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Subject: Oireachtas Environment Committee debate on Climate Action Bill
Date: 15:07:30 Yesterday (27/02/2013)

Dear Michael,

I am writing to you in your capacity as Chair of the Oireachtas Committee on Environment, Culture and the Gaeltacht regarding your forthcoming debate on the Climate Action Bill. I have been involved for many years in climate mitigation research and would welcome an opportunity to discuss the findings of my research to the Committee.

I have researched how the energy system can transition to a low carbon future, the implications agriculture on our carbon mitigation ambitions, the technology choices, the economic implications and the implications of different targets. To do this I have built a number of energy modelling tools and generated the only long term climate mitigation scenarios for Ireland. My research has been referenced extensively in the NESC interim report on climate change, final report and in most of the background papers.

I attach two recent publications that you and the other Committee members may find of interest,

1. Chiodi A., Gargiulo M., Rogan F., Deane J.P., Lavigne D., Rout U.K. and Ó Gallachóir B.P. 2013 *Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system* **Energy Policy** Vol 53 pages 169 – 189.
   This internationally peer reviewed scientific journal paper presents the first and only long term energy scenarios for Ireland and focuses in particular on scenarios that achieve ambitious long term mitigation targets.
2. Ó Gallachóir B.P., Chiodi A., Gargiulo M., Deane J.P., Lavigne D. and Rout U.K. 2013 *Irish TIMES Energy Systems Model (CCRP 2008 3.1).* Report published by EPA
   This report presents results from scenario analysis focussing on how Ireland can meet our short term and long term greenhouse gas emissions reduction targets at least cost.

I look forward to hearing from you.

Yours sincerely,

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Chiodi et al EP 2013 Energy Mitigation Scenarios for Ireland to 2050.pdf

O Gallachoir et al 2013 - Irish TIMES Energy Systems Model.pdf

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

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HIGHLIGHTS

- We developed a techno-economic energy model of Ireland to the year 2050.
- Reductions between 80% and 95% of GHG emissions can be technically achieved.
- A 50% emissions cut in agriculture requires a 95% reductions from the energy system.
- Extending current policies implies greater electrification and efficiency measures.
- The additional cost to achieve mitigation remain less than 2% of GDP levels in 2050.

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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.

1. Introduction

1.1. Policy context

The most recent Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007a) shows that eleven of the last 12 years (1995–2006) rank among the 12 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).

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Table 1
EU low carbon roadmap GHG reduction compared to 1990.

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

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, 2009). 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 1 summarises the results from the EU Low Carbon Roadmap (EC, 2011), highlighting that certain sectors (notably electricity generation and energy in buildings), can achieve deep emissions cuts more readily than others (notably agriculture and transport).

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).

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. First, in contrast to the EU generally, greenhouse gas emissions increased by 24% between 1990 and 2005 as shown in Table 2 (EEA, 2010; EPA, 2011a)

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 Mt to 69.0 Mt. The impact of this is shown in Table 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.

Table 2
GHG Emissions in EU-27 and Ireland.

	1990		2005		
	EU-27	*IE*	*EU-27*	*IE*	
Total GHG emissions	5588.8	55.6	5148.8	69.0	[MtCO2eq]
Variation relative to 1990	–	–	*−7.9%*	*24.1%*	
2050 target	1117.8	11.1	1117.8	11.1	[MtCO2eq]
Reduction required	*−80%*		*−78%*	*−84%*	
Energy-related CO_2	4283.9	30.2	4084.5	45.0	[MtCO2eq]
Variation relative to 1990	–	–	*−4.7%*	*49.0%*	
2050 target	856.8	6.0	856.8	6.0	[MtCO2eq]
Reduction required	*−80%*	–	*−79%*	*−87%*	

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 Fig. 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).

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[1] 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

[1] 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).

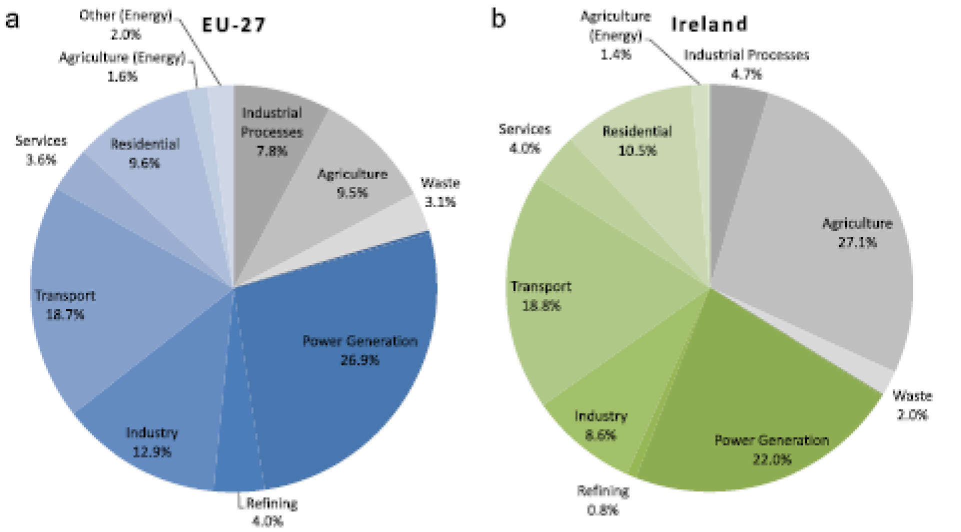

Fig. 1. Comparing 2005 GHG emissions share in EU-27 and Ireland. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

agriculture GHG emissions will be reduced by 4.4% in the period 2005–2020 (EPA, 2011c). 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,[2] 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 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 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.

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 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 presents the results, comparing the different mitigation scenarios in terms of impacts on the energy system and economic impacts. Section 4 draws some conclusions, discussing the relevance and the main recommendations for policy makers in Ireland.

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 WORLD[3] 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)

[2] I.e., assumed here to remain constant over the period 2020–2050.

[3] ⟨http://iea-etsap.org/web/applicationGlobal.asp⟩.

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).

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).[4]

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.

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 (Ó Gallachóir et al., 2010c).

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 Fig. 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).

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).

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), 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 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.).

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 4, in conjunction with GEM-E3's[5] 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[6].

[4] ⟨http://iea-etsap.org/⟩.

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

[6] 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.

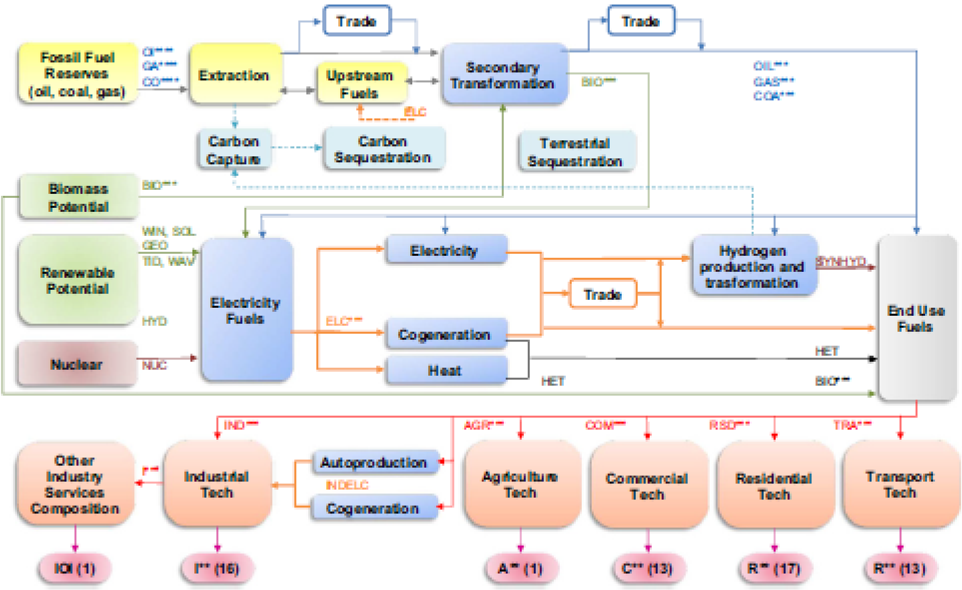

Fig. 2. Irish TIMES Reference Energy System (Gargiulo et al., 2010).

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

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

$$ESD\ driver(t)=(1+DDR(t)*elasticity(t))^{periodlength}*(1-AEEI) \quad (2)$$

where t is the reference year for the demand driver.

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:

$$Demand(t)=(Demand(t-1)*Driver(t)) \quad (3)$$

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:

$$Demand(t)=\left(\sum_{t} Number\ Of\ Dwelling(t)*Specific\ Consumption(t)\right) \quad (4)$$

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 5 presents an extract of this database for private car transport demand sector.

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 6, for the year 2050 is 14.4 GW (Chiodi, 2010; DETI & DCENR, 2008; SEI, 2004).

The ocean energy resource potential is aligned with the ocean energy roadmap (SEAI, 2010) and set at 29 GW in 2050, while the total resource capacity limit for domestic bioenergy has been set at 1230 ktoe for the year 2020 and at 3500 ktoe by 2050. The potential for each individual commodity is shown in Table 7, are based on the results of Bioenergy Strategy Group (BSG, 2004) and 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.

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).

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

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			
RWMN	Water heat.multi.all.new	PJ		Transport (13)	
RWRE	Water Heat.single.rural.ex	PJ	TAI	Aviation international	PJ
RWRN	Water heat.single.rural.new	PJ	TAV	Aviation generic.	PJ
RWUE	Water heat.single.urban.ex	PJ	TBI	Road bus intercity.	Mp*km
RWUN	Water heat.single.urban.new	PJ	TBU	Road bus urban.	Mp*km
			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			
CREF	Refrigeration.	PJ		Agriculture (1)	
CWLE	Water heat.large.	PJ	AGR	Agriculture, fishery, forestry	PJ
CWSE	Water heat.small.	PJ			
ONE	Other sector.	PJ			
				Non energy (1)	
			NEO	Others	PJ

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

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

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

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

Table 5
Private car transport technology database.
Source: Irish TIMES model.

	Code	Description	Activity unit	Capacity unit
Existing	TCARDST100	Car.DST.00.base-year.	(Mp*km)	(1000vehicles)
	TCARGSL100	Car.GSL.00.base-year.	(Mp*km)	(1000vehicles)
	TCARLPG100	Car.LPG.00.base-year.	(Mp*km)	(1000vehicles)
New	TCAR_PIH	Car.plug-in.hybrid	(Mp*km)	(1000vehicles)
	TCARSBDL101	Car.biodiesel.01	(Mp*km)	(1000vehicles)
	TCARSDME110	Car. dimethyl.ether.10	(Mp*km)	(1000vehicles)
	TCARSDST101	Car. diesel.01	(Mp*km)	(1000vehicles)
	TCARSDST210	Car. diesel.hybrid.10	(Mp*km)	(1000vehicles)
	TCARSELC110	Car. electric.10	(Mp*km)	(1000vehicles)
	TCARSETH101	Car. ethanol.01	(Mp*km)	(1000vehicles)
	TCARSFTD110	Car. FT-diesel.10	(Mp*km)	(1000vehicles)
	TCARSGAS101	Car. gas.01	(Mp*km)	(1000vehicles)
	TCARSGH2110	Car. compressed.hydrogen.internalcombustion.10	(Mp*km)	(1000vehicles)
	TCARSGH2210	Car. compressed.hydrogen.fuelcell.10	(Mp*km)	(1000vehicles)
	TCARSGSL101	Car. gasoline.01	(Mp*km)	(1000vehicles)
	TCARSGSL201	Car. gasp;ine.hybrid.01	(Mp*km)	(1000 vehicles)
	TCARSLH2110	Car. liquified.hydrogen.IC.10	(Mp*km)	(1000 vehicles)
	TCARSLPG101	Car. LPG.01	(Mp*km)	(1000 vehicles)
	TCARSMtaH101	Car. methanol.internalcombustion.01	(Mp*km)	(1000 vehicles)
	TCARSMtaH210	Car. methanol.fuelcell.10	(Mp*km)	(1000 vehicles)

Table 6
Wind resource potential.

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 7
Bioenergy potential.

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

[a] Assumptions based on BSG.
[b] Assumption based on Smyth et al.

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 2.5 that characterize single scenarios) are applied in all scenarios, and no constraints 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.

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, 2011; EPA, 2011b). In this paper, we do not 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. Results

This results for the Irish TIMES emissions reduction scenarios for Ireland are grouped into three main sub-sections. First 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.

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

3.1.1. Emissions trajectories

Fig. 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 33.7 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 1.5 Mt. 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.

Fig. 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 Mt 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 Mt and 0.7 Mt, respectively (reductions of 89.0% and 98.8% relative to *REF*).

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.

Fig. 5 presents the evolution of total final consumption (TFC) of energy by sector for the scenarios. Comparison with Fig. 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.

3.1.2.1. Transport sector. Fig. 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.

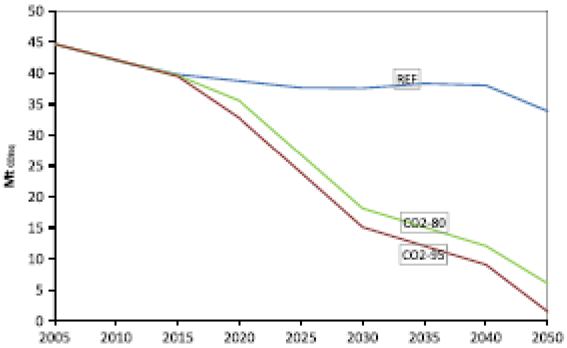

Fig. 3. Total CO_2 emissions trajectories by scenario (Mt).
Source: Irish TIMES model.

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*.

Focusing on on-land (i.e., road and rail) transportation, Fig. 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.

3.1.2.2. Residential and services sector. The residential sector exhibits some differences at TFC level across the scenarios mainly after 2020 (Fig. 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),

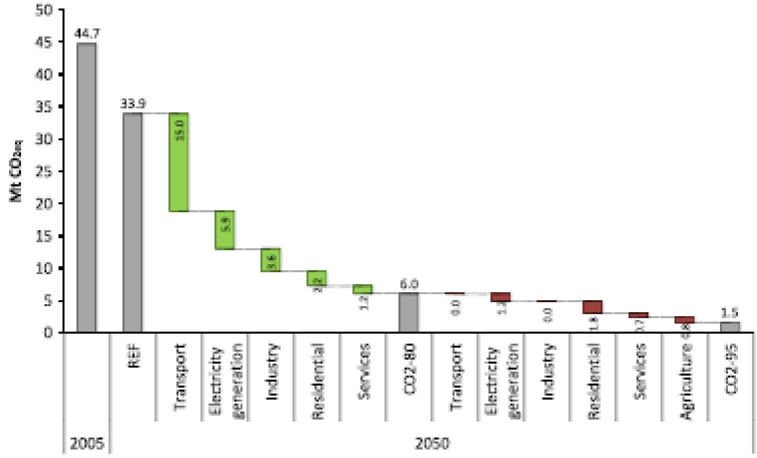

Fig. 4. Decomposition of total CO_2 emissions in *REF*, *CO2-80* and *CO2-95* (Mt).
Source: Irish TIMES model.

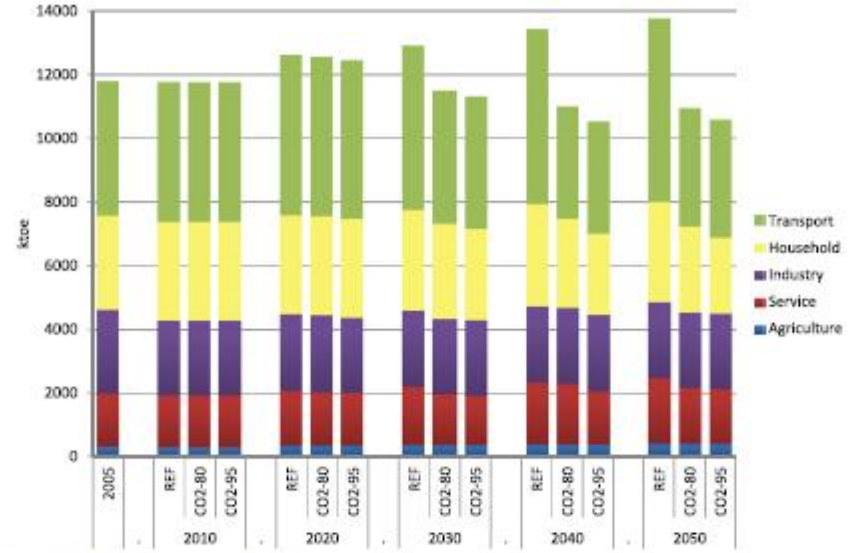

Fig. 5. Final energy demand by sector in *REF*, *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

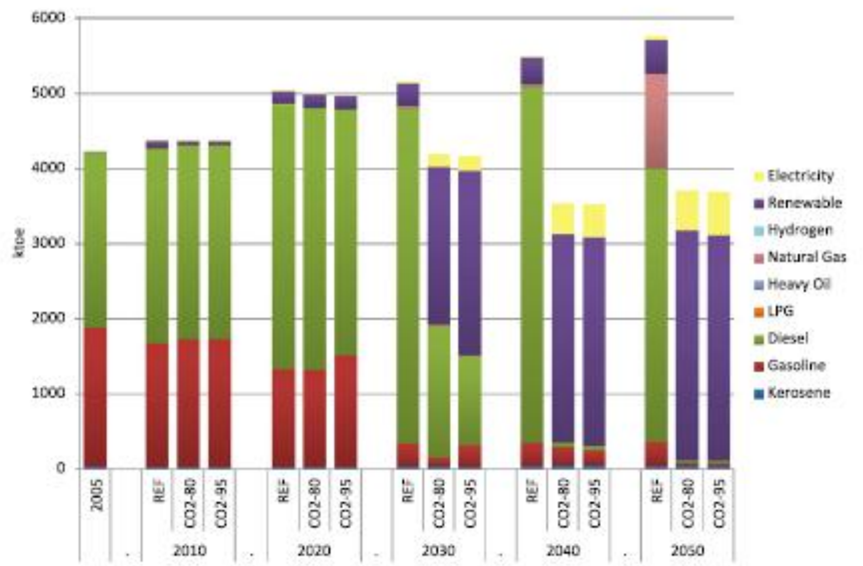

Fig. 6. Transport energy demand in *REF*, *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

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).

For the services sector (Fig. 9) the results are similar to the residential sector, i.e., an increasing share of electricity, renewables and gas, displacing completely coal and peat[7] and oil use. The effect of the emissions reduction targets is to accelerate this

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

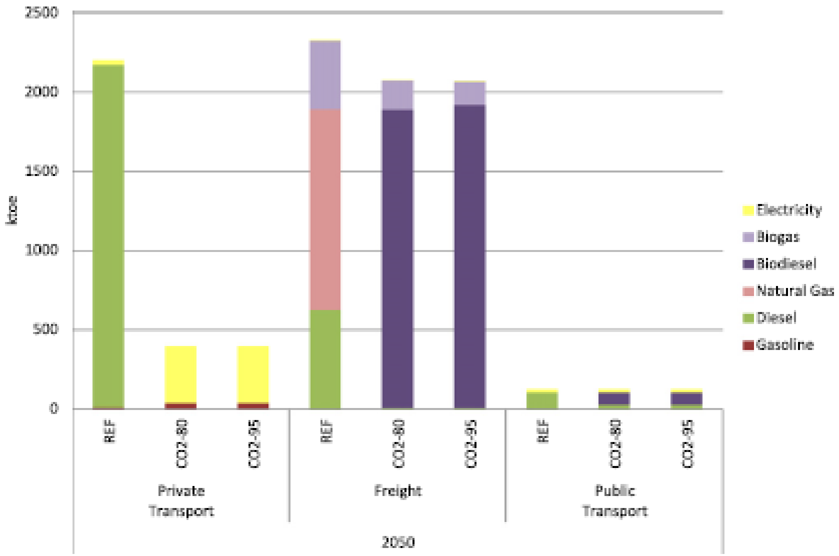

Fig. 7. 2050 transport energy by end-use in *REF, CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

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.

3.1.2.3. Industry sector. Moving to industry, Fig. 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.

3.1.2.4. Electricity use and fuel mix. Fig. 11 summarizes the electricity consumption by end-use sectors for the three scenarios. In the *REF* scenario, electricity demand increases from 2038 ktoe (23,707 GW h) 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 (39,055 GW h) in 2050 in *CO2-80* and 4885 ktoe (56,814 GW h) 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%).

The electricity generation fuel mix is shown in Fig. 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 lead 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

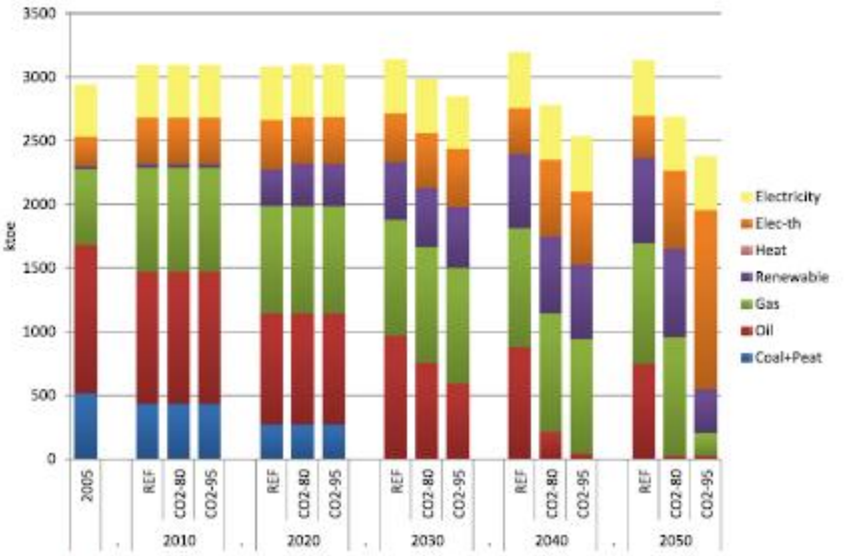

Fig. 8. Residential energy demand in *REF*, *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

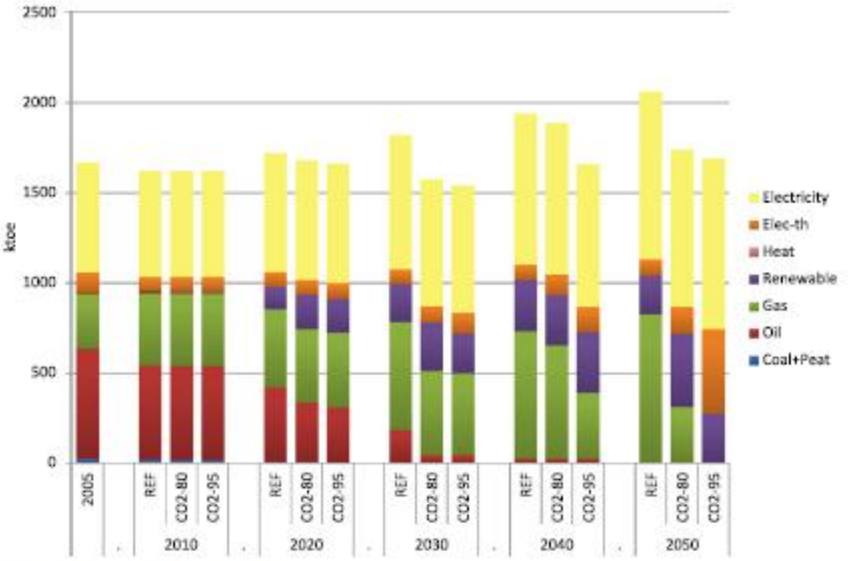

Fig. 9. Services energy demand in *REF*, *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

(wind energy) and 30.8% dispatchable renewable generation, (25.3% from biomass steam turbine, 3.5% from biogas and 2.0% from hydro power).

3.1.2.5. 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). Fig. 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 67.8% 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 85.1% 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

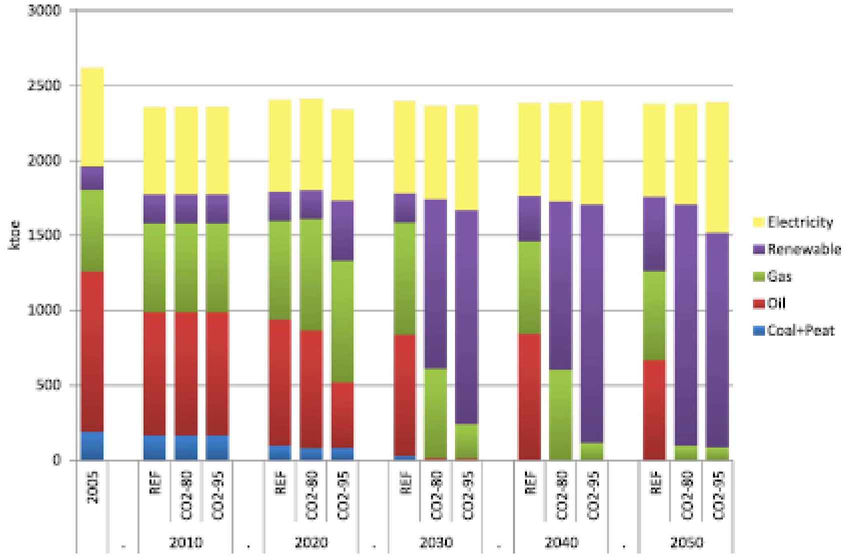

Fig. 10. Industry energy demand in *REF*, *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

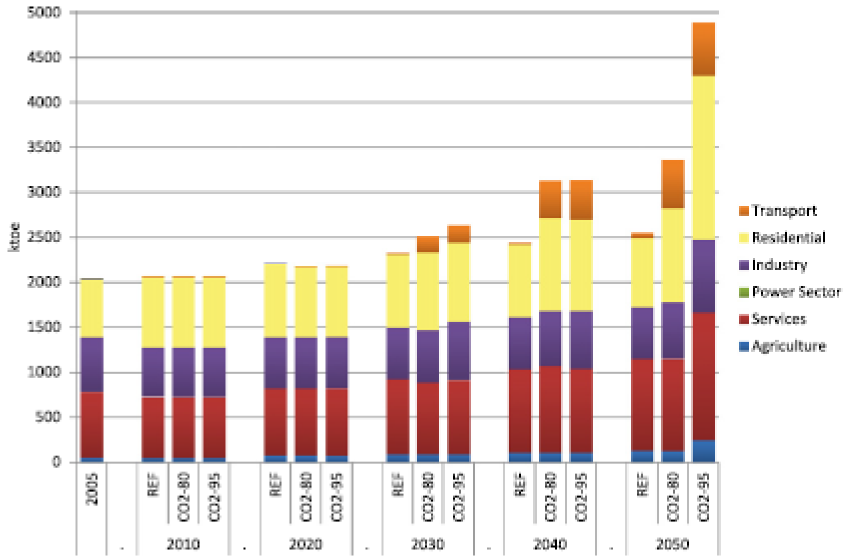

Fig. 11. Electricity consumption by sector in *REF*, *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

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. of. This complete decarbonisation can be achieved only displacing Gas CCS (as shown previously in Fig. 12) with additional renewable generation. Because of the 70% constraint on intermittent generation (Section 2.4) biomass and biogas are the selected options.

3.1.2.6. 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

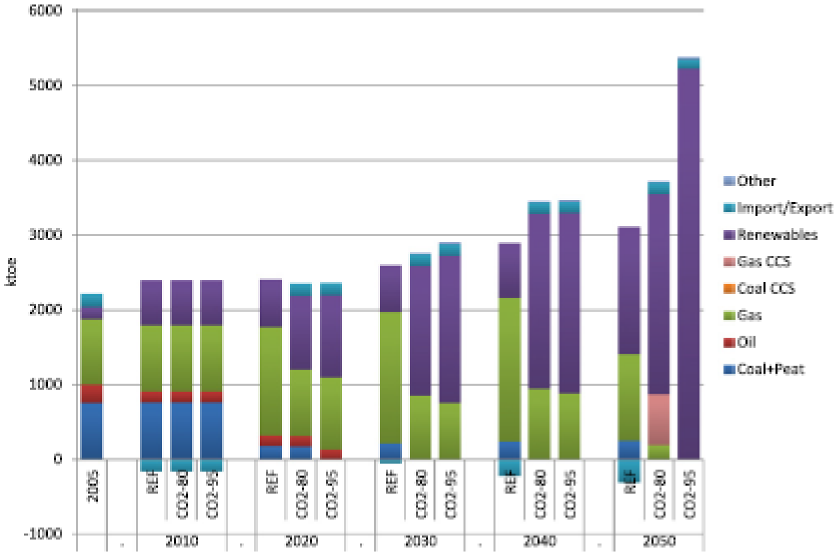

Fig. 12. Electricity generation by plant in *REF*, *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

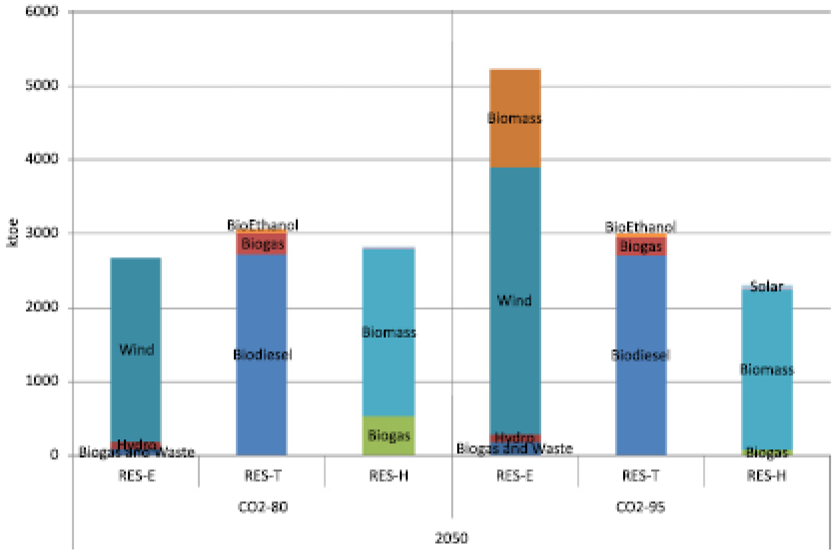

Fig. 13. Renewables consumption by mode in *CO2-80* and *CO2-95* (ktoe).
Source: Irish TIMES model.

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 Figs. 14 and 15.

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).

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.

3.2. *The role of short term mitigation policies*

Fig. 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 Fig. 16 that after few periods beyond 2020, the *NETS-20/CO2-80* scenario pathways aligns to that of the *CO2-80* scenario.

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 Fig. 17) and the associated reduction in final energy consumption by improvements in the energy efficiency (Fig. 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.

3.3. *Economic impacts of mitigation*

3.3.1. *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 contributes to GDP growth.

Table 8 summarises the marginal CO_2 abatement costs for the four mitigation scenario clusters presented in this section. Two

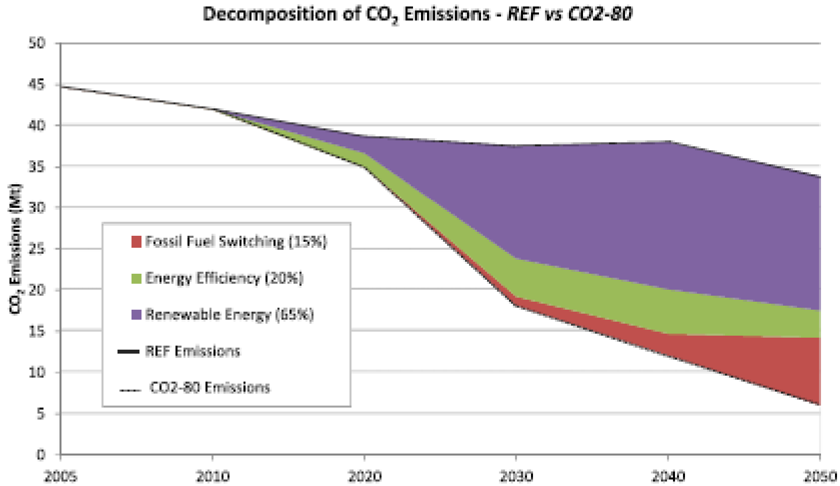

Fig. 14. Decomposition analysis of CO_2 emissions between *REF* and *CO2-80* scenarios.
Source: Irish TIMES model.

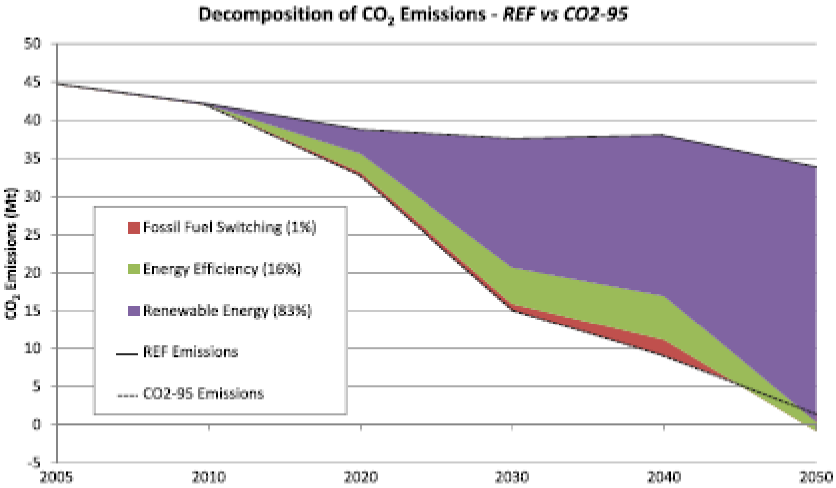

Fig. 15. Decomposition analysis of CO_2 emissions between *REF* and *CO2-95* scenarios.
Source: Irish TIMES model.

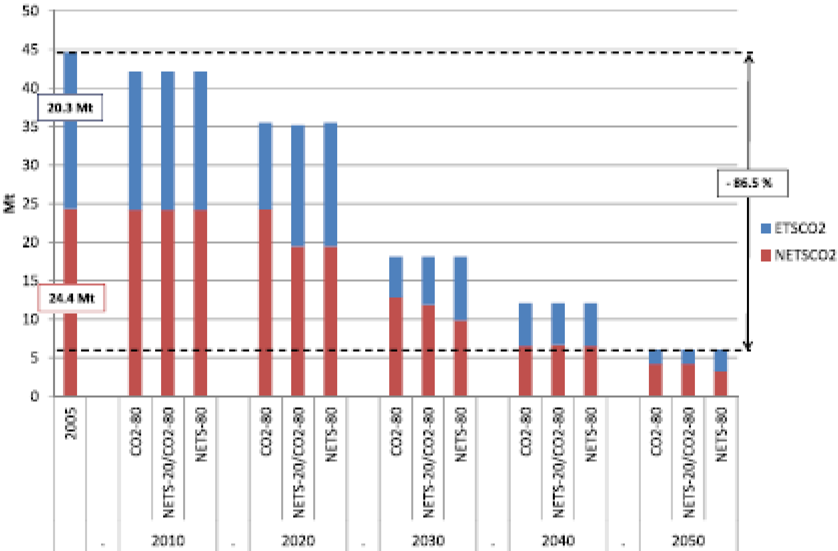

Fig. 16. ETS and Non-ETS CO_2 emissions trajectories in *CO2-80, NETS-20/CO2-80* and *NETS-80* (ktoe).
Source: Irish TIMES model.

additional intermediate scenarios with different emissions reduction target (−85% and −90%) are also included as sensitivity.

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: first 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. Second 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

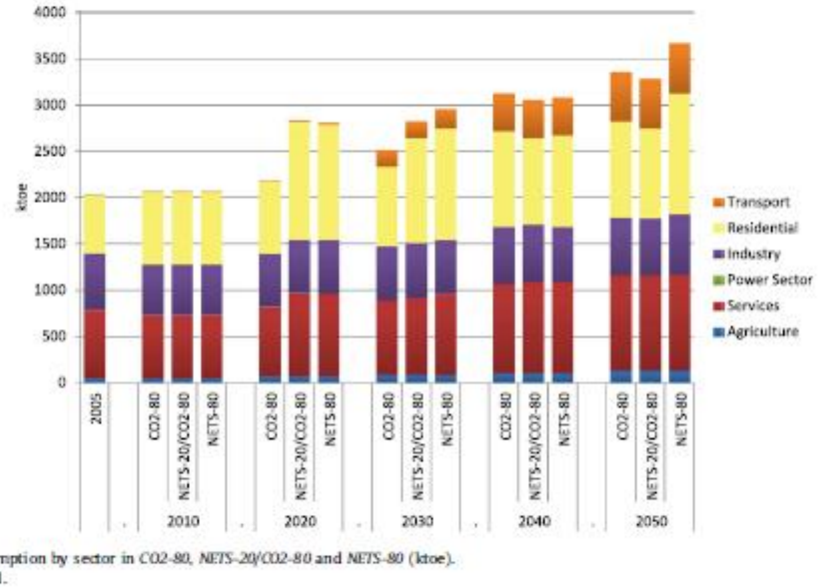

Fig. 17. Electricity consumption by sector in *CO2-80*, *NETS-20/CO2-80* and *NETS-80* (ktoe).
Source: Irish TIMES model.

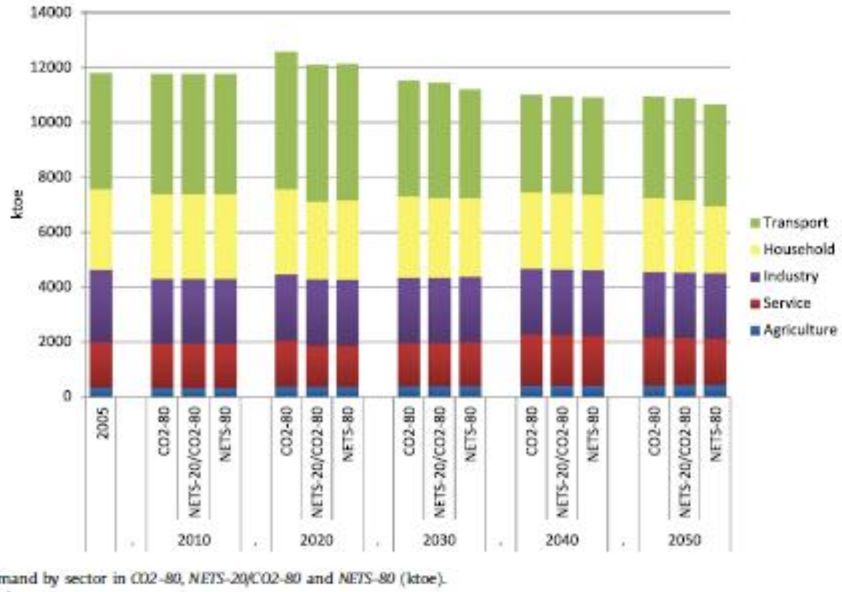

Fig. 18. Final energy demand by sector in *CO2-80*, *NETS-20/CO2-80* and *NETS-80* (ktoe).
Source: Irish TIMES model.

(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, 2006; SECURE, 2009) indicate for similar policy assumptions (Johannesburg Agreement scenario

Table 8
CO_2 shadow prices.
Source: Irish TIMES model.

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

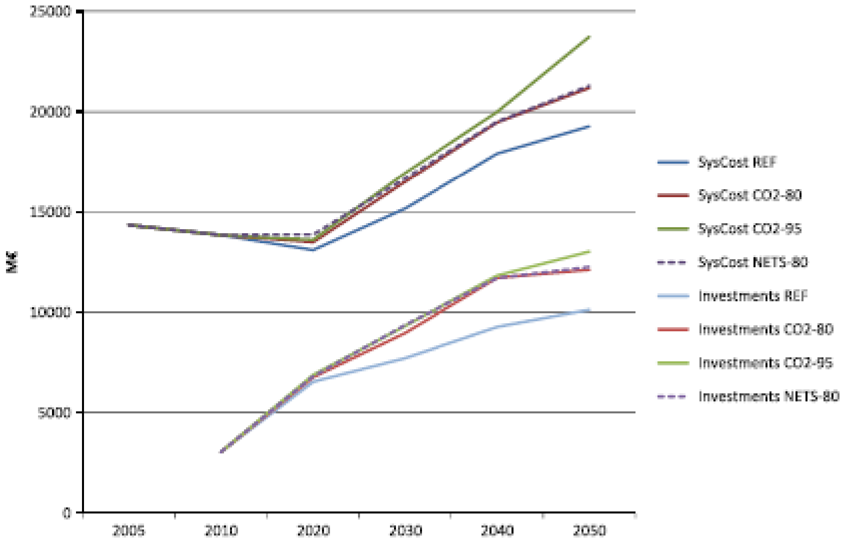

Fig. 19. Comparing total system costs with investments.
Source: Irish TIMES model.

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)[8] for the year 2050.

3.3.2. *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 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 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.

Fig. 19 focuses on the total energy system costs and its investment portion[9] 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 2020–2050). 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*.

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. Fig. 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,[10] 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[11] 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.

[8] 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).
[9] These represent undiscounted costs by period.
[10] In the base year (2005) no investments are allowed.
[11] It does not correspond to the full macroeconomic cost of mitigation.

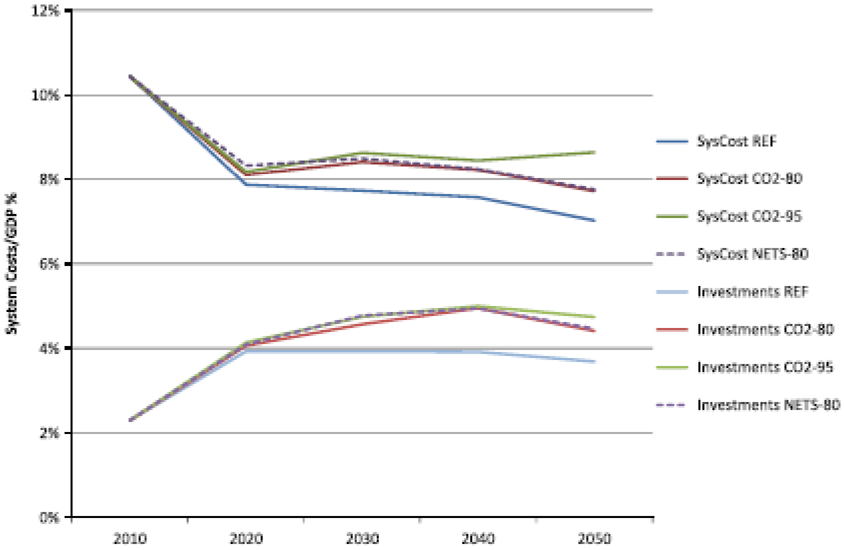

Fig. 20. Comparing system costs with GDP.
Source: Irish TIMES model.

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 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.

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Irish TIMES Energy Systems Model

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Executive Summary

Ireland faces very challenging short-term targets in the period to 2020 arising from EU obligations that are specified in EU Directives and Decisions. In addition to these short-term targets, the EU has committed to a long-term greenhouse gas (GHG) emissions reduction of 80–95% below 1990 levels by 2050, and will require Member States to participate in effort-sharing to deliver deep emissions cuts. Policy-makers require comprehensive, robust, knowledge-based information to inform their decisions on how to meet these targets in a manner that will most benefit the Irish economy.

This project draws on and contributes to the wealth of international energy-systems modelling research activity. It involved building, developing, calibrating, testing and running a (partial equilibrium) energy-systems optimisation model for Ireland – the Irish TIMES model. The model was developed by University College Cork in collaboration with the Economic and Social Research Institute, E4SMA and KanORS over the period March 2009–November 2011.

The real value of the Irish TIMES model is in the new insights it gives into some of the key challenges and decisions facing Ireland in energy and climate policy. The Irish TIMES model provides a means of assessing the implications of alternative future energy system pathways for: (i) the Irish economy (technology choices, prices, output, etc.), (ii) Ireland's energy mix and energy dependence, and (iii) the environment. It is used in this project to assess the implications of emerging technologies and of mobilising alternative policy choices, such as meeting renewable energy targets and carbon-mitigation strategies. The two key new perspectives this research project gives are: (i) a full energy-systems modelling approach and (ii) a focus on the medium term (to 2050) as well as the short term (to 2020).

The scenario results respond directly to a number of key policy questions that could not be readily addressed before this model was developed. These relate to Ireland's targets for: (i) renewable energy to 2020, (ii) GHG reduction to 2020 and (iii) long-term GHG emissions reduction to 2050. The results point to:

1 Alternative pathways for renewable energy to that currently being followed under Ireland's National Renewable Energy Action Plan (NREAP);

2 The need to urgently reassess Ireland's renewable energy policies in light of the non-ETS emissions reduction target;

3 A particular focus on renewable heat, renewable transport and electrification of heat, in contrast to the current dominant focus on wind-generated electricity;

4 The impacts of imposing a higher emissions reduction target on Ireland's energy system to compensate for limited mitigation options in agriculture;

5 The significant challenges in moving to a low-carbon economy in 2050 with renewable energy accounting for 65–85% of energy supply (compared with 6.5% in 2011);

6 Electrification of heat in particular but also of transport, resulting in the share of energy use delivered by electricity increasing from 18% currently to 31–47% of energy use in 2050.

1 Introduction

Ireland faces very challenging short-term targets in the period to 2020 arising from EU obligations that are specified in EU Directives and EU Decisions. These include improving Ireland's energy efficiency by 9% by 2016 and by 20% by 2020, increasing renewable energy deployment (from 6.5% in 2011) to 16% of gross final energy consumption (GFC) by 2020 and achieving at least a 10% renewable share of road and rail transport energy and (most challengingly) reducing GHG emissions in non-emissions trading sectors (non-ETS) by 20% relative to 2005 levels. It is important to note that energy-related GHG emissions account for more than half of non-ETS GHG emissions.

In addition to these short-term targets, the EU has committed to a long-term GHG emissions reduction of 80–95% below 1990 levels by 2050 and will require Member States to participate in effort-sharing to deliver deep emissions cuts.

Mitigation strategies for deep cuts in emissions require significant financial investment: therefore, the development of strategies based on poor information and analysis will be expensive and wasteful. Policy-makers need comprehensive, robust, knowledge-based information to inform their decisions on how to meet these targets in a manner that will most benefit the Irish economy. In particular, given Ireland's current economic difficulties, it is vital that modelling capacity is improved as a matter of urgency and that the information base that feeds into policy decisions is improved greatly. This research project – the development of the Irish TIMES Energy Systems Model – makes a considerable contribution to Ireland's need to expand its capability in energy modelling significantly.

The project involved building, developing, calibrating, testing and running a (partial equilibrium) energy-systems optimisation model for Ireland, called Irish TIMES. The Irish TIMES model forms part of the MARKAL/TIMES family of modelling tools currently being used in over 200 institutions in 69 countries. This project draws on and contributes to the wealth of international energy-systems modelling research activity through the International Energy Agency Energy Technology Systems Programme (IEA-ETSAP) Implementing Agreement. The model was developed by University College Cork (UCC), in collaboration with the Economic and Social Research Institute (ESRI), E4SMA and KanORS over the period March 2009–November 2011.

The Irish TIMES model provides a range of future energy system configurations for Ireland that vary according to a range of policy constraints for the period out to 2050, but in each case delivering projected energy service demand requirements optimised to least cost. It provides a means of testing energy policy choices and scenarios, and assessing the implications for: (i) the Irish economy (technology choices, prices, output, etc.), (ii) Ireland's energy mix and energy dependence, and (iii) the environment, focusing mainly on GHG emissions. It is used to both 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 scenarios developed respond directly to a number of key policy questions (that could not be readily addressed before this model was developed) relating to Ireland's targets for: (i) renewable energy to 2020, (ii) GHG reduction to 2020 and (iii) long-term GHG emissions reduction to 2050. It is important to note that TIMES focuses on the contribution that technology choices may make in future scenarios.

There are clear limitations that need to be borne in mind when interpreting the results – most notably, these results are not attempts to forecast the future. The scenarios are based on different policy assumptions, and the results from one scenario are best interpreted by comparing them with the results from other scenarios, rather than as absolute results. Regarding the absolute results, they clearly depend on the robustness of future projections of economic growth and fuel prices that drive the model. In addition, as the focus of this model is on technology choice, the representation of behavioural effects is currently represented in only a limited manner.

Despite the limitations, the real value of the Irish TIMES model is in the new insights it gives into some of the key challenges and decisions facing Ireland in terms of energy and climate policy. The two key new perspectives this research project provides are a full energy-systems modelling approach and a focus that can examine the medium term (to 2050) as well as the short term (to 2020).

2 Methodology

Irish TIMES is a partial equilibrium model of Ireland's energy system, built with TIMES, the techno-economic modelling tool developed by IEA-ETSAP.[1] TIMES (The Integrated MARKAL-EFOM System) is a linear programming model generator, which provides a technology-rich basis for estimating energy dynamics over a long-term, multiple-period time horizon. It is usually applied to the analysis of the entire energy sector of a country or a region, but may also be applied to study single sectors (e.g. the electricity sector) in detail. It maximises the total surplus, equivalent to minimising the total discounted energy system cost, over the entire time horizon while respecting environmental and many technical constraints. There is a considerable body of ongoing international research involving TIMES (and its predecessor MARKAL) models. The recent IEA-ETSAP report (IEA-ETSAP, 2011) covering the period 2008–2010 summarises over 350 publications (including 86 peer-reviewed papers).

Figure 2.1 shows in schematic form how a TIMES model operates. The core model contains a large database of energy supply-side and demand-side technologies (over 1350 in the case of Irish TIMES). 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 exogenous model inputs are shown in Fig. 2.1 entering from the left-hand side (energy supply) and right-hand side (energy service demands) of the model. On the supply side, these include indigenous energy resource availability, primary energy (mostly fuel) prices and available energy imports. On the demand side, separate energy service demand projections are inputted, derived from macro-economic projections of the economy to 2050.

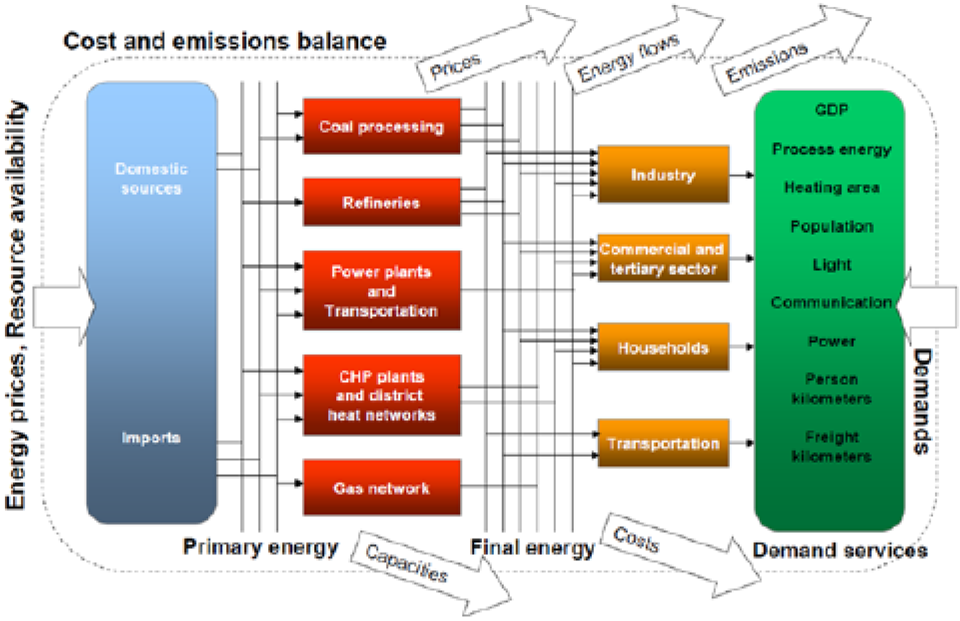

Figure 2.1. TIMES Model Schematic (Remme et al., 2001).

1 International Energy Agency Energy Technology Systems Analysis Programme (www.etsap.org).

The model is designed to determine the optimal energy system that meets the energy service demands over the entire time horizon at least cost, indicating the optimal mix of technologies and fuels at each period, the associated emissions, mining and import activities and the equilibrium level of the demand. The model outputs are shown on the top and bottom of Fig. 2.1, namely energy commodity prices (price of diesel versus biodiesel), energy flows (e.g. petajoules [PJ] of biomass by type), quantities of GHG and transboundary emissions (the current focus in Irish TIMES is on GHG emissions), capacities of technologies (e.g. installed megawatts [MW] of wind power) and energy costs (comprising capital costs, operation and maintenance [O&M] costs, fuel costs, etc.). Running the model in the absence of a policy constraint generates a set of results associated with a 'reference scenario'. This will not normally be completely aligned with national energy forecasts that are generated by simulating the anticipated future energy use, mainly because TIMES optimises the energy systems providing a least-cost solution. When a (single of many) policy constraint is then imposed on the model (e.g. minimum share of renewable energy, maximum amount of GHG emissions or minimum level of energy security), the model generates a different least-cost energy systems. When the results are compared with those from the reference scenario, the different technology choices that deliver the policy constraint at least cost can be identified.

The widest current applications of TIMES are related to the analysis of policies designed to reduce GHGs from energy and materials consumption. Since the framework depicts individual technologies, it is particularly useful for evaluating policies that promote the use of technologies of greater efficiency in energy or materials, or the development and use of new technologies. It provides a means of quantifying the economic cost associated with a range of climate mitigation strategies and the impacts of climate change policies on economic growth.

Originally extracted from the PET[36] model ([Pan European TIMES], which includes EU27, Iceland, Norway, Switzerland and Balkan countries) and then updated with local and more detailed data and assumptions, the Irish TIMES model represents the energy system of Ireland and its possible long-term evolution. The actual system encompasses 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 Fig. 2.2.

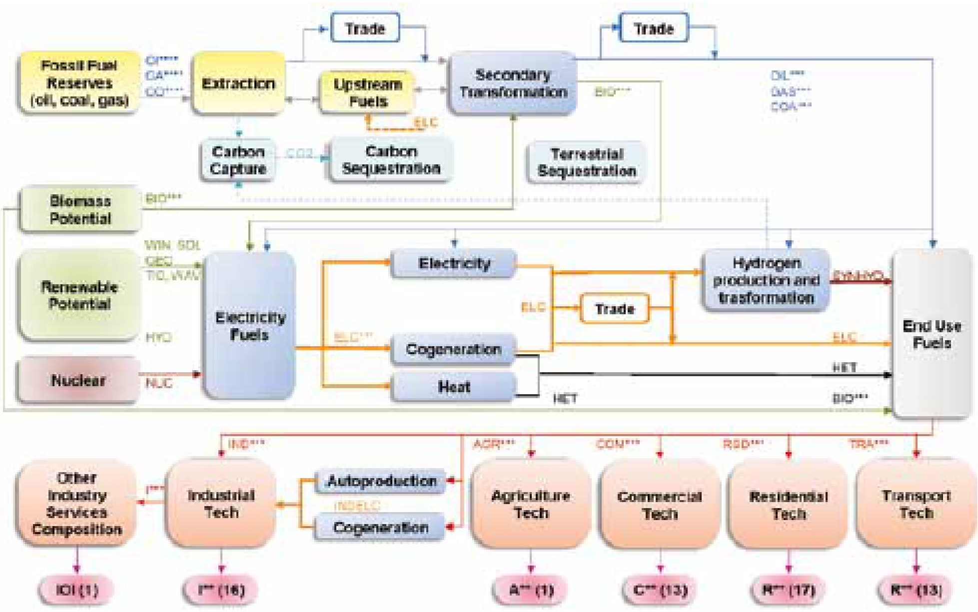

Figure 2.2. Irish TIMES Reference Energy System (Gargiulo et al., 2010).

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 combined heat and power [CHP]), and its demand sectors (residential, commercial, agricultural, transport, industrial).

As noted above, 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). The model is driven by exogenous demand specified by the list of each energy service demands (60 in the case of Irish TIMES), actual values in the base year (calibration) and values for all milestone years till 2050 (projection), along with environmental or other constraints (e.g. national and EU targets for Ireland). More details can be found in the full Irish TIMES report (available for download at: http://erc.epa.ie/safer/reports) and in Chiodi et al. (2012a).

2.1 Policy Scenario Definitions

Many types of policy scenarios can be explored using Irish TIMES, and generally developed by imposing constraints on the energy system – for instance, a minimum share of renewable energy or a maximum amount of CO_2 emissions. In addition to undertaking scenario analysis, Irish TIMES may also be used to assess and quantify the impacts of policy measures on future energy use, for example a carbon tax or a renewable energy feed in tariff. This section introduces the main scenarios used in this report, which are linked to Ireland's short-term and long-term targets relating to renewable energy and climate mitigation.

2.1.1 Reference Energy System Scenario

The Reference Energy System (REF) scenario provides a useful starting point for conducting different scenario analyses using the model. It represents the pathway for meeting Ireland's future energy service demands at least cost. The REF scenario is comparable with a baseline or reference energy forecast, although significantly here it represents a least-cost energy system and in that way differs from a simulated energy forecast.

2.1.2 REN-16 scenario

In the REN-16 scenario, the energy system is subject to 2020 renewable target specified by Directive 2009/28/EC (EU, 2009a), including also a minimum 10% renewable energy share of road and rail transport. The pathway comprises 6.6% minimum share of renewable energy by 2010 and 11.7% by 2015 in accordance with Ireland's National Renewable Energy Action Plan (NREAP) (Department of Communications, Energy and Natural Resources [DCENR], 2010). In contrast to the NREAP, however, this scenario does not impose additional constraints for end-use sectors, i.e. no further targets for RES-E, RES-T and RES-H.

2.1.3 NETS-CO2 scenario

In the NETS-CO2 scenario the energy system is subject to the 2020 emissions reduction targets specified by Directive 2009/29/EC (EU 2009b) and Effort Sharing Decision 2009/406/EC (EU, 2009c). Non-ETS energy-related emissions are hence subject to a 19.5 Mt $CO_{2,eq}$ target (-20% relative to 2005), while ETS are subject to a 16.0 Mt $CO_{2,eq}$ target (-21% relative to 2005 levels). By 2015 an interim target of 10% emissions reduction (relative to 2005) is also imposed in both sectors. This scenario makes no reference to targets for non-energy related GHG emissions, thereby implicitly assuming that they also reduce by 20% relative to 2005 levels.

2.1.4 NETS-GHG scenario

This scenario (similar to NETS-CO2) also assumes the national targets for ETS emissions under Directive 2009/29/EC and non-ETS emissions under Decision 2009/406/EC are met, but explores the effect on the energy system of additional GHG emissions reduction measures to compensate lower reduction levels in agricultural non-energy emissions, based on exogenous projections. Agriculture GHG projections are based on EPA projections (EPA, 2011), which assume that total emissions arising from non-energy agriculture will decrease by 4.4% over the period 2005–2020 to 17.8 Mt of $CO_{2,eq}$. In order to meet Decision 2009/406/EC non-ETS energy-related emissions are hence subject to a 31.5% emissions reduction target (16.7 Mt $CO_{2,eq}$) relative to 2005 levels by 2020, while ETS sectors are subject to a 21% emissions reduction target relative to 2005 (resulting in an overall energy-related CO_2 reduction -26.7%). By 2015 an interim of 10% emissions reduction is also imposed.

2.1.5 CO2-20 scenario

This scenario imposes an overall reduction target of 20.5% on energy-related CO_2 emissions by 2020 relative to 2005 levels rather than a separate 21% ETS target and 20% non-ETS target. It is worth nothing that the CO2-20 scenario is not aligned with national or European legislation, but has been presented here to quantify the impact of not having separate ETS or non-ETS targets.

2.1.6 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) in the CO2-80 scenario. The pathway includes specific interim targets in line with the EU Low Carbon Roadmap (EC, 2011), 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 (notably agriculture) are reducing on a similar pathway to energy-related emissions.

2.1.7 CO2-95 scenario

In the CO2-95 scenario, an 80% GHG emissions reduction target would apply to the whole economy. This scenario assumes that the energy system will need to achieve deeper emissions cuts to compensate for agriculture not achieving an 80% reduction. According to the EU Low Carbon Roadmap (EC, 2011), GHG emissions in agriculture are capable of reducing by up to 49% by 2050. This scenario assumes a 50% emissions reduction in agriculture is achievable in Ireland and imposes a 95% emissions reduction target below 1990 levels by 2050 on the energy system to ensure the overall 80% target is achieved.

2.1.8 NETS-80 scenario

The NETS-80 scenario imposes an 80% emissions reduction target on energy-related CO_2 emissions by 2050 (similar to the CO2-80 scenario) but in this case assumes that the target will be imposed separately on ETS and non-ETS sectors, i.e. emulating that current EU climate policies, as specified by Directive 2009/29/EC and Decision 2009/406/EC, will be extended beyond 2020. This scenario assumes that energy-related emissions will reduce to 20% of 1990 emissions by 2050 in ETS and separately in non-ETS sectors. Reductions of 40% and 60% below 1990 levels are set for ETS and non-ETS sectors by 2030 and 2040. Non-energy emissions are implicitly assumed to reduce at similar rates to energy-related emissions.

3 Renewable Energy Targets for 2020

This section focuses on scenario results that address the following questions:

- How can Ireland meet its renewable energy targets for the year 2020 as stipulated in EU Directive 2009/28/EC (EU, 2009a) at least cost?
- Is current renewable energy policy aligned with the least-cost results delivered by Irish TIMES?

3.1 How can Ireland meet its Renewable Energy Targets for the Year 2020 at Least Cost?

The scenario results shown in Fig. 3.1 compares the contribution from renewable energy (by mode of energy use) to Ireland's GFC in the REF scenario (i.e. without the mandated 16% target applied) and the REN-16 scenario (i.e. applying the 16% renewable energy target to be achieved by 2020). Also shown in Fig. 3.1 for comparison are Ireland's NREAP targets for each mode (i.e. transport, heat and electricity). The results in Fig. 3.1 suggest an alternative approach to meeting Ireland's renewable energy target to that contained in Ireland's NREAP.

In the NREAP the modal targets are to achieve 10% RES-T (renewable energy representing 10% of road and rail transport energy), 12% RES-H (renewable energy representing a 12% share of thermal energy for heating and cooling) and 42.5% RES-E (i.e. renewable energy representing a 42.5% share of gross electricity consumption, or GEC) by 2020. As indicated in Fig. 3.1, the effect of these modal targets in terms of overall energy use is that RES-E represents 8.5%, RES-H 4.2% and RES-T 3.4% of GFC in 2020. The least-cost solution (REN-16) points to an increased contribution from renewable heat representing 6.9% of GFC, which is equivalent to 18% RES-H compared with the current 12% RES-H target in the NREAP. The results from REN-16 also indicate a lower contribution from renewable electricity (34% RES-E compared with 42.5% in the NREAP). This is an interesting finding that warrants further investigation. In addition, the results from REN-16 suggest a lower contribution from renewable transport (3.1% of GFC compared with 3.4% in the NREAP). It is worth noting however that renewable generated electricity is included in RES-E in Fig. 3.1 even if that electricity is employed

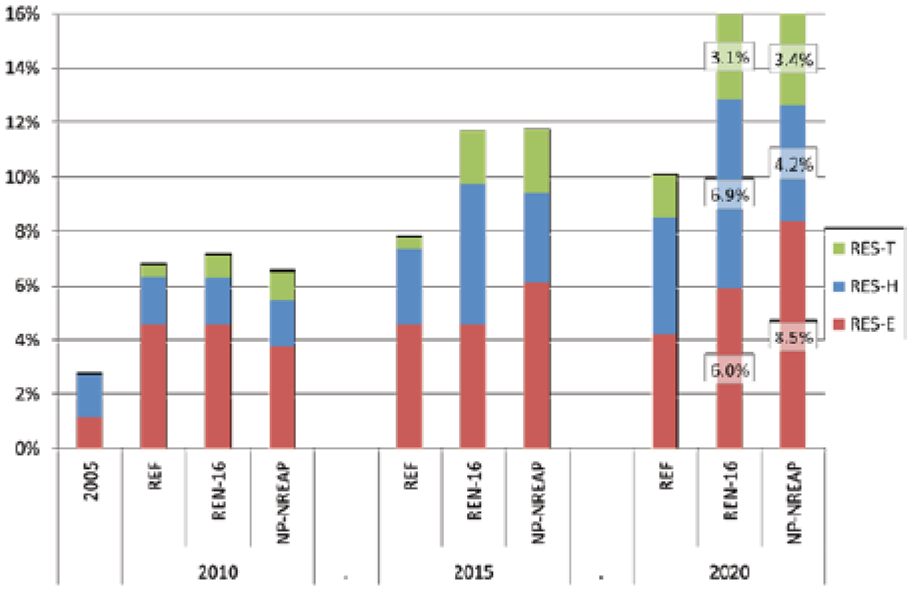

Figure 3.1. Comparing *REF* and *REN-16* renewable shares with the National Renewable Energy Action Plan (NREAP).

to power electric vehicles (EVs). Moreover, because of the different mix of transport renewable energy in REN-16, this 3.1% renewable energy contribution to GFC is equivalent to 13% RES-T, compared with 10% RES-T in the NREAP. This is because when the share of renewable energy to transport energy (RES-T) is calculated, certain renewable sources are weighted more than others.[2] However, this does not apply when calculating the contribution of renewable sources to overall energy use

3.2 Is Current Renewable Energy Policy Aligned with a Least-cost Pathway?

In terms of informing policy choices, analysis of Fig. 3.1 should not lead to the conclusion that Ireland's target for renewable electricity should be reduced and its target for renewable heat increased. There is significant impetus behind – and progress towards – increasing the amount of renewable-electricity generation, which has grown from 5% in 2000 to 18% in 2011 (Howley et al., 2012). It is sensible to continue on this path in the context of longer-term aspirations beyond 2020. What Fig. 3.1 does suggest is that the role that renewable heat can potentially take in Ireland should be re-examined. It also suggests that renewable energy policy in Ireland should be amended. The current policy focuses mainly on achieving the renewable electricity target. There is much less focus on renewable transport, and currently no adequate policy mechanisms for promoting renewable heat. These issues need to be addressed as a matter of urgency.

The Irish TIMES REN-16 results also indicate different technology choices compared with those underpinning the NREAP. The REN-16 results do not include EVs or ocean energy (which are included in NREAP) and do include biogas for transport and heating. The differences are most notable in RES-T, as shown in Fig. 3.2. REN-16 results point to half of biofuels in transport coming from biogas, while the NREAP points to biodiesel and bioethanol. This suggests that the potential for biogas as a transport fuel be re-examined. The results from this least-cost approach concur with other research that focuses on other benefits of biogas as a transport fuel (Smyth et al., 2010; Thamsiriroj and Murphy, 2011; Thamsiriroj et al., 2011). Fig. 3.3 presents the results for RES-H, again comparing the REN-16 results with the

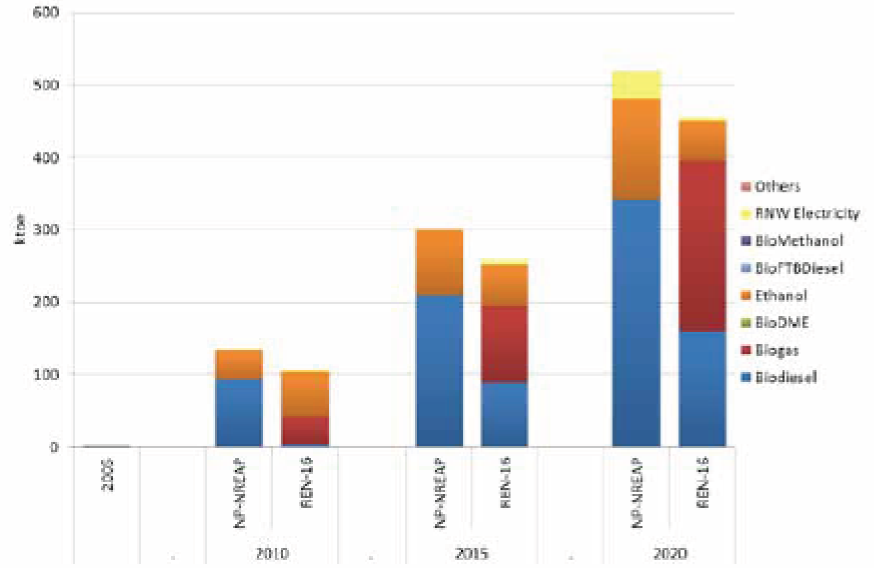

Figure 3.2. Renewable energy consumption for transport sector (ktoe).

2 This is in accordance with EU Directive 2009/28/EC (EU, 2009a). Second-generation biofuels and biofuels generated from waste are allocated a weighting factor of 2. Renewable-generated electricity powering electric vehicles are allocated a weighting of 2.5.

renewable heat pathway stipulated in Ireland's NREAP. The higher volumes of renewable thermal energy in REN-16 are striking, and the different technology choices also noticeable. In particular, REN-16 does not include geothermal or solar thermal energy and chooses solid biomass and biogas as the preferred sources. Further details on the renewable energy scenarios are available in Ó Gallachóir et al. (2012).

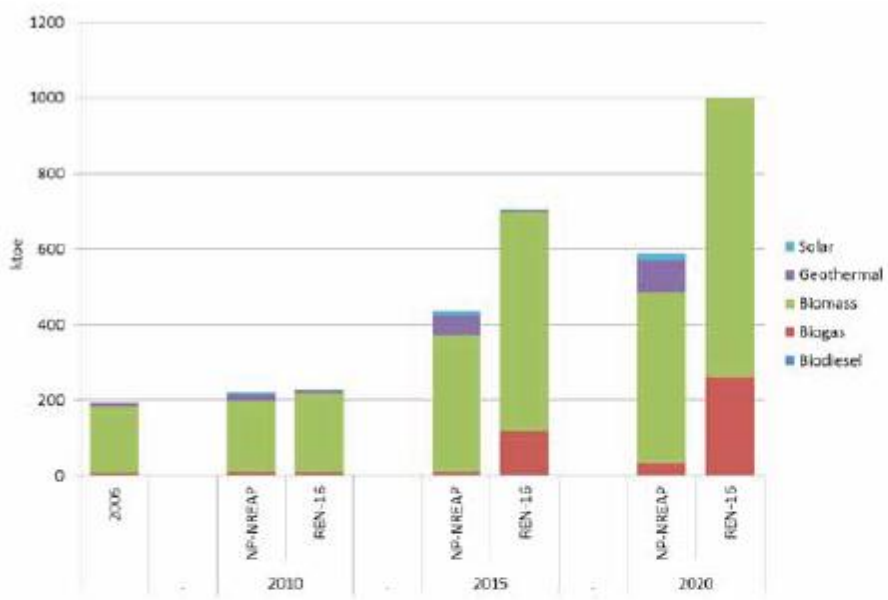

Figure 3.3. Renewable thermal energy consumption (ktoe).

4 Greenhouse Gas Emissions Reduction Targets for 2020

This section focuses on scenario results that address the following questions:

- What are the implications of Ireland's target for greenhouse gas (GHG) emissions reductions, particularly in non-ETS sectors as stipulated in EU Decision 406/2009 (EU, 2009c) for Ireland's energy system?
- If agriculture-related GHG emissions to 2020 are in line with the Ireland's Food Harvest 2020 policy,[3] can Ireland's energy system achieve deeper emissions reductions to compensate for growth in agriculture, and at what cost?

Two scenarios (NETS-CO2 and NETS-GHG) are built in Irish TIMES to inform decisions regarding Ireland's target to reduce non-ETS GHG emissions by 20% below 2005 levels by 2020 as stipulated in EU Decision 406/2009. The NETS-CO2 scenario imposes a 20% constraint on the energy system only. This implicitly assumes that the other non-ETS sectors of the economy (notably agriculture) can also deliver a 20% GHG emissions reduction target by 2020. The NETS-GHG scenario assumes that agriculture-related GHG emissions follow a trend aligned to the Food Harvest 2020 policy. In this case, the non-ETS emissions reduction target for the energy system is increased to 31.5% to compensate for a lower than 20% reduction achieved by agriculture. The purpose of these scenarios is to inform decisions regarding the different sectoral contributions to meeting Ireland's overall non-ETS sector target. Further details are available in Chiodi et al. (2012b).

4.1 Implications of Ireland's 2020 Target for Greenhouse Gas Emissions Reductions for Ireland's Energy System

Figure 4.1 shows Ireland's energy-related non-ETS emissions from 2005 to 2020, comparing the REF scenario results with the NETS-CO2. In particular, Fig. 4.1 indicates which sectors contribute most

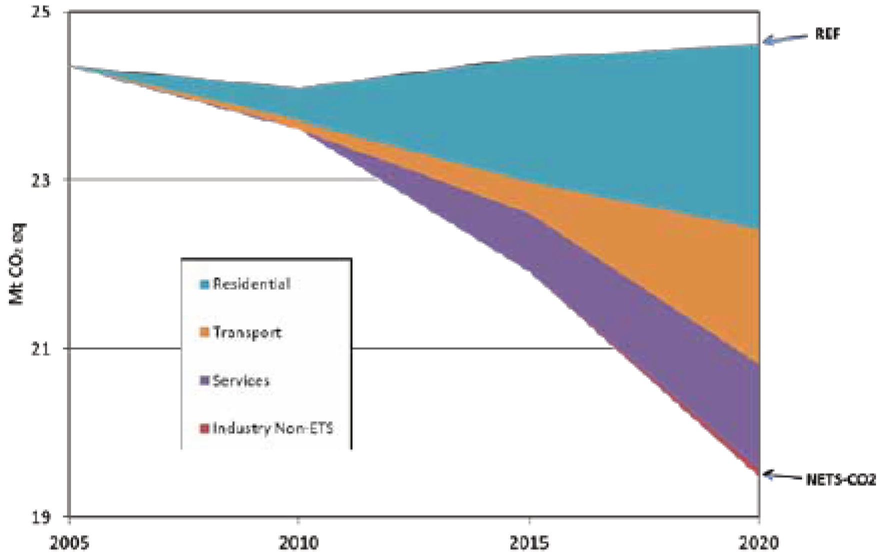

Figure 4.1. Comparing non-ETS CO_2 emissions in REF and NETS-CO2 (Mt).

3 Food Harvest 2020 (DAFF, 2010) envisages significant growth in agri-food output in Ireland to 2020 (including notably a 50% increase in milk production and a 40% increase in food and beverages added value).

to non-ETS emissions reduction. It is important to note that the REF scenario represents a least-cost energy system pathway and hence already includes cost-effective energy-efficiency improvements and renewable energy deployment. The REF scenario also incorporates the effects of the 2008 and 2011 Building Regulations (DEHLG, 2008 and DEHLG, 2011), which means that new buildings in the model have a significantly improved energy performance compared with existing buildings (Dineen and Ó Gallachóir, 2011). In this NETS-CO2 scenario, the results suggest that significant non-ETS emissions reductions may be achieved within the residential (accounting for 42.1% of the emissions reduction compared with REF), transport (accounting for 31.3% of the emissions reduction) and services (24.4% of the emissions reduction) sectors.

The emissions reductions in the NETS-CO2 scenario are achieved through increased energy efficiency and as a result of two key fuel-switching pathways: (i) increasing the amount of biofuels used in transport significantly and (ii) the electrification of heating in buildings. In the case of the latter, electrification of heating shifts CO_2 emissions from the non-ETS sectors (heating in the residential and services sectors) to the ETS sectors (i.e. electricity generation). While electrification of transport (i.e. introducing EVs) delivers a similar result, this technology does not feature significantly in the results because of the current and future anticipated costs of EVs (in particular, the battery costs).

These results again underline the need to reassess Ireland's renewable energy policies in the light of the non-ETS emissions reduction target. The results point to a focus on renewable heat, renewable transport and electrification of heat, in contrast to the current dominant emphasis on wind-generated electricity. In order to meet Ireland's targets for renewable heat and to achieve further emissions reductions it will be necessary to develop effective policy measures for fuel-switching. Two previous schemes have encouraged fuel-switching to renewable heating, namely the Greener Homes scheme in the residential sector[4] and the ReHeat scheme in the commercial, industrial, services and public sectors.[5] However, these schemes ended in 2011.

4.2 Impacts of Agriculture-related Greenhouse Gas Emissions to 2020 on Ireland's Energy System

Figure 4.2 also graphs Ireland's energy-related non-ETS emissions from 2005 to 2020, but in this case comparing the NETS-CO2 with the NETS-GHG results. It captures the effect of the additional burden placed on the energy system to compensate for agriculture. In NETS-CO2, a 20% non-ETS emissions reduction target is imposed on the energy system, whereas in NETS-GHG the energy system faces a 31.5% non-ETS emissions reduction target, due to agriculture not achieving a 20% reduction.

The NETS-GHG scenario points to further use of biofuels for transport, compared with NETS-CO2 (resulting in 21% RES-T) and further electrification of heat in buildings. Figure 4.3 provides an interesting comparison between the renewable energy pathway envisaged in Ireland's NREAP with that arising from the NETS-GHG scenario.

It is important to note that the NREAP is designed to meet Ireland's target under the EU Renewable Energy Directive 2009/28/EC (EU, 2009a) rather than Ireland's target for non-ETS emissions under Decision 406/2009 (EU, 2009c). The renewable energy arising from the NETS-GHG scenario accounts for 18.5% of overall energy use, hence exceeding the EU Renewable Energy Directive target for Ireland of 16%. The scenario results also suggest that the current policy focus will likely result in failure to meet the non-ETS target.

4 See http://www.seai.ie/Grants/GreenerHomes/Scheme_Statistics/ for more details.

5 See http://www.seai.ie/Grants/Renewable_Heat_Deployment_Programme/ for more details.

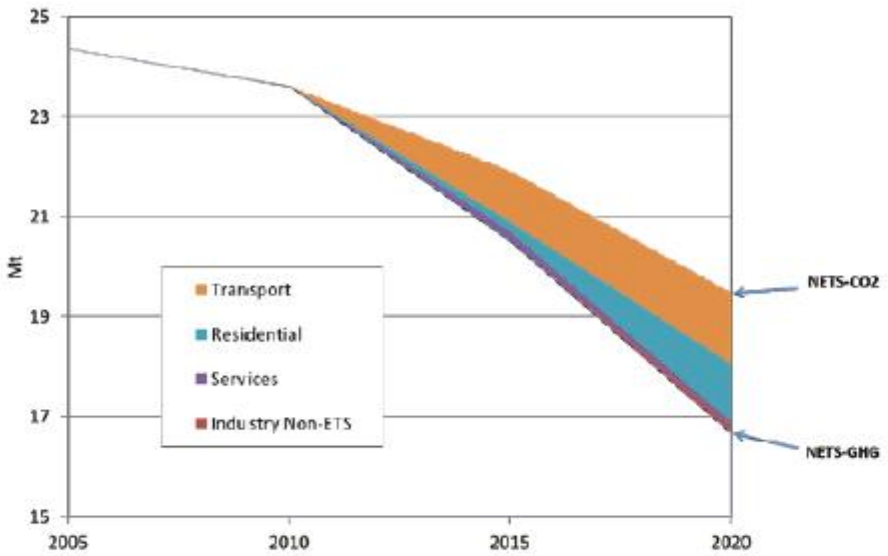

Figure 4.2. Comparing non-ETS CO_2 emissions in NETS-CO2 and NETS-GHG (Mt).

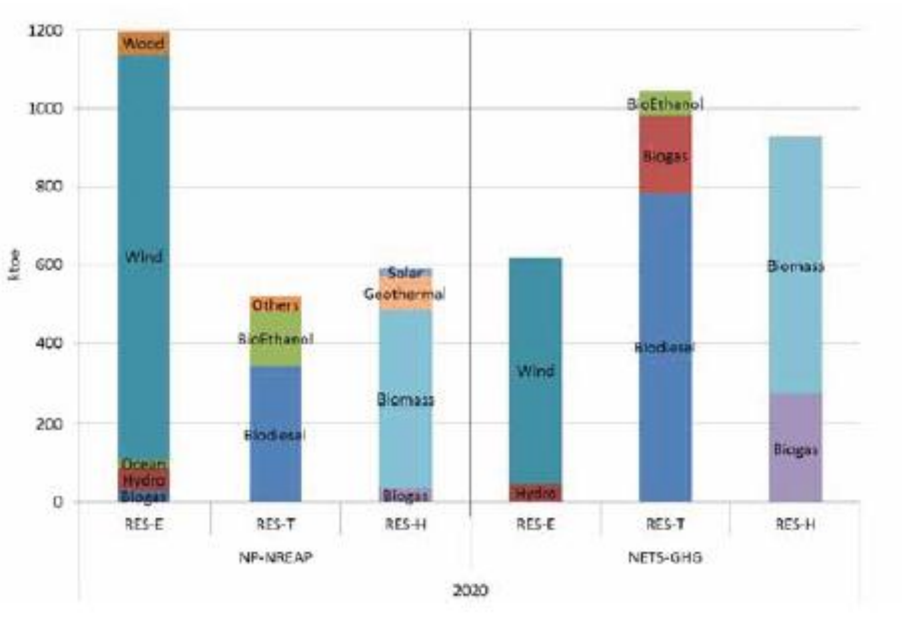

Figure 4.3. Comparing renewable energy in the National Renewable Energy Action Plan (NREAP) and NETS-GHG (ktoe).

Other interesting facets of Fig. 4.3 relate to the different technology choices. The NETS-GHG scenario understandably points to greater contributions from renewable heat and renewable transport technologies as these are the non-ETS sectors. The contribution from renewable electricity in the NREAP is double that shown in the NETS-GHG scenario. Given the fact that wind-generated electricity does not contribute directly to the non-ETS target, this again is understandable. As mentioned earlier, the key message from these results is not that the momentum in wind-energy deployment is arrested, but that the resolve to increase renewable transport and renewable heat energy is augmented, if Ireland intends meeting the non-ETS target. It is also worth recalling that, in the NETS-GHG scenario, the energy system emissions reduction is 31.5% compared with 2005 levels, compensating for agriculture emissions growing in line with the Food Harvest 2020 policy.

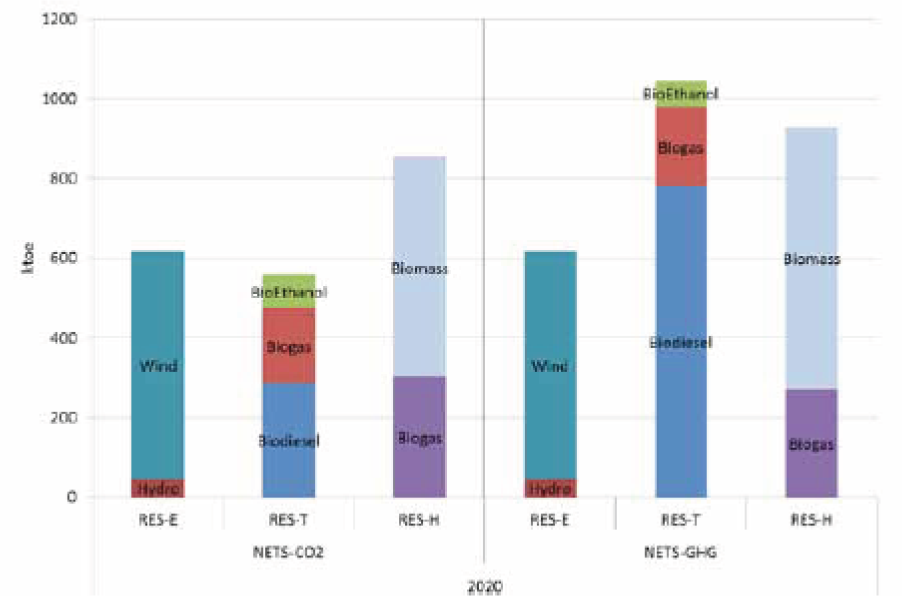

Figure 4.4. Renewables consumption by mode in NETS-CO2 and NETS-GHG (ktoe).

Figure 4.4 captures the explicit impact of this in terms of renewable energy, by comparing the renewable energy results for NETS-CO2 and NETS-GHG. In NETS-CO2, the amount of biofuels required is similar to the NREAP (if compared with the left-hand side of Fig. 4.3), although the mix is quite different because of the penetration of biogas as a transport fuel in NETS-CO2. Moving from NETS-CO2 to NETS-GHG requires almost a doubling of biofuels, which is necessary to compensate for agriculture not meeting a 20% emissions reduction target.

This raises a further interesting policy issue – if more biofuels are used to enable the agriculture sector to generate GHG emissions in line with Food Harvest 2020, separate to the issue of costs, to what extent will this result in land-use competition issues that may in turn impact on Food Harvest 2020?

There is a significant challenge in quantifying the costs of climate-mitigation policies, in determining how these costs should be allocated and in developing an effective mechanism to ensure that the costs are then allocated as they should be. To date, the Irish TIMES project has focused on shedding light on two aspects that do not purport to meet this challenge but do provide some useful inputs to discussions and analysis. The CO_2 marginal abatement costs can be extracted readily from the model results, that is, the cost of delivering the last (marginal) tonne of abatement in a particular scenario. The second metric developed is a crude measure of the cost of mitigation as a proportion of GDP in a particular time period. This is estimated by calculating the difference in total energy system costs between a mitigation scenario and the REF scenario in each time period and by then dividing this by the cumulative GDP generated in that period.

Table 4.1 shows the marginal cost of CO_2 abatement in 2015 and in 2020 for three scenarios. Focusing on the 2020 results, the marginal cost of meeting non-ETS target increases from $€_{2000}158/tCO_2$ to $€_{2000}213/tCO_2$ moving from a 20% non-ETS CO_2 emissions reduction to a 20% non-ETS GHG emissions reduction. This increase quantifies the effect of the energy system facing a 20% target compared with a 31.5% target (compensating for a lower emissions reduction in agriculture). One way to interpret these numbers is to consider no policy measures other than a carbon tax being applied. In this scenario, the marginal cost is equivalent to the level of tax that would need to be applied to meet the scenario target. For comparison in terms of the scale these costs represent, the current level of carbon tax in Ireland is €20/tCO_2. This suggests that it will be very expensive to meet the non-ETS mitigation target for 2020.

Table 4.1. CO_2 shadow prices in 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

A third scenario – the CO2-20 scenario – is also shown in Table 4.1. This imposes an overall reduction target of 20.5% on energy-related CO_2 emissions by 2020 relative to 2005 levels rather than a separate 21% ETS target and 20% non-ETS target. It is worth nothing that the CO2-20 scenario is not aligned with national or European legislation, but has been presented here to quantify the impact of not having separate ETS or non-ETS targets. The CO2-20 emulates the approach adopted by the European Commission (EC) at EU level to determine the EU ETS and non-ETS targets (EC, 2008). Firstly, the least-cost pathway for meeting the overall EU 2020 20% GHG emissions reduction targets (relative to 1990 levels) was established, pointing to a 21% emissions reduction target for ETS sectors and a 10% reduction target for non-ETS sectors (in both cases relative to 2005 levels). Initial individual Member State non-ETS emissions reductions targets were then determined using a least-cost optimisation approach. In the results of this 'cost efficient policy case' Ireland's non-ETS GHG emissions reduction were 17% below 2005 levels (Table 4 of SEC(2008) 85 Vol. II). The EU analysis indicated that the cost-efficient policy case can be achieved at a marginal abatement cost of €40–€50/tCO_2. The ability of individual Member States to invest in mitigation was then 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 Irish TIMES results in Table 4.1 raise a number of questions regarding the analysis that underpinned Ireland's obligations under 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 ($€_{2000}$158/tCO_2), which suggests the target set for Ireland is far from cost optimal. 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 target emissions reduction on the energy system), the marginal abatement cost increases further to $€_{2000}$213/tCO_2. This abatement cost is more than four times higher than the marginal abatement cost of €40–€50/tCO_2 deemed sufficient for Ireland to achieve a 17% non-ETS GHG emissions reduction in the analysis carried out (EC, 2008) to inform the Effort Sharing Decision 2009/406/EC. The CO2-20 scenario however points to a marginal abatement cost of $€_{2000}$46/t CO_2, which aligns much more closely with the EU analysis figures. Figure 4.5 illustrates the implications of this in terms of Ireland's non-ETS emissions reduction target. The energy-related CO_2 emission trajectories for the NETS-CO2 scenario and the CO2-20 scenarios to 2020 are compared in Fig. 4.5 (along with the REF scenario results). Focusing on the non-ETS emissions reduction only, Fig. 4.5 suggests that a return to 2005 levels by 2020 in non-ETS emissions would have been significantly more cost optimal than the 20% emissions reduction target allocated to Ireland. It is worth noting here that these scenarios focus on the energy system only and hence implicitly assume that agriculture can meet an equivalent emissions reduction target. A 0.3% reduction in emissions relative to 2005 levels by 2020 for agriculture is however consistent with the analysis underpinning the emissions associated with the Food Harvest 2020 policy.

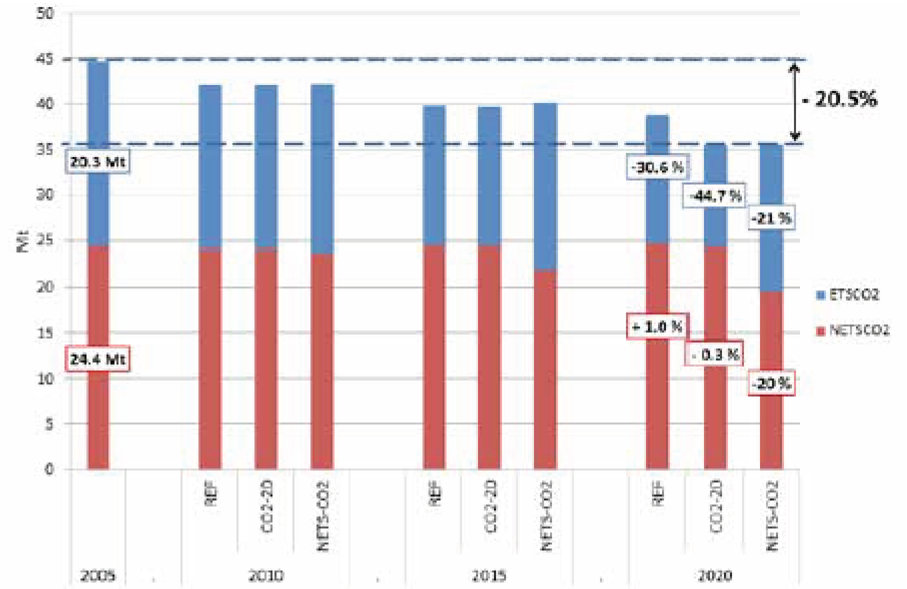

Figure 4.5. ETS and non-ETS CO_2 emissions trajectories in REF, CO2-20 and NETS-CO2 (Mt).

Table 4.2 provides a simple metric to indicate the impacts of the energy system and of mitigation policies on Ireland's economy, comparing the total system costs (including investment costs, operation and maintenance costs, fuel costs, transmission and distribution costs, delivery costs, etc.) with economic activity (GDP) for the scenarios generated. The first row in Table 4.2 estimates that Ireland's energy system costs will be reduced over the time horizon to 2020 from over 10% of GDP to less than 8%. Focusing on the last column in Table 4.2, the results suggest that the mitigation costs associated with the most ambitious scenario (NETS-GHG) will represent 0.7% of GDP in 2020. A key caveat to these results is the assumption in this model that energy service demands in the REF scenario are maintained as constant in the mitigation scenarios. This means the increased energy costs associated with mitigation do not have a direct impact on GDP, which is assumed to be the same across all scenarios.

Table 4.2. Energy system costs (GDP) – the cost of mitigation.

		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

5 Greenhouse Gas Emissions Reduction Targets for 2050

This section focuses on scenario results that address the following questions:

- Can Ireland's energy system deliver our Irish energy service demands to 2050 and also achieve an 80% reduction in energy-related GHG emissions relative to 1990 levels?
- If the agriculture sector does not achieve an 80% GHG emissions reduction by 2050, what are the implications for the energy system?
- What are the cost implications of deep decarbonisation and of the energy system compensating for agriculture achieving lower emissions reductions?

During this project, UCC developed the first detailed energy and energy-related CO_2 emissions scenarios for Ireland, based on new macro-economic projections for Ireland to 2050 that were generated by the ESRI.

Ireland does not have a specific target for GHG emissions reduction beyond 2020. The Climate Change Response Bill 2010 (DEHLG, 2010) proposed the target of 80% emissions reduction by 2050 relative to 1990 levels. The EU has committed to achieving emissions reduction in the range of 80–95% below 1990 levels by 2050. The scenarios here were developed in order to inform the discussions regarding Ireland moving towards a low-carbon economy by 2050 and are illustrated in Fig. 5.1. In the CO2-80 scenario, an 80% emissions reduction target is applied to the energy system only. Further scenarios were developed to compensate for agriculture not meeting an 80% emissions reduction target. In the absence of agriculture emissions projections for Ireland beyond 2020, initially a projection was developed based on assuming that agriculture GHG emission levels in 2050 were the same as 2020 levels. Based on this assumption, the energy system would be required to meet a 127% CO_2 emissions reduction by 2050 relative to 1990 levels. This is the CO2-127 scenario shown in Fig. 5.1. The energy system would be required to generate -8 Mt CO_2 emissions in 2050. Biomass carbon capture and storage (CCS) is a technology that delivers negative emissions but this is not yet available in Irish TIMES. An alternative approach was adopted whereby Ireland's agriculture emissions were assumed to achieve a 50% reduction by 2050. This is the same percentage reduction as suggested in the EU Low Carbon Roadmap (EC, 2011) for agriculture emissions within the EU as a whole. Using this exogenous assumption, the energy

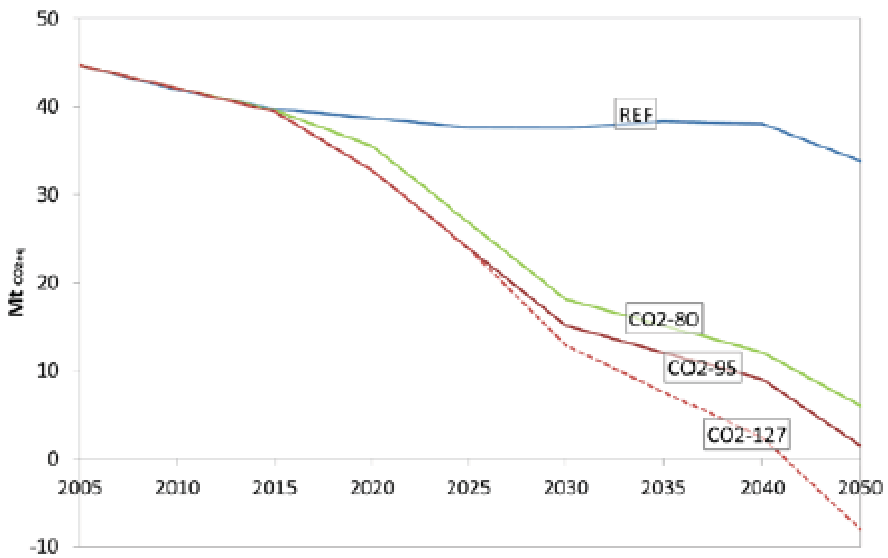

Figure 5.1. Mitigation scenario pathways to 2050 (Mt).

system is then required to deliver a 95% emissions reduction by 2050 and this was adopted here as the CO2-95 emissions scenario. The emissions reduction is applied to total CO_2 emissions. A further scenario not shown here (NETS-80) was also developed, in which the 80% emissions reduction target is imposed separately on ETS and non-ETS emissions.

Figure 5.1 underlines the scale of the long-term challenge facing Ireland. If agriculture can achieve a 50% reduction in GHG emissions by 2050, the entire energy system must achieve a 95% reduction in CO_2 to deliver an overall GHG emissions reduction of 80%. This means the maximum energy-related CO_2 that the energy system can produce in 2050 is 1.5 Mt. This is equivalent (in terms of today's energy system) to less than 10% of current emissions from electricity generation, noting that electricity accounts for just 18% of Ireland's energy use.

5.1 Can Ireland's Energy System meet Energy needs in 2050 and Achieve an 80% Reduction in Energy-related Greenhouse Gas Emissions?

The model results from the 2050 scenarios indicate that these deep emissions cuts are technically possible, while also meeting Irish future energy service demands by incorporating radical changes in energy demand-side and supply-side technologies. The results point to which energy efficiency and renewable energy technologies will have a determining role in delivering the target at least cost. Figure 5.2 shows the CO_2 emissions results from these long-term scenarios, comparing the REF scenario with CO2-80 and CO2-95. The results illustrate the contribution of individual sectors to CO_2 emissions reduction. Reductions are important in the whole energy system, but mainly in transport, electricity generation and industry.

5.2 What are the Implications for the Energy System if Agriculture does not achieve 80% Greenhouse Gas Emissions reduction by 2050?

Figure 5.3 compares the final energy use in the REF, CO2-80 and CO2-95 scenarios. The results in the period 2030–2050 show differences in each scenario in terms of the amount of energy required to meet future energy service demands. This illustrates the improvement in end-use energy efficiency as Ireland moves increasingly towards an increasingly low-carbon energy system. It is worth noting that the REF scenario also already includes cost-effective efficiency improvements delivered over the time horizon. Comparing the results in 2050, final energy use in the CO2-80 and CO2-95 scenarios is 20.5% and 23.1% less than REF.

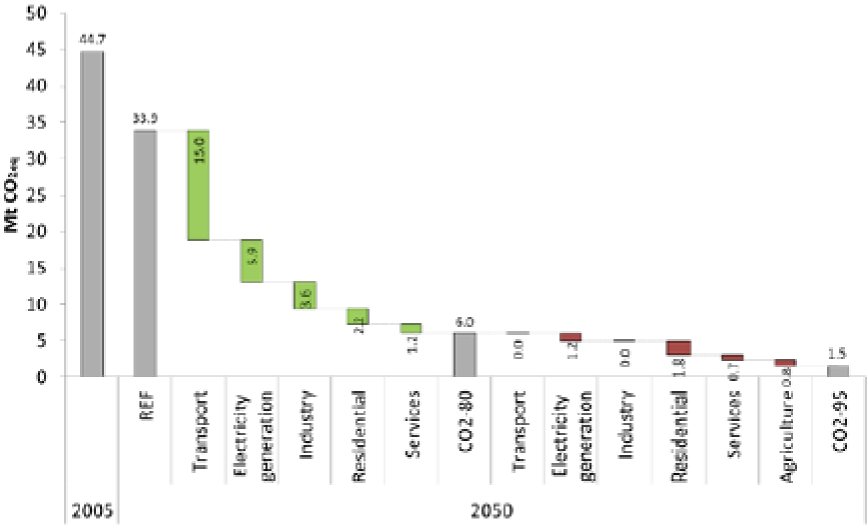

Figure 5.2. Decomposition of 2050 CO_2 emissions between REF, CO2-80 and CO2-95 (Mt).

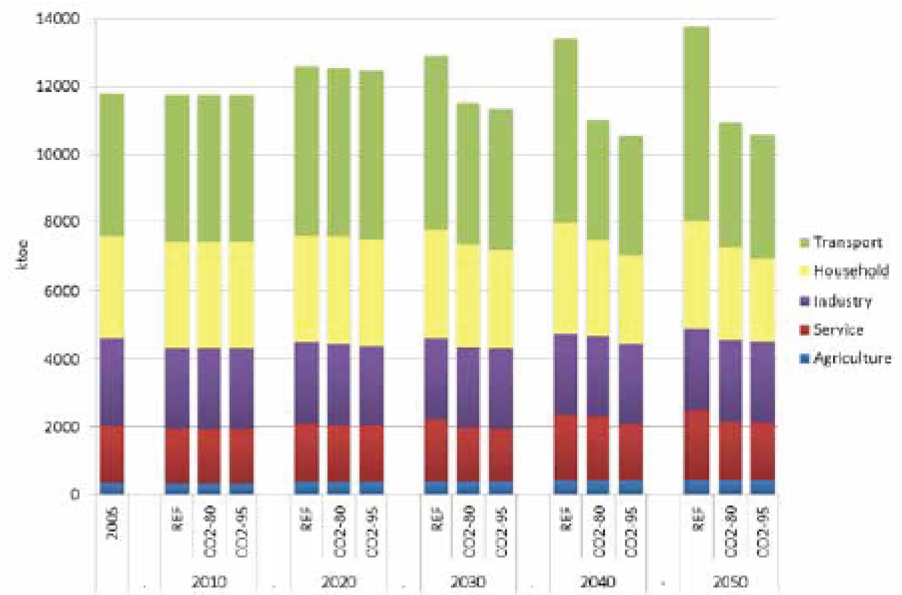

Figure 5.3. Final energy demand by sector in REF, CO2-80 and CO2-95 (ktoe).

Figure 5.4 shows the changes in the fuel mix for electricity generation for the period 2005–2050 comparing the three scenarios. The REF scenario points to significant decarbonisation and the mitigation scenarios deepen this further. The CO2-80 scenario is dominated by renewable energy, with natural gas CCS and natural gas combined cycle gas turbine (CCGT) power plants also contributing. Renewable generated electricity in 2050 accounts for 71.9% of GEC in CO2-80, compared to 100% renewable electricity generation (in addition to imports of 2.3% of GEC) in CO2-95. The remaining electricity in CO2-80 is provided by gas CCS (accounting for 18% of GEC). The additional efforts required to move from CO2-80 to CO2-95 (i.e. delivering further reductions of 4.5 Mt) are mainly concentrated in the power sector (gas CCS displaced by biomass) and increased electrification of heating in the residential and services sector.

In the CO2-95 scenario, a complete decarbonisation of the Irish electricity system in 2050 can be seen (comprising 67% wind and 28% biomass, including biogas, a small contribution from hydro power and the remainder from electricity imports). Also evident in Fig. 5.4 is the increase in total electricity generation across the scenarios because of the electrification of heating.

This electrification is more clearly visible in Fig. 5.5, which shows the growth in electricity usage. Moving from REF to CO2-80 electrification of transport starts to take place in 2030, as does the growth in electrification of residential heating. In CO2-95 more significant electrification of residential heating occurs and the impact of this is that electricity demand more than doubles between 2005 and 2050.

Electrification of heat in particular but also of transport results in the share of energy use delivered by electricity increasing from 18.8% in REF (similar to current levels) to 31.0% in CO2-80 and 46.7% in CO2-95.

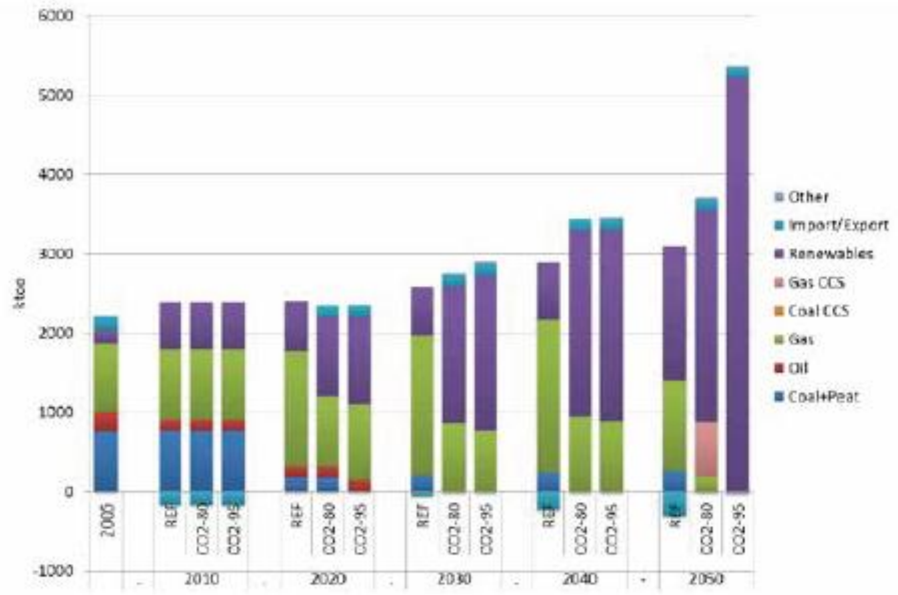

Figure 5.4. Electricity generation by fuel in REF, CO2-80 and CO2-95 (ktoe).

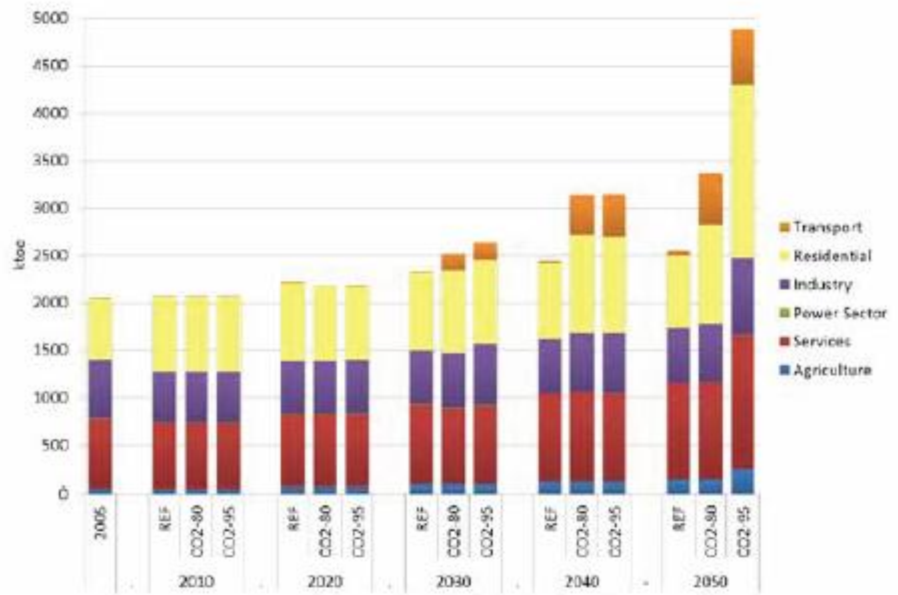

Figure 5.5. Electricity consumption by sector in REF, CO2-80 and CO2-95 (ktoe).

Regarding transport energy use, Fig. 5.6 compares the different scenario results in 2050, distinguishing between private transport, freight and public transport. Most of transport energy is also decarbonised with private cars diverting to EVs, freight and public transport to biofuels (comprising biodiesel and biogas).

Figure 5.7 compares the CO2-80 and CO2-95 results in terms of renewable energy usage in 2050 by mode. Renewable energy in 2050 is 8.4 Mtoe in the CO2-80 scenario (accounting for 67.8% of GFC, compared with 25.3% of GFC in the REF scenario). In the CO2-95 scenario, renewable energy reaches 10.4 Mtoe, representing 85.1% of GFC. The main renewable energy resources used are biomass (biodiesel and biogas for transport and biomass for heat) and wind.

The significant difference between the scenarios is the full move to renewable generated electricity in CO2-95. Some of the biomass that was used for thermal energy in CO2-80 is used for electricity generation in CO2-95.

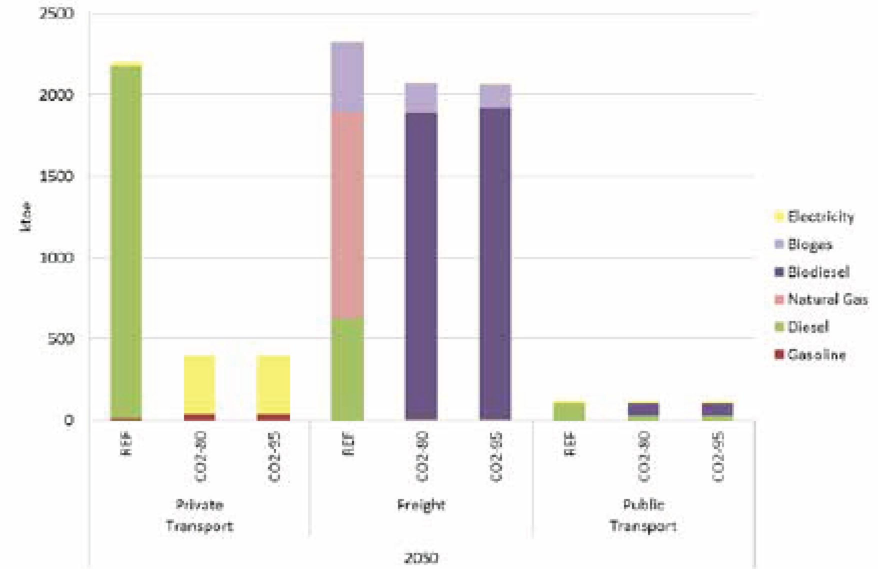

Figure 5.6. 2050 transport energy by end-use in REF, CO2-80 and CO2-95 (ktoe).

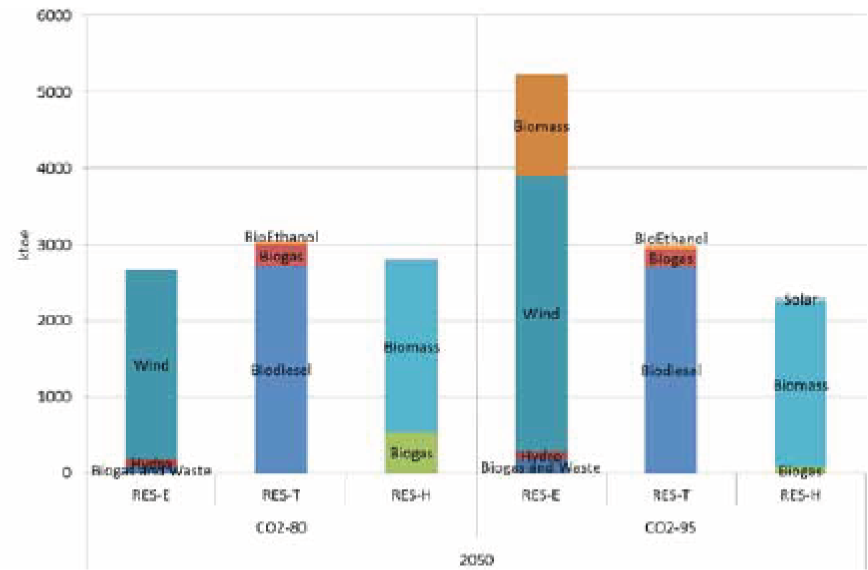

Figure 5.7. Renewables consumption by mode in CO2-80 and CO2-95 (ktoe).

5.3 What are the Cost Implications of Deep Decarbonisation and of the Energy System Compensating for Agriculture achieving Lower Emissions Reductions?

The economic impacts of these scenarios use the same metrics as those used for the 2020 GHG emissions reduction scenarios, namely the marginal cost of CO_2 abatement and the ratio between energy-systems costs and GDP. Table 5.1 summarises the marginal abatement costs for the CO2-80 and CO2-95 scenarios relative to REF. The results suggest a significant increase in marginal abatement costs by 2050 from €$_{2000}$273 to €$_{2000}$1308 in the CO2-80 and CO2-95 scenarios respectively. Two additional intermediate scenarios with different emissions reduction target (-85% and -90%) are also included for comparison. This indicates the challenge in moving beyond an 80% CO_2 emissions reduction scenario.

A further scenario result is also provided here: the NETS-80 scenario. This underlines the impacts of extending current EU mitigation policies (Directive 2009/29/EC and Decision 2009/406/EC) beyond 2020 with separate targets between ETS and non-ETS sectors, resulting in greater electrification (already important in the previous cases) to reduce emissions in end-use sectors (mainly the residential sector). The results confirm that emission reductions are generally cheaper in the ETS sector. This means that applying the same target to ETS and non-ETS sectors separately results in higher overall costs. More work is required to elaborate further the impact on long-term pathways of changing the short-term targets. In this analysis, the 20.5% total CO_2 emissions reduction target in 2020 is imposed relative to 2005 levels in CO2-80 and the 2020 target to 26.8% for CO2-95 increased, compensating for agriculture not meeting a 20% emissions reduction target in 2020. In the NETS-80 scenario, separate 2020 targets of 21% for ETS and 20% for non-ETS energy-related CO_2 emissions are imposed.

Figure 5.8 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. In the REF scenario the energy system costs 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, 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 costs of mitigation are 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 costs of the CO2-95 mitigation scenario (again relative to the REF scenario) are less than 2% of GDP in 2050. The NETS-80 and NETS-20/CO2-80 deliver higher system costs in the period 2020–2030.

Table 5.1. CO_2 shadow prices.[6]

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-80	141	97	87	554	€$_{2000}$/tonne CO_2

6 Equivalent European studies such as WETO-H2 (EC, 2006) and SECURE (EC, 2010) 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 €$_{2000}$312/ton (392 €$_{2005}$/ton) and €$_{2000}$159 ton (€$_{2005}$200 /ton) for the year 2050.

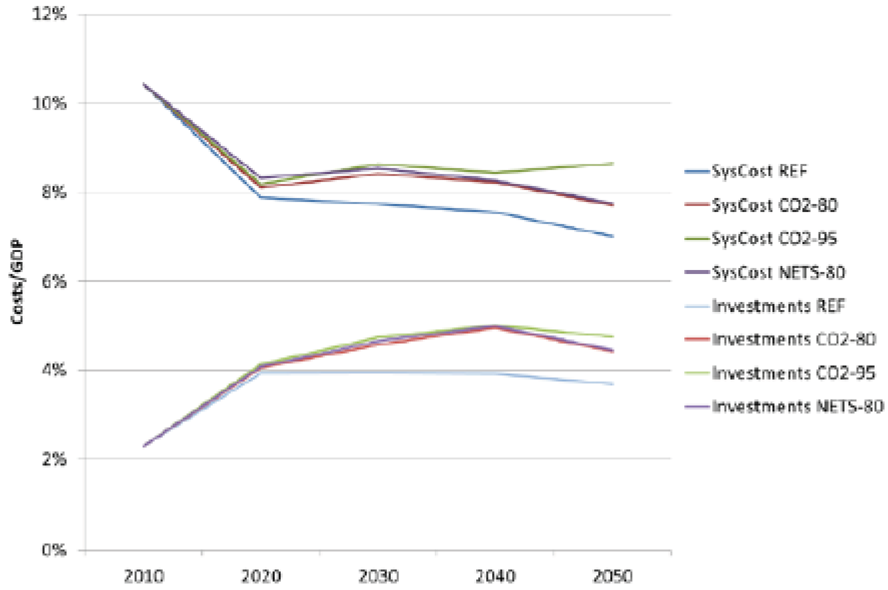

Figure 5.8. Comparing system costs with gross domestic product (GDP).

In all mitigation scenarios, increased systems costs are driven by investments that will range between 4.4 and 5.0% of GDP in the period 2030–2050. Further details on the 2050 scenarios and results can be found in Chiodi et al. (2012a).

6 Conclusions

This project provides Ireland for the first time with energy-system configurations and technology pathways that deliver short- and medium-term policy targets at least cost, namely, how Ireland can meet the requirements under the EU Renewable Energy Directive, the EU Effort Sharing Decision 2009/406/EC on non-ETS emissions and long-term emissions reduction targets at least cost.

Section 3 indicates that the EU 16% renewable energy target[7] could be optimally achieved by 2020 with a different pathway to that currently being followed under Ireland's NREAP. Notably, the results here suggest a higher amount of biomass usage for renewable heat than current targets (i.e. 18% RES-H rather than 12% RES-H). Moreover, the policy focus in Ireland is dominated by achieving 40% of renewable electricity, while renewable transport receives a much lower focus and there are no current policy mechanisms in place to promote renewable heat. The results for renewable heat highlight the importance of developing reliable production chains to allow this potential to be achieved. Furthermore, the Irish TIMES model indicates negligible contributions of ocean energy in the electricity sector by 2020 due to their high costs, while EVs will have a marginal role in the transport sector, which instead relies on increasing shares of biofuels. The results also indicate half of biofuels in transport coming from biogas, while the NREAP points to biodiesel and bioethanol, suggesting that this focus should be re-examined. Achievement of the renewables target also contributes to a GHG reduction of 3.0 Mt of $CO_{2,eq}$ by 2020, delivered mainly by savings in the power sector and industry.

The analysis in Section 4 raises a number of questions regarding Ireland's obligations under Decision 2009/406/EC to reduce non-ETS GHG emissions by 20% below 2005 levels. 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: (i) electrification of heating in buildings (i.e. shifting CO_2 emissions from the non-ETS sectors to the ETS sectors, namely electricity generation) and (ii) significantly increasing the amount of biofuels used in transport. This points to the need to reassess Ireland's renewable energy policies in the light of the non-ETS emissions reduction target. The results suggest a focus on renewable heat, renewable transport and electrification of heat, in contrast to the current dominant focus on wind-generated electricity. The results also show that ETS companies in Ireland are likely to have a 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. The results point to further renewable energy use in transport and further electrification of heat in buildings.

The results in Section 5 indicate that challenging CO_2 emissions reductions such as 80% and 95% (equivalent to 80% GHG emissions reduction) relative to 1990 levels can be achieved technically in Ireland. They underlined which energy-efficiency and renewable-energy technologies will have a determining role in delivering the target at least cost. Reductions are important in the whole energy system, but mainly in transport, power sector and industry sectors.

Comparing the final energy use in the CO2-80 scenario with REF shows a 21% improvement in end-use energy efficiency, increasing further to 23% in the CO2-95 scenario. Renewable energy accounts for 25.3% of GFC in the REF scenario, increasing to 67.8 in CO2-80 and 85.1% in CO2-95. The main renewable energy resources used are biomass (biodiesel and biogas for transport and biomass for heat) and wind. Electrification of heat in particular but also of transport results in the share of energy use delivered by electricity increasing from 18.8% in REF (similar to current levels) to 31.0% in CO2-80 and 46.7% in CO2-95. Renewable generated

7 Under the EU Renewable Energy Directive (2009/28/EC)

electricity accounts for 71.9% of GEC in CO2-80, compared with 100% renewable electricity generation in CO2-95. The remaining electricity in CO2-80 is provided by gas CCS (accounting for 18% of GEC). The additional efforts required to move from CO2-80 to CO2-95 (i.e. delivering further reductions of 4.5 Mt) are mainly concentrated in the power sector (gas CCS is displaced by biomass) and increased electrification of heating in the residential and services sector.

Although the Irish TIMES model is currently not able to endogenously include non-energy agriculture emissions, the CO2-95 scenario underlines the implications for Ireland of failing to reduce emissions within agriculture. The energy sector is forced to compensate for any under-achievement in mitigation. The results suggest a significant increase in system costs from 48 to 66% relative to 2005 levels and marginal cost from €273 to €1,308 in the CO2-80 and CO2-95 scenarios respectively.

Further work is required in a number of areas to improve the results and to extend the scope of the analysis. An important step in this regard is the Irish TIMES Phase 2 project that commenced in November 2011 and will focus on:

1. Updating the model with new projections of Ireland's economy to 2050, new fuel price and resource availability projections and new technology options and costs.
2. Investigating the impacts of high levels of renewable generated electricity on the power system by soft-linking Irish TIMES with a higher temporal resolution power systems model (PLEXOS). This research has already generated a novel approach and some interesting results (Deane et al., 2012).
3. Developing economy-wide mitigation scenarios. The work to date has focused on modelling the energy system in isolation with exogenous assumptions regarding emissions reduction in agriculture. This research will cover both the energy system and the agriculture system together.
4. Incorporating behaviour into Irish TIMES. The model can currently choose technology solutions to achieved mitigation targets. Incorporating elastic demand will also enable the option of energy-service demand reduction to compete with technology change as energy costs increase. In addition, separate work funded by the IEA-ETSAP (Daly et al., 2012) has begun on a methodology for introducing modal choice into the transport sector.
5. Further elaborating the impact on long-term pathways of changing the short-term targets, building on the current analysis, which:
    a. Imposes the 20.5% total CO_2 emissions reduction target in 2020 relative to 2005 levels in CO2-80;
    b. Increases the 2020 target to 26.8% for CO2-95, compensating for agriculture not meeting a 20% emissions reduction target in 2020; and
    c. Imposes separate 2020 targets of 21% for ETS and 20% for non-ETS energy-related CO_2 emissions in the NETS-80 scenario.
6. Improving the representation of interconnection and energy imports and exports. This is being achieved by reintegrating Irish TIMES within the Pan European TIMES model and scenario analysis.

It is worth noting that the Research Prioritisation Steering Group (Forfás, 2011) published its report as this project was being completed. While the focus of the steering group was not on research that informs policy choices, this was discussed and the Irish TIMES project is very well aligned with their conclusions:

> Research plays an important role in helping Government to achieve its policy objectives ... facilitates us in meeting our objectives at minimum cost ... Research programmes designed to inform the policy process play a vital role in agenda setting and increase the likelihood of translating important findings in relation to ... , environment and other research domains into feasible and implementable services and systems. In a number of areas, policy is negotiated with the European Union, out of which emerge obligations, regulations and income transfers. The quality of our negotiating effort is directly shaped by the quality of the evidence-based research that we bring to the negotiating table. High quality research, informing both our negotiating position and then the implementation of decisions, is required if we are to succeed.

The results in Section 3 challenge the underlying basis for Ireland's obligations under Decision 2009/406/EC to reduce non-ETS GHG emissions by 20% below 2005 levels. Irish negotiating effort at the time was diminished because of the absence of a modelling tool such as Irish TIMES. As Ireland enters negotiations regarding its contribution to 2030 and 2050 EU targets for energy efficiency, renewable energy and climate mitigation, this modelling tool provides the capacity to improve both the Irish negotiating position and then the implementation of decisions.

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Acronyms

CCS	Carbon capture and storage
CCGT	Combined cycle gas turbine
CJHP	Combined heat and power
ESRI	Economic and Social Research Institute
EV	Electric vehicles
IEA-ETSAP	Energy Technology Systems Programme
GEC	Gross electricity consumption
GFC	Gross final energy consumption
NREAP	National Renewable Energy Action Plan
non-ETS	Non- emissions trading sectors
PET[36]	Pan European TIMES
RES-E	Renewable energy representing a 42.5% share of gross electricity consumption
RES-H	Renewable energy representing a 12% share of thermal energy for heating and cooling
RES-T	Renewable energy representing 10% of road and rail transport energy
UCC	University College Cork