSV 4	*0*	*0*	*37*	*37*	*37*	*ktoe*
- Miscanthus crop - RSV 5	*0*	*0*	*7*	*7*	*7*	*ktoe*
- Miscanthus crop - RSV 6	*0*	*0*	*3*	*22*	*22*	*ktoe*
- Miscanthus crop - RSV 7	*0*	*0*	*0*	*106*	*174*	*ktoe*
Willow Crop (Total)	6	33	143	255	316	ktoe
- Willow crop - RSV 1	*6*	*33*	*79*	*79*	*79*	*ktoe*
- Willow crop - RSV 2	*0*	*0*	*8*	*8*	*8*	*ktoe*
- Willow crop - RSV 3	*0*	*0*	*12*	*12*	*12*	*ktoe*
- Willow crop - RSV 4	*0*	*0*	*20*	*20*	*20*	*ktoe*
- Willow crop - RSV 5	*0*	*0*	*25*	*40*	*40*	*ktoe*
- Willow crop - RSV 6	*0*	*0*	*0*	*12*	*12*	*ktoe*
- Willow crop - RSV 7	*0*	*0*	*0*	*85*	*146*	*ktoe*
Forestry residues	122	176	212	269	326	ktoe
Biogas from landfill and other	57	57	57	57	57	ktoe
Biogas from Grass	0	744	1136	1136	1136	ktoe
Municipal waste - BMSW	142	543	706	869	1031	ktoe
Recycled Vegetable Oil	0	1	2	2	2	ktoe
Oil Seed Rape/Algae	2	30	41	95	133	ktoe
Agricultural residues - wet	67	78	79	79	79	ktoe
Wood processing residues	75	92	117	115	137	ktoe
TOTAL	630	2021	2887	3395	3805	ktoe

Table A-4. Bioenergy potential in Irish TIMES (chapters 4 and 6)

Costs (€$_{2000}$/GJ)

	Commodity	2010	2020	2030	2040	2050	Unit
Domestic	Agricultural residues-dry	4.6	5.2	5.2	5.2	5.2	€/GJ
	Maize/Wheat	17.7	17.7	17.7	18.7	19.8	€/GJ
	Miscanthus crop - RSV 1	2.8	4.4	4.8	5.1	5.4	€/GJ
	Miscanthus crop - RSV 2	3.0	4.8	5.3	5.6	5.9	€/GJ
	Miscanthus crop - RSV 3	3.3	5.3	5.8	6.1	6.4	€/GJ
	Miscanthus crop - RSV 4	3.6	5.7	6.3	6.6	7.0	€/GJ
	Miscanthus crop - RSV 5	3.9	6.1	6.7	7.1	7.5	€/GJ
	Miscanthus crop - RSV 6	4.1	6.6	7.2	7.6	8.1	€/GJ
	Miscanthus crop - RSV 7	4.4	7.0	7.7	8.1	8.6	€/GJ
	Willow crop - RSV 1	4.3	6.9	7.6	8.0	8.4	€/GJ
	Willow crop - RSV 2	4.8	7.6	8.3	8.8	9.3	€/GJ
	Willow crop - RSV 3	5.2	8.3	9.1	9.6	10.1	€/GJ
	Willow crop - RSV 4	5.6	8.9	9.8	10.4	11.0	€/GJ
	Willow crop - RSV 5	6.0	9.6	10.6	11.2	11.8	€/GJ
	Willow crop - RSV 6	6.5	10.3	11.4	12.0	12.7	€/GJ
	Willow crop - RSV 7	6.9	11.0	12.1	12.8	13.5	€/GJ
	Forestry residues	6.8	6.8	6.8	6.8	6.8	€/GJ
	Biogas from landfill	3.3	4.7	5.1	5.4	5.6	€/GJ
	Grass	6.6	6.6	6.6	6.9	7.2	€/GJ
	Municipal waste - BMSW	0.4	0.2	0.2	0.2	0.2	€/GJ
	Recycled Vegetable Oil	5.5	5.5	5.5	5.8	6.1	€/GJ
	Oil Seed Rape/Algae	23.1	23.1	23.1	23.1	23.1	€/GJ
	Agricultural residues - wet	0.0	0.0	0.0	0.0	0.0	€/GJ
	Wood processing residues	1.9	1.9	1.9	1.9	1.9	€/GJ
Imported	Bio Ethanol - RSV 1	19.0	18.0	16.2	16.2	16.2	€/GJ
	Bio Ethanol - RSV 2	19.0	19.5	19.5	20.4	21.3	€/GJ
	Bio Ethanol - RSV 3	19.0	21.1	24.0	25.1	26.3	€/GJ
	Bio Ethanol - RSV 4	19.0	23.2	29.4	29.4	29.4	€/GJ
	Biodiesel - RSV 1	26.6	30.6	28.9	28.9	28.9	€/GJ
	Biodiesel - RSV 2	26.6	33.0	34.1	36.0	38.0	€/GJ
	Biodiesel - RSV 3	26.6	35.3	40.3	42.6	45.0	€/GJ
	Biodiesel - RSV 4	26.6	38.6	48.7	51.4	54.3	€/GJ
	Wood Pellets - RSV 1	11.0	6.7	5.4	5.4	5.4	€/GJ
	Wood Pellets - RSV 2	11.0	7.1	6.2	6.2	6.2	€/GJ
	Wood Pellets - RSV 3	11.0	7.9	6.9	6.9	6.9	€/GJ
	Wood Pellets - RSV 4	11.0	8.5	7.9	7.9	7.9	€/GJ
	Bio Rape Seed	31.1	33.3	35.6	37.8	40.0	€/GJ
	Wood Chip - RSV 1	5.4	3.3	2.7	2.7	2.7	€/GJ
	Wood Chip - RSV 2	5.4	3.5	3.0	3.0	3.0	€/GJ
	Wood Chip - RSV 3	5.4	3.9	3.4	3.4	3.4	€/GJ
	Wood Chip - RSV 4	5.4	4.2	3.9	3.9	3.9	€/GJ

Table A-5. Bioenergy cost assumption in Irish TIMES (€$_{2000}$/GJ) (chapters 4 and 6)

A.3. Macro-economic drivers

The Irish TIMES model is driven by a macroeconomic scenario covering the period to 2050, which is based on the ESRI HERMES macroeconomic model of the economy to 2030, with key variables extended to 2050. HERMES is used for medium-term forecasting and scenario analysis of the Irish economy. GDP, GNP, private income, population, number of households and other macroeconomic indexes 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. A full list of available energy service demands may be found in Ó Gallachóir et al. (2012). Some examples include residential space heating (PJ), commercial refrigeration (PJ), industry iron & steel (millions of tonnes, Mt), transport car distance (millions of passenger kilometres, Mpkm) and transport road freight (millions of tonne kilometres, Mtkm).

Chapters 2, 3 and 5 has used the macro-economic forecasts of Bergin et al. (2010) as demand drivers, as summarized in Table A-6.

Driver	Description	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2050
GDP	GDP	0.10%	3.16%	2.12%	1.36%	1.95%	1.98%	1.63%	1.49%
POP	Population	1.49%	0.85%	1.07%	0.89%	0.59%	0.54%	0.47%	0.34%
HOU	Number of Households	2.76%	1.82%	1.92%	1.84%	1.60%	1.14%	0.91%	0.61%
RSD	Residential sector	-1.23%	2.97%	2.19%	1.64%	2.14%	2.17%	1.82%	1.69%
TRA	Transport sector	-0.27%	2.83%	3.34%	2.31%	2.26%	2.27%	1.91%	1.74%
TRAc	Transport demand by Households	-3.52%	2.77%	1.47%	0.98%	2.03%	2.15%	1.78%	1.76%
AGR	Agriculture	-0.06%	0.76%	0.69%	0.72%	0.41%	0.43%	0.08%	-0.07%
IISNF	Industry: Iron & Steel and non-ferro	2.21%	5.35%	2.15%	0.51%	2.22%	2.21%	1.83%	1.64%
ICH	Industry: Chemical	2.21%	5.35%	2.15%	0.51%	2.22%	2.21%	1.83%	1.64%
INMPP	Industry: Other energy intensive (Buildings)	-13.83%	7.33%	3.83%	2.39%	0.69%	0.69%	0.69%	0.69%
IOI	Industry: Other industries	-0.78%	5.44%	2.30%	0.76%	1.89%	1.92%	1.56%	1.41%
COM	Services sector	2.02%	2.00%	1.85%	1.57%	2.01%	2.04%	1.69%	1.56%

Table A-6. Trends of demands drivers in Irish TIMES (chapters 2, 3 and 5)

In chapters 4 and 6 Irish TIMES has used a more recent set of HERMES medium-term forecasts, which have been also used to generate the scenarios underpinning the 2013 edition of the ESRI's Medium-Term Review (FitzGerald et al., 2013). The new projections are summarized in Table A-7.

Driver	Description	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2050
GDP	GDP	0.06%	2.24%	3.96%	2.20%	1.98%	1.21%	1.21%	1.21%
POP	Population	1.96%	0.40%	0.80%	0.71%	0.60%	0.44%	0.44%	0.44%
HOU	Number of Households	2.78%	0.98%	1.10%	1.11%	1.12%	1.07%	0.92%	0.60%
RSD	Residential sector	-0.27%	1.39%	3.56%	2.22%	2.33%	1.21%	1.21%	1.21%
TRA	Transport sector	-2.51%	3.41%	4.33%	1.45%	1.73%	1.21%	1.21%	1.21%
TRAc	Transport demand by Households	-2.86%	1.29%	3.61%	1.98%	2.28%	1.01%	1.01%	1.01%
AGR	Agriculture	-1.56%	2.55%	2.55%	1.60%	1.50%	1.21%	1.21%	1.21%
IISNF	Industry: Iron & Steel and non-ferro	3.88%	3.73%	5.04%	3.25%	1.16%	1.21%	1.21%	1.21%
ICH	Industry: Chemical	3.88%	3.73%	5.04%	3.25%	1.16%	1.21%	1.21%	1.21%
INMPP	Industry: Other energy intensive (Buildings)	-12.88%	-0.55%	10.51%	2.60%	4.07%	1.21%	1.21%	1.21%
IOI	Industry: Other industries	1.42%	3.31%	5.44%	3.25%	1.54%	1.21%	1.21%	1.21%
COM	Services sector	0.86%	1.65%	3.31%	1.51%	2.05%	1.21%	1.21%	1.21%

Table A-7. Trends of demands drivers in Irish TIMES (chapters 4 and 6)

Additional information regarding the demand drivers and their use in Irish TIMES may be found from: <http://www.ucc.ie/en/energypolicy/irishtimes/>.

A.4. Discount rates

The model uses a general discount rate (year dependent), as well as technology specific discount rates (period dependent). The former is used to: a) discount fixed and variable operating costs, and b) discount investment cost payments from the point of time when the investment actually occurs to the base year chosen for the computation of the present value of the total system cost. The latter are used only to calculate the annual payments resulting from a lump-sum investment in some year. Thus, the only place where the technology specific discount rate intervenes is to compute the Capital Recovery Factors.

Each individual investment physically occurring in year *k*, results in a *stream of annual payments* spread over several years in the future. The stream starts in year *k* and covers years *k, k+1, …, k+ELIFE-1,* where *ELIFE* is the economic life of the technology. Each yearly payment is equal to a fraction *CRF* of the investment cost (*CRF* = Capital Recovery Factor). Note that if the technology discount rate is equal to the general discount rate, then the stream of *ELIFE* yearly payments is equivalent to a single payment of the whole investment cost located at year *k*, in as much as both have the same discounted present value. If however the technology's discount rate is chosen different from the general one, then the stream of payments has a different present value than the lump sum at year *k*. It is the user's responsibility to choose technology dependent discount rates, and therefore to decide to alter the effective value of investment costs.

In the Irish TIMES economic values are specified in constant Euros of the year 2000. Costs – of building a process, maintenance, or importing a commodity – in year y are given in constant euros of year y, without inflation. Economic values of different years are discounted to the base year 2000 with a general social time preference or real term discount rate. In the Irish TIMES a 6% real term discount rate is assumed, but lower or higher values can be used in sensitivity runs. The technology specific discount rates used in the Irish TIMES are shown in Table A-8.

Sector	**Technology discount rate**
Agriculture	9%
Commercial	12%
Industry	12%
Power Sector	8.2% between 2005-2010 9% from 2015
Residential	17.5%
Transport	
- Public	8%
- Private	17.5%
- Trucks	12.5%

Table A-8. Technology discount rates in Irish TIMES