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Irish TIMES Energy Systems Model Phase 2

Authors: Paul Deane, Alessandro Chiodi and Brian Ó Gallachóir

Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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- Office of Evidence and Assessment
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EPA RESEARCH PROGRAMME 2014–2020

Irish TIMES Energy Systems Model Phase 2

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EPA Synthesis Report

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by

Environmental Research Institute, University College Cork

Authors:

Paul Deane, Alessandro Chiodi and Brian Ó Gallachóir

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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Project Partners

Brian Ó Gallachóir
University College Cork
Environmental Research Institute
Lee Road
Cork
Ireland
Tel.: +353 21 490 3037
Email: b.ogallachoir@ucc.ie

John Curtis
Economic and Social Research Institute
Whitaker Square
Sir John Rogerson's Quay
Dublin 2
Ireland
Tel.: +353 1 863 2000
Email: j.curtis@esri.ie

Trevor Donnellan
Teagasc
Rural Economy Research Centre
Athenry
Co. Galway
Ireland
Tel.: +353 91 845220
Email: trevor.donnellan@teagasc.ie

James Breen
Department of Agribusiness and Rural Development
University College Dublin
Dublin 4
Tel.: +353 1 716 7764
Email: james.breen@ucd.ie

Maurizio Gargiulo
E4SMA
Via Livorno 60
Environment Park
I-10144 Turin
Italy
Tel.: +39 011 225 7351
Email: maurizio.gargiulo@e4sma.com

Amit Kanudia
KanORS
Office 4
First Floor
DDA Market
Vasundhara Enclave
Delhi 10096
India
Tel.: +91 11 2261 6656
Email: amit@kanors.com

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Executive Summary

Irish TIMES (The Integrated Markal-Efom System) is Ireland's only fully integrated long-term energy systems model; the model is unique in its ability to provide cross-sectoral evidence-based analysis for climate and energy policy. This report details research outputs from the EPA-funded phase II of the Irish TIMES Project, which was a collaborative effort lead by University College Cork's Energy Policy and Modelling Group, involving the Economic and Social Research Institute, University College Dublin and Teagasc as project partners.

The research highlights presented in this synthesis report are shortened versions of published and submitted papers. The research makes an important contribution to Ireland's technical capability in quantifying the challenges of moving to a low-carbon economy. It also makes valuable contributions to the international collaborative research effort in TIMES energy systems modelling (used in over 70 countries to inform policy decisions) co-ordinated by the International Energy Agency's Energy Technology Systems Analysis Program. In all, six research papers are summarised in this report.

Renewable electricity will make a strong contribution to Ireland's ambitions to reduce its carbon footprint. Variable generation sources for renewable energy, e.g. wind, wave and solar energy, require careful consideration in technical long-term energy models such as the Irish TIMES model. New soft-linking techniques to improve the technical outputs of the model for the power system were developed in this phase of the research. Soft-linking techniques are used to enhance the output from Irish TIMES (or indeed any other energy system model) in areas where higher temporal resolution is valuable. This is presented in this report as three papers: (1) the technique is applied to the power system with high levels of variable renewable energy generation; (2) the technique is applied at a European level; and (3) it is applied to a power system with high levels of electrical heating. It is shown that soft-linking and the multi-model approach greatly improve the technical robustness of results from the model. The results highlight the importance of integrated modelling of interconnected regions, as cross-border power flows play a significant role in market dynamics, especially in the presence of geographically dispersed variable renewable energy generation sources such as wind and solar energy. This is important from a policymaking perspective, as poor model-based evidence can lead to poorly informed policy decisions.

In the heat sector, the primary source of residential heating in Ireland is oil-fired (kerosene and gasoil) central systems. Indeed, Ireland's residential sector is one of the most oil dependent in Europe based on consumption per capita. Modelling results show that electrification of residential heating may increase by the year 2020 in order that Ireland can meet its non-EU Emissions Trading Scheme emission reduction target in a cost-optimal fashion and that greater electrification of existing oil-fired central heating systems through air source heat pump (ASHP) technology should warrant further investigation. Additional analysis is specifically required to assess the economic and other barriers to ASHP deployment, such as financing of and payment for systems.

Economic activity has long been a key driver of energy demand and, consequently, of energy-related greenhouse gas emissions and is, therefore, an important element in energy and climate mitigation modelling. The impact of the economic recession on energy consumption could potentially create distortions in the policies that each European country should apply to achieve the 2020 target and long-term targets on greenhouse gas emissions. The link between economy recovery, energy service demand, energy consumption, CO_2 emissions and price and system costs is extremely important to identify and adopt the appropriate policies to achieve reduction targets.

Energy security is especially important for Ireland as one of Europe's most imported-energy-dependent countries. Research is presented in this report that models energy security scenarios for Ireland using long-term macroeconomic forecasts to 2050, with oil production and price scenarios from the International Monetary Fund, within the Irish TIMES energy systems model. The analysis focuses on developing a least-cost optimum energy system for Ireland under scenarios of constrained oil supply and subsequent sustained

long-term price shocks to oil and gas imports. The results point to gas (both renewable and natural gas) becoming the dominant fuel source for Ireland to 2050.

Agriculture currently accounts for about 30% of Ireland's greenhouse gas emissions, which is significantly higher than that of other industrialised countries, yet comparable with the global level at 25% (this includes emissions associated with other land use change and forestation). This highlights the fundamental importance of considering agriculture in energy system modelling. Within this phase of research, a model and methodology were developed for the integration of agricultural systems modelling and energy systems modelling. The research extended the Irish TIMES energy systems modelling approach by incorporating agriculture into the model in order to provide richer insights into the dynamics and interactions between the two (e.g. in competition for land use). An integrated modelling approach provides important insights into the most cost-effective mitigation pathways and draws evidence for new comprehensive policy strategies that are able to discern between the full range of technical solutions available. In this particular analysis, it was shown that technical solutions in agriculture may contribute to some reductions in emissions – however, these reductions represent less than a 20% reduction relative to 1990 levels – while the bulk of cost-optimal reductions in emissions remain in the energy-related sectors. Compared with the findings of the Low Carbon Roadmap, the results indicated that, for Ireland, achieving an 80% to 95% reduction in greenhouse gas emissions by 2050 would be very challenging without also reducing the level of activity in the agriculture sector.

The full versions of the papers are as follows:

Chiodi, A., Donnellan, T., Breen, J. *et al*., 2015. Integrating agriculture and energy to assess GHG emissions reduction: a methodological approach. *Climate Policy* 16: 215–236. DOI: 10.1080/14693062.2014.993579.

Deane, J.P., Chiodi, A., Gargiulo, M. *et al*., 2012. Soft-linking of a power systems model to an energy systems model. *Energy* 42: 303–312.

Deane, J.P., Gracceva, F., Chiodi, A. *et al*., 2015. Soft-linking exercises between TIMES, power system models and housing stock models. In Giannakidis, G., Labriet, M., Ó Gallachóir, B. *et al*. (eds), *Informing Energy and Climate Policies Using Energy Systems Models: Insights from Scenario Analysis Increasing the Evidence Base*. Springer International Publishing, Cham, pp. 315–331.

Deane, J.P., Driscoll, Á. and Ó Gallachóir, B.P., 2015. Quantifying the impacts of national renewable electricity ambitions using a North–West European electricity market model. *Renewable Energy* 80: 604–609. DOI: 10.1016/j.renene.2015.02.048.

Gargiulo, M., Chiodi, A., Deane, P. *et al*., 2012. Impact of economic recession on the costs of climate mitigation. Proceedings of the 12th IAEE European Energy Conference, Energy Challenge and Environmental Sustainability, Venice, Italy, 9–12 September 2012.

Glynn, J., Chiodi, A., Gargiulo, M. *et al*., 2014. Energy security analysis: the case of constrained oil supply for Ireland. *Energy Policy* 66: 312–325.

1 Introduction and Model Description

University College Cork (UCC) developed the Irish TIMES (The Integrated Markal-Efom System) energy systems model in the period 2009 to 2011 (under a previous EPA-funded project[1]) and used it to build a range of medium- (to 2020) and long-term (to 2050) energy and emissions policy scenarios in order to inform policy decisions. This project, Irish TIMES Phase 2 (undertaken in the period 2012 to 2014) improved and extended the capacity of the Irish TIMES model and included a focus on the medium term (to 2030). We developed a multi-model approach to gain further insights into the power system results using a soft-linking methodology (Chapters 2 and 3). We also explored the impact of the economic recession on the future evolution of the energy system (Chapter 4) and we examined energy security and built scenarios to understand the implications of energy security issues on future potential pathways (Chapter 5). We also developed the AGRI-TIMES module, in order to explore mitigation scenarios that focus on both energy and agriculture (Chapter 6). Irish TIMES Phase 2 was also moved beyond Ireland by developing a north-west European electricity model (Chapter 7).

1.1 Model Description

The Irish TIMES Integrated Energy System model provides a technology-rich, least-cost future energy system pathway subject to technology, economic and resource constraints. Integrated energy systems models approach energy as a system rather than as a set of discrete elements. This has the advantage of providing insights into the most important substitution options that are linked to the system as a whole and that cannot be understood when analysing a single technology, commodity or sector. A focus on the electricity sector, for example, risks excluding possible unforeseen step changes in electricity demand, due to, for instance, the electrification of transport or heating. Current energy systems are the result of complex country-dependent, multi-sector developments. By considering energy supply and demand across all sectors simultaneously, systems analysis applies systems principles to aid decision-makers in problems of identifying, quantifying and controlling a system.

The Irish TIMES model is the energy system model for Ireland, built with TIMES modelling framework. TIMES has been developed and made available through the ETSAP (Energy Technology Systems Analysis Program) Implementing Agreement, a multi-lateral technology initiative, initiated in 1976 under the aegis of the International Energy Agency (IEA), with the aim of carrying out a joint programme of energy technology systems analysis. TIMES is written in GAMS (General Algebraic Modelling System) code and CPLEX and XPRESS are typically the solvers used. A key characteristic of this model generator is that the code is transparent and well-documented,[2] distributed free of charge, and maintained, improved and updated through a collaborative research initiative co-ordinated by ETSAP.

TIMES, along with its predecessor Markal, are model generators currently in use in nearly 200 institutions across 70 countries. They have and are being used to generate energy systems models for local, national or multi-regional energy systems, providing a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. They are usually applied to the analysis of the entire energy sector, but may also be applied to study individual sectors in detail. They compute a dynamic inter-temporal partial equilibrium on integrated energy markets with the objective (objective function) of producing least-cost energy systems while respecting environmental and technical constraints. The energy system cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels and minus the residual value of technologies at the end of the horizon.

The strong point of the TIMES modelling framework is that it combines a detailed technology-rich database with an economically optimising solver. It is able to generate

1 https://www.epa.ie/pubs/reports/research/climate/Irish%20TIMES%20Energy%20Systems%20Model.PDF (accessed September 2016).

2 http://www.etsap.org/documentation.asp

robust energy policy scenarios over medium to long time horizons and can offer strategic insight into long-term policy formation. This is especially important for the energy sector, which has large capital investments with long project lifetimes. The modelling perspective of these tools is that of a benevolent central planner in the form of a single decision-maker (mono-objective) making rational choices surrounding all energy-related issues on technologies and fuels at the lowest cost to the economy and to society. This clearly does not reflect reality, where there are many decision-makers and not all decisions are rational, but it does provide very useful guidance on how to achieve policy decisions (e.g. emissions targets) using a least-cost approach. The complex dynamics (incorporating technologies, fuel prices, infrastructures and capacity constraints) of the entire energy system can be analysed through this modelling approach to better inform policy choices.

Like all energy models, TIMES models also have a number of limitations that should be considered when interpreting the results and scenario analyses. In some instances, these are simply limitations born of the structure of the model that are inevitable, based on the way the model is built. In other instances, they could be considered weaknesses and, in these cases, research should be carried out to generate improvements. The following list presents the main limitations:

1. *Time resolution*. Long-term energy systems models are generally inadequate to capture daily supply and demand curves. Even though there are no limitations on the number of time slices in TIMES models, it would become computationally unwieldy if the model had to make decade-long decisions as well as hourly decisions.
2. *Macro-economic assumptions*. The results of the scenarios are tied to the assumptions and results of the macro-economic model, which, by themselves, are inherently uncertain. While scenario analysis, by its nature, tries to counteract this uncertainty by producing a range of results, this uncertainty is, nevertheless, present.
3. *Limited macro-economic feedback.* TIMES models are generally not able to take account of feedback between the output of the energy system analysis and the macro-economy.
4. *Behaviour.* TIMES models have limited capacity to simulate behavioural aspects. This is a limitation of most energy (and indeed macro-economic) models, in that consumer behaviour is generally limited to a simple price response and non-price-related behaviour is generally very poorly treated.

The Irish TIMES model is able to generate a vast number of outputs, assessing implications for (1) the economy (including energy prices, investments in the energy system, marginal CO_2 abatement costs, etc.); (2) the energy mix (fuels and technologies) and energy dependence; and (3) the environment, in particular greenhouse gas (GHG) emissions. The core model contains a large database (approximately 1700 in the case of Irish TIMES) of 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 exogenous model inputs are the energy supply resources and costs, and energy service demands of the model. These include, on the supply side, 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.[3]

3 http://www.ucc.ie/en/energypolicy/irishtimes/

2 Gaining Additional Insights Into Electricity

No single energy modelling tool, such as Irish TIMES, can address all aspects of the full energy system in great detail; greater insights and progress can be gained by drawing on the strengths of multiple modelling tools, rather than trying to incorporate them all into one comprehensive model. This section presents a soft-linking methodology that employs detailed simulation outputs from a dedicated power systems model to gain insights and understanding of the generation electricity plant portfolio results for the electricity sector from a separate energy systems model. A detailed description of this work has been published (Deane *et al*., 2012).

The motivation for this soft-linking approach is to provide a transfer of information from the strong points of the power systems model to the energy systems model and use this information to improve and develop understanding of energy systems model results. Part of this motivation is derived from a view that the methodology takes an optimised generation portfolio for a specific year from an energy systems model and undertakes a detailed high-resolution chronological simulation of the same portfolio in the power systems model with added degrees of technical detail. Results presented here show that, in the absence of key technical constraints, an energy systems model can potentially undervalue flexible resources, underestimate wind curtailment and overestimate the use of baseload plant.

In this methodology, one specific year (2020) was chosen from the energy systems model results and examined in greater detail in a power systems model. The energy systems model used in this analysis is the Irish TIMES model, which was developed using the TIMES modelling tool. The power systems modelling tool used was PLEXOS for Power Systems[4] and a model of the Irish power system in PLEXOS is presented in this analysis

These increases in electrification and in wind generation may pose significant challenges for the power system. This can, therefore, be considered relevant, as it aims to determine whether the electrical portfolios generated in the Irish TIMES model are technically feasible or not and aims to gain insight into the appropriateness of the derived generation portfolio. Implications for projected emissions are also illustrated. Note that while this methodology is presented here for the Irish TIMES model, it could also be applied to other countries and models that may have high projected levels of variable renewable energy generation in future power systems.

2.1 Soft-linking Methodology

The goal of the methodology is ultimately to have an improved understanding of the energy systems model's results in relation to the electrical power sector and to understand what elements of the power system are important. Figure 2.1 shows a schematic representation of the methodology in the form of a flow chart. Depending on differences that arise and insights that are gained, the energy systems model inputs or technical parameters can be adjusted to aim for improvement in the results.

To demonstrate the soft-linking methodology as outlined above, we applied soft-linking to an energy systems model, Irish TIMES and an equivalent power systems model.

To assess the methodology, a series of yearly model runs (scenarios) was undertaken in the power systems model with added degrees of technical complexity. This was done to assess and quantify the added benefit of each of these parameters to the modelling process. The first of these scenarios (*Scenario Simple*) was a simple unit commitment and dispatch simulation with no technical constraints other than maximum generation capacity of each individual plant. A second scenario (*Scenario Start Costs*) added the start costs of each plant to the problem formulation. A third model scenario (*Scenario MSG*) also added minimum stable generation, a fourth added ramp rates (*Scenario Ramp rates*) for each plant, while a final scenario (*Scenario Reserve*) added full modelling of upwards reserve requirement. This final scenario can be interpreted as the most complete model of the power system and the one that provides the most realistic results in terms of power system operation. Therefore, the differences between this scenario

4 Energy Exemplar, PLEXOS for Power Systems, available online: www.energyexemplar.com

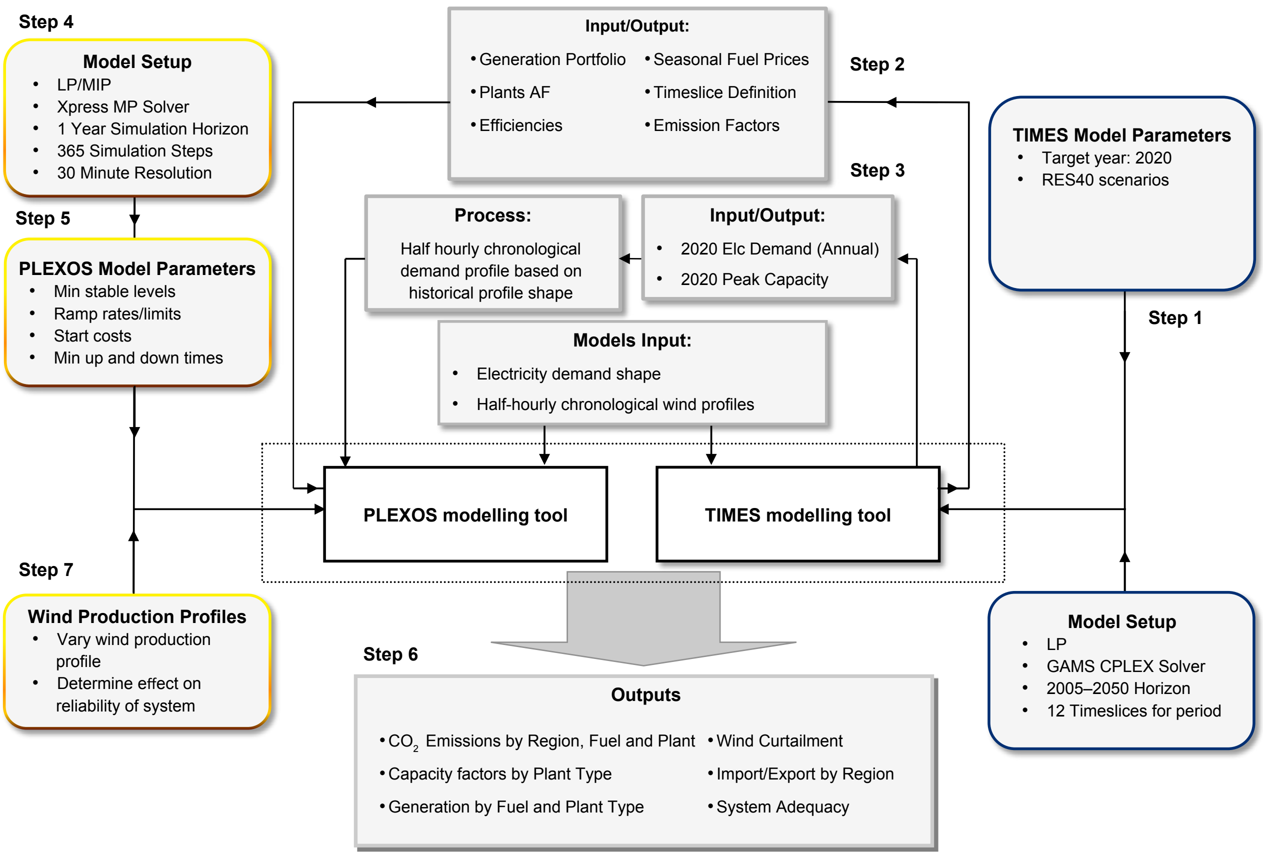

Figure 2.1. Flow chart of soft-linking methodology. Reproduced from Deane *et al.* (2012) with permission from Elsevier.

Table 2.1. Summary of individual model scenarios for power systems model simulations

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

and the results from the energy systems model are the most important. These scenarios are summarised in Table 2.1. A series of simulations was also undertaken in the power systems model to determine the effect of low-wind production years to investigate the robustness of the derived power system. This was done by using actual historical wind power production data from the year 2010, which was a low-wind production year in Ireland, with an annual capacity factor of 24%.

2.2 Results

Looking first at the results from the energy systems model and the Simple scenario from the power systems model (see Figure 2.2), it can be seen that results are broadly similar. However, as more technical detail is added to the power systems model, the results for certain plants diverge, indicating the significance and importance of technical portrayal in modelling the electrical power system.

Results of the detailed unit commitment and dispatch show that the power systems model commits more of the less efficient combined cycle gas turbine (CCGT) units than the energy systems model across all technical scenarios examined. This is because these units come online when the newer CCGT units are out for maintenance or as a result of forced outages, and they are an important source of flexibility for the system. The energy model exploits the coal-powered plant to its full capacity, whereas, in the power systems model, these units are used less, particularly with the inclusion of more technical parameters as the start cost becomes

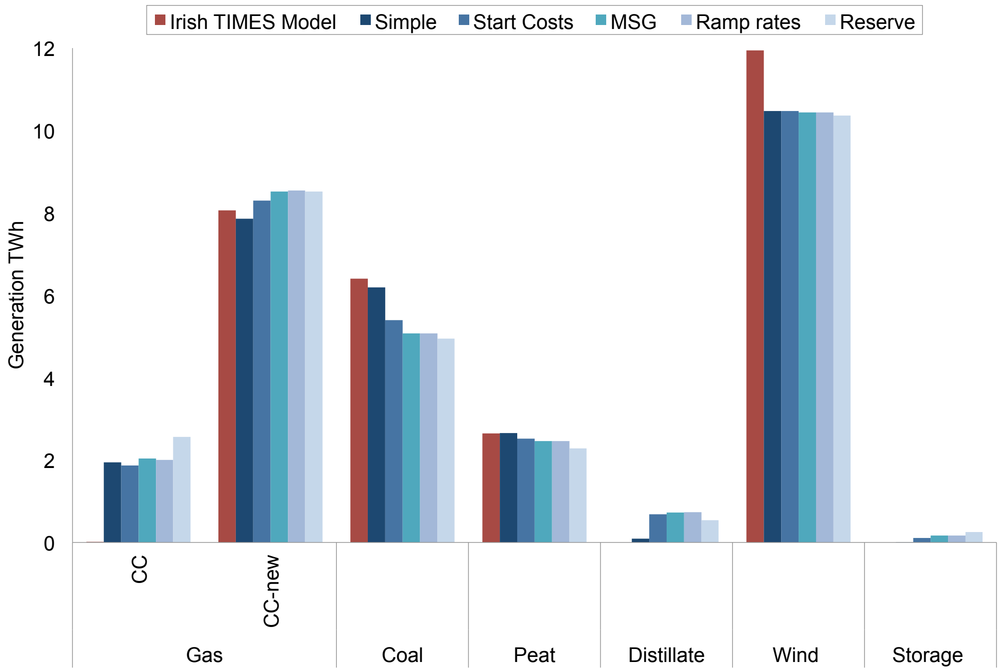

Figure 2.2. Annual energy generation in 2020 for the less efficient (CC) and the newer (CC-new) combined cycle gas turbine units and for each power system model scenario. Reprinted from Deane *et al.* (2012) with permission from Elsevier.

incorporated into the objective function and coal generation is "pulled back" to allow gas and other generation sources to come online and run above their minimum stable level. As shown in Figure 2.2, the distillate-fuelled plants, while having a low capacity factor in the energy systems model, are shown to provide an important peaking ability and this value is only seen when higher levels of technical detail are modelled in the power systems model. Pumped storage is also an important contributor to spinning reserve and is brought online more often to provide this service. Likewise, the value of the pumped storage plant capacity only becomes apparent when this level of detail is included in the power systems model. In relation to wind energy, it can be seen that wind production is lower in the power systems model scenarios than in the energy system model run, indicating that wind curtailment is occurring. Results of the power systems model show that annual wind curtailment rises from 7% for the Simple scenario to 8% for the Reserve scenario, whereas the Irish TIMES model shows no wind curtailment. This stresses the importance of the correct modelling of flexible resources, such as storage, in the determination of system flexibility and suitability for renewable energy integration. Results for the low-wind-year simulations were broadly similar, however, as annual wind generation was lower, but an increase was seen in thermal generation.

Results of the detailed unit commitment and dispatch of the power system were also used to assess the flexibility of the generation portfolio developed by the Irish TIMES model and understand what technical details are important when modelling an electrical power system. Insights gained from this type of analysis can be useful in understanding why results differ between the two models. In general, all thermal units decrease their cycling as more technical detail is added to the model. In-place, flexible resources, for example pumped storage, become more important as they are cycled more often to deal with changing demand while thermal units stay online longer.

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

2.3 Conclusions

A soft-linking methodology that can be used to verify and gain insight into electricity sector results from energy systems models using a power systems model has been presented and detailed. Results for one specific year

have been presented. The work in this chapter shows that the soft-linking methodology provides important insights into results and provides a useful method to cross-check the technical appropriateness of the optimised power system results arising from an energy systems model. In this particular analysis, it was shown that, while the optimised portfolio from the Irish TIMES model was a reliable and adequate power system, the value of key flexible elements, such as storage, were undervalued. It was also shown that, while the energy systems model does not use the older CCGT gas units or distillate-fired units, they are important elements in the system. Wind curtailment was approximately 8% higher than expected and emissions were higher than estimated by Irish TIMES when compared with detailed results from the power systems model. These insights could only be gained by the addition of key technical criteria to the modelling process, such as imposing start costs, minimum stable generation levels and reserve requirements on the model. In relation to these constraints, it was shown in this analysis that start costs have a marked effect on the modelling of the power system and have important implications for the modelling of CO_2 emissions.

3 Electrification of Residential Heating – Good Idea or Bad Idea?

Previous studies have indicated a significant possible contribution that can be made by air source heat pumps (ASHP) replacing older oil-fired boilers in residential dwellings as one element of a pathway for Ireland to meet ambitious targets for 2020 to reduce GHG emissions by 20% below 2005 levels for sectors not covered by the EU Emissions Trading Scheme (ETS). In this chapter, we describe the development of a multi-model and soft-linking approach to determine what level of electrification of heating in the residential sector in Ireland is cost-optimal to meet GHG emissions reduction targets for the year 2020. This research is described in detail in Deane *et al*. (2015a).

The methodology combines an energy systems model, a power system model and an archetype residential energy model for Ireland. Results show that relying solely on an energy systems model may lead to an overestimation of the extent of electrification of residential heating. Our multi-model approach suggests that between 270,000 and 340,000 existing oil-fired residential dwellings could be with converted to ASHP technology without compromising the operation of the electrical power system. This equates to approximately 38% to 47% of existing dwellings currently using oil-fired central heating. This would remove 1,832 kt of CO_2 emissions from the non-ETS sector, which corresponds to 3.9% of overall non-ETS emissions in 2005. It represents an overall net system reduction in emissions in Ireland of 879 kt CO_2.

3.1 Context

The primary source of residential heating in Ireland is oil-fired (kerosene and gasoil) central systems. Indeed, Ireland's residential sector is one of the most oil-dependent in Europe based on consumption per capita; Belgium is second with a higher share of gas/oil.[5] In Ireland, oil-fired central heating is predominately found in rural areas where detached houses are common. Typical floor areas for this type of dwelling are generally large and can range from 100 to 180 m^2. From 1990 to 2007, the average floor area of new houses granted planning permission grew from 130 m^2 to 161 m^2 (an increase of 24%). Natural gas is a more popular choice in urban areas, as many of these areas are connected to the national grid network. In urban areas, the majority of the housing stock is semi-detached and terraced housing, while in rural areas detached housing is more common. Electricity is primarily used in flats/apartments, although a small consistent number of other dwellings employ storage heaters with a 500- to 800-MW night-time storage heating system on the power system. Figure 3.1 shows the current existing residential stock in Ireland based on central heating type (oil, gas or electricity), year of construction and housing type from data in the most recent census.

3.2 Methodology

A number of models were used in this analysis to determine the impact of increased electric residential heating. The questions can be summed up as follows: (1) what levels of electrification of residential heating form part of a least-cost energy system in 2020 for Ireland to meet its national targets for emissions reductions in the non-ETS sectors; (2) can the power system operate with this extra level of electrification (provided by the answer to question 1) and what are the associated impacts, including the increase in power system CO_2 emissions; and (3) how many dwellings (and which type) should have heat pumps installed and by how much can oil-based CO_2 emissions be offset as a result? Half-hourly heating profiles were developed using 1 year of half-hourly residential gas-metered data collected in Ireland from June 2010 to May 2011 at 1892 households.[6]

The results are presented from each of the three models described below, each addressing a particular question and adding new insights sequentially. Firstly, results from the Irish TIMES energy systems model pointed to

5 IEA (2011), Oil Information Document. OECD Publishing. Available online: http://dx.doi.org/10.5257/iea/oil/2011

6 Smart Metering Trial Data. Irish Social Science Data Archive. Available online: http://www.ucd.ie/issda/data/commissionforenergyregulationcer

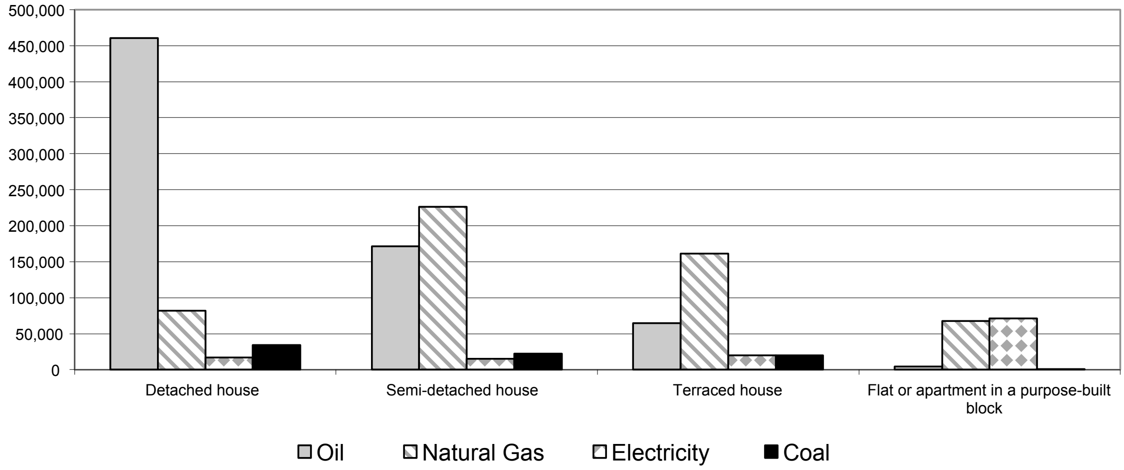

Figure 3.1. The number of dwellings by age, dwelling profile and type of heating system for existing residential houses in Ireland.

the level of electrification forming part of an energy systems configuration designed to meet Ireland's non-ETS target for 2020 at least-cost. Secondly, the PLEXOS power system model was used to determine the impact of this increase in electricity demand on the power system in terms of generation adequacy and increased CO_2 emissions. Finally, the ArDEM model, an archetype dwelling model (described by Dineen and Ó Gallachóir, 2011), was used to estimate the number of dwellings that could be heated with this level of installed heat capacity and the net saving in CO_2 emissions compared with existing oil-fired boilers.

3.3 Results

3.3.1 Level of electrification

Results for the Irish TIMES model suggest that electrification of residential heating should rise by the year 2020 in order for Ireland to meet its non-ETS emission reduction target in a cost-optimal fashion. Imposing the legally binding non-ETS emissions reduction target (in accordance with current EU GHG policy frameworks through Directive 2009/29/EC and Decision 2009/406/EC) results in high levels of electrification. Electrification reaches a level of approximately 914 kilotonnes of oil equivalent (ktoe) (10.6 TWh) by the year 2020. This represents the heating requirements of approximately 817,000 dwellings and the results suggest that it will be met mainly through the use of technologies such as direct electric heating and heat pumps, which will displace oil- and coal-based systems. By 2020, electric heat accounts for 44 % of total residential heating demand and constitutes an almost four-fold increase on 2010 levels.

3.3.2 Power system implications

Generation adequacy is essentially determined by comparing the ability of generation capacity to meet electricity demand. A statistical indicator called the loss of load expectation (LOLE) was used to measure any imbalance between them. LOLE is the probability that the generation capacity available is less than the forecast load for any given half-hour period. When this indicator is at an appropriate level, called the generation adequacy standard, the supply/demand balance is judged to be acceptable. The generation adequacy standard for Ireland is 8 hours LOLE over the entire year. This analysis found that the LOLE for Ireland was breached for a scenario of 1500 MW of installed electrical capacity of ASHP, so only the 500 MW and 1000 MW scenarios of installed capacity are considered further in the analysis.

The 2020 Irish power system was simulated with 0 MW, 500 MW and 1000 MW of installed ASHP electrical capacity to quantify the level of CO_2 emissions associated with electrification. The results are presented in Table 3.1 and show that ASHP with an installed electrical capacity of 1000 MW will require 1696 GWh of electricity per annum and deliver 5087 GWh of residential heat using ASHP with an assumed SPF (seasonal performance factor) of 3. The associated increase in CO_2 emissions in the power sector for this scenario is 953 kt. A sensitivity analysis was also undertaken where the heating profile was again increased by 10%

Table 3.1. Results for power system analysis for 2020

ASHP electrical installed capacity	2020 baseline	500 MW	1000 MW
Power system CO_2 emission (kt)	12,729	13,209	13,682
Full annual generation in SEM (GWh)	42,501	43,371	44,235
Carbon intensity of power system (gCO_2/kWh)	300	305	309
Annual heat pump electric load (GWh)	–	848	1696
Assumed heat pump SPF	–	3	3
Annual heat pump delivered heat (GWh)	–	2544	5087
Heat pump CO_2 emissions due to delivery of heat (kt)	–	479	953

SEM, single electricity market.

and also shifted and lagged from 1 to 5 days and the results showed a corresponding increase of 2% in CO_2 emissions.

3.3.3 How many homes?

To determine the net savings in CO_2 emissions, the ArDEM model was used to estimate the number of dwellings that could be heated with both 500 MW and 1000 MW of installed ASHP electrical capacity. It is assumed for this analysis that the ASHP are replacing existing oil-fired boilers that are at least 20 years old, as it is unlikely that newer boilers would be replaced before the end of their useful life. Two retrofit scenarios are considered, the first where the ASHP would replace oil boilers and no other retrofit works would be carried out to the dwelling. As many of the dwellings considered are old and of poor construction quality this would lead to situations where the ASHP would operate in poorly insulated, energy-inefficient dwellings. This is not desirable from an energy efficiency or CO_2 abatement perspective. In the second scenario, the ASHP would to be installed and, at the same time, the roof and wall insulation of the dwelling would be retrofitted to modern standards. This would reduce the heating energy requirement for a "typical" house from 18,709 kWh/yr to 14,904 kWh/yr. This would allow greater efficiency and a greater number of dwellings to be converted from oil to electricity for the same load on the electricity generation system.

The results in Table 3.2 show that 1000 MW of ASHP capacity could provide the annual space heating and water requirements to meet the demand of 271,951 unaltered dwellings; however, if these dwellings had shallow retrofits (such as wall and ceiling insulation), then this heat load can meet the requirements of approximately 341,315 dwellings. The associated reduction in emissions for the full system is approximately 879 kt of CO_2; however, because of the ETS and non-ETS divide, effectively 1841 kt of emissions are removed from the non-ETS sectors and 879 kt are "placed" in the ETS sector.

3.4 Conclusion

This analysis investigated the potential role of electrification of residential heating through ASHP as a cost-optimal pathway for Ireland to meet the national

Table 3.2. Results from dwelling energy assessment model

	500 MW scenario		1000 MW scenario	
	Unaltered dwellings	Improved roof and wall Insulation	Unaltered dwellings	Improved roof and wall Insulation
Energy required for main space and water heating (GWh)	2544	2544	5087	5087
Energy requirement per dwelling (kWh/yr)	18,702	14,902	18,706	14,904
Numbers of dwellings converted	136,002	170,691	271,951	341,315
Total CO_2 for existing oil boiler (kt/annum)	921	916	1841	1832
Total CO_2 with new ASHP (t/annum)	479	479	953	953
Net reduction in CO_2 (kt/annum)	441	436	888	879

non-ETS GHG emissions reduction target. The results show that using an energy system model alone to answer this question may lead to an overestimation of the contribution of this technology, by almost a factor of two in terms of energy. The reason is due to the aggregated representation of the power system and the time resolution that is required to limit computational complexity in the energy systems model. This research highlights the value of a multi-model or soft-linking approach to verify the technical appropriateness of results.

Ireland faces strong challenges in the pursuit of the emission reduction non-ETS target. This work has shown that greater electrification of existing oil-fired central heating systems through ASHP technology should warrant further investigation. However, ultimately, it is the house owner who will have to pay for these systems. It is probably fair to assume that a home owner's decision to install a heating system will be influenced more by economic than by CO_2 considerations, so additional analysis is required to assess the economic and other barriers to deployment, such as financing and payment for systems.

4 Impact of Economic Recession on the Costs of Climate Mitigation

Economic activity has long been a key driver of energy demand and, consequently, of energy-related GHG emissions, and therefore is an important element in energy and climate mitigation modelling. The EU has established ambitious long-term GHG emissions reduction targets for the year 2050 (80% to 95% below 1990 levels) and this will require a radical transformation of EU energy systems in order to achieve the required decoupling of economic growth from GHG emissions growth. It is therefore fundamental, in the current economic context, to understand the link between economy recovery, energy service demand evolution and subsequent energy consumption, and energy-related CO_2 emissions. This chapter explores the impact of two different future economic activity growth projections on the evolution of short and medium-term energy demands and long-term GHG targets. Ireland is an interesting case study for this analysis. Between 1990 and 2007, Ireland's energy-related CO_2 emissions grew by 2.5% per annum, prompted by economic growth levels of 6.5% per annum, in terms of real gross domestic product (GDP). Between 2007 and 2010, economic activity in Ireland contracted by 10% and energy-related CO_2 emissions fell by 12%. Over the past two years, two different sets of economic forecasts have been produced that show deeper and longer lasting effects of economic recession. This chapter quantifies the impact of these different economic recovery pathways on long-term mitigation costs, namely the cost to achieve an 80% GHG emissions reduction target. The full details of this research are described by Gargiulo *et al.* (2012).

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 and emerging targets for 2030. Under the Emissions Trading Directive (2009/29/EC), approximately half of GHG emissions are due to large point source emitters (within industry, power generation and transformation) and are regulated under the ETS. The collective target for all participants in the ETS is a 21% reduction in GHG emissions relative to 2005 levels[7] by 2020. Under the EU Effort Sharing Decision (2009/406/EC), for the remaining half of GHG emissions (including agriculture) (i.e. non-ETS emissions), the target for Ireland is to achieve a 20% reduction relative to 2005 levels. Recent national projections suggest that agriculture GHG emissions will be reduced by 4.4% in the period 2005 to 2020 (EPA, 2011). There are, as yet, no published projections for agriculture GHG emissions available for Ireland for the period beyond 2030. If agriculture emissions remain at similar levels to those predicted to be reached in 2020 (assuming they remain constant over the period 2020 to 2050), 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 (EC, 2011), GHG emissions in agriculture are anticipated to reduce at the EU level by 36% to 37% by 2030 and by 42% to 49% by 2050. According to this roadmap, the other (primarily energy) sectors are anticipated to achieve more significant reductions than agriculture. This indicates that the share of GHG emissions from agriculture will grow over time and the role of the energy sector will reduce, suggesting 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 between 1990 and 2007[8] 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 on how the recession and different economic forecasts impact on the costs of climate mitigation policy.

7 For the period after 2020, Directive 2009/29/EC assumes that ETS emissions will reduce by 1.74% per annum (i.e. equivalent to a cumulative reduction of 1.3% relative to 1990 by 2050).

8 http://www.epa.ie/climate/emissionsinventoriesandprojections/#.VbIW5vlzTwt

This chapter focuses on different scenarios of economic recovery and how each will impact on Ireland's energy service demand, energy consumption, CO_2 emissions, energy system costs and the marginal CO_2 mitigation price. Two sets of economic forecasts were used for future macro-economic drivers. One forecast was generated early in the economic recession (2009), while a second was generated a year later (2010). In each successive set of forecasts, the impacts of the recession were deemed to have a deeper and longer lasting effect. The starting point to understanding the link between economic recovery and energy service demand evolution is the comparison of these forecasted scenarios; this is followed by the development of new sensitivity analysis with different economy recovery assumptions (slow, fast and very fast) to generate new macro-economic drivers and energy service demands.

4.1 Methodology

Within this analysis, two different future economic activity growth projections from the Economic and Social Research Institute (ESRI) were used to develop the different energy service demands in the Irish TIMES model. This work quantifies the impact of these two different economic recovery pathways on long-term mitigation costs, namely the cost to achieve an 80% GHG emissions reduction target. The two energy service demand scenarios for the Irish TIMES are called *Dem2009* (based on economic activity growth in 2009) and *Dem2010* (based on economic activity growth in 2010). By comparing the energy service demand projections from the 2009 and 2010 forecast, a greater understanding of the impact of the recession on the cost of climate mitigation can be achieved. Figures 4.1 and 4.2 contrast some of the more important projections and energy service demands in the Irish TIMES model.

Figure 4.1 compares the GDP projection for the two different economic activity growth projections from the ESRI. These GDP projections are used to develop the two sets of energy service demands in the Irish TIMES model. Projections from 2009 (Dem2009) were more optimistic about the possibility of a quick and strong recovery of the economy on the medium and long term, while the 2010 economic projections are for a slower growth trend. The 2010 GDP projection in the year 2015 is about 8% lower than the 2009 projection, in 2020 it is about 14% lower and in the period 2030 to 2050 there is a difference of 25% in the GDP growth.

The projected growth of a number of demand drivers in the two different economic activities forecasts is more or less the same and hence the corresponding energy service demand projections are also similar. In the residential sector, population and household growth are the same in both the economic activities projections,

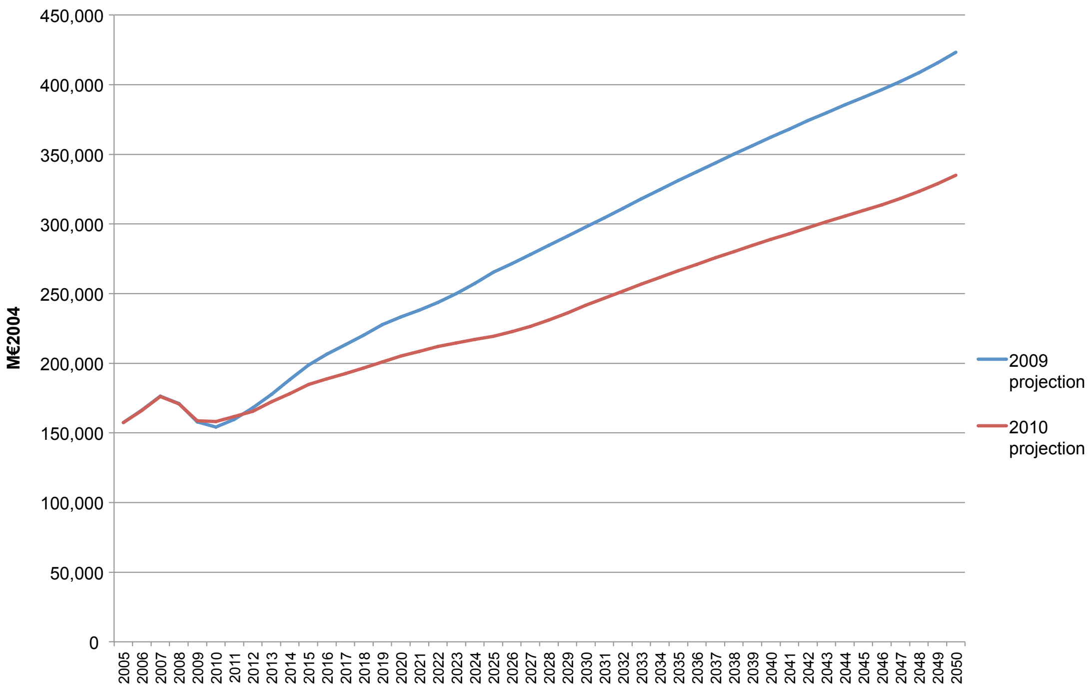

Figure 4.1. Comparing the 2009 and 2010 GDP projections (data source: ESRI). The projected cost is shown in millions of euros at 2004 prices (M€2004).

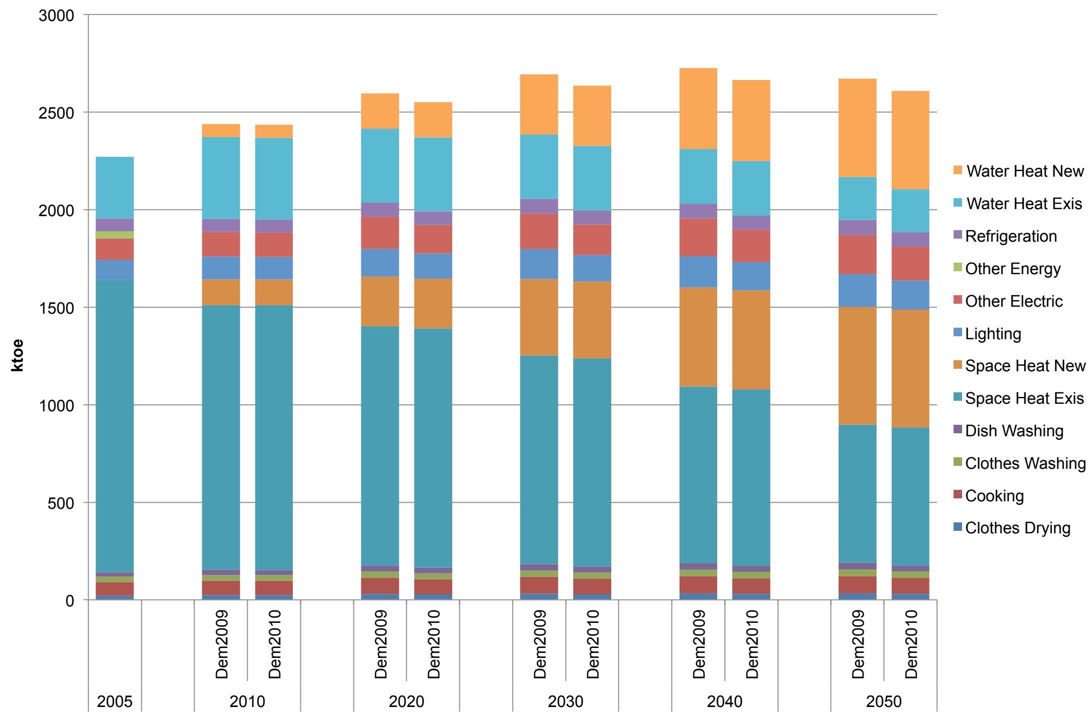

Figure 4.2. Energy service demand projection in residential sector (in ktoe).

although the private income value is slightly different. The effect of this difference is shown in Figure 4.2 and mainly affects the energy service demand of lighting and other electric appliances, because space heating and water heating depend on the population and number of households.

4.2 Results

The Irish TIMES model was run in two scenarios with the different energy services demands, derived from two projections of macro-economic driver as described in section 4.1. The model was run to the year 2050 and a constraint on a GHG emission reduction of 80% was imposed in both models. Due to different macro-economic drivers and consequent different economic recovery speeds, this section provides the marginal CO_2 abatement costs associated with different demand projections (or, in other words, to different economy recovery scenarios) for Ireland.

The energy consumption by sector with the two demand projections (Dem2009 and Dem2010) is shown in Figure 4.3. In the 2020 projection, the final energy consumption based on Dem2010 is about 7% lower than the total energy consumption from the Dem2009 projection. By individual sector, the energy consumption for the 2010 projection in the transport sector is lower than that in the 2009 projection, the industry sector is 15% lower and the services sector is about 3% lower, while in the residential sector it is only 1% lower than in the 2009 projection. Between 2020 and 2050, the average consumption difference is 10% and in 2050 the Dem2010 results are 13% lower than for Dem2009 with a 16% difference in the transport sector and 17% difference in the industrial sector.

Figure 4.4 shows electricity consumption by fuel and compares the Dem2009 and Dem2010 scenarios. In 2020, the only difference between these scenarios is a higher penetration of renewable energy in Dem2009 due to the higher demand values. In the 2030 and 2040 scenarios, gas carbon capture and storage (CCS) technology penetrates, while in the Dem2010 this happens only in 2050. It is important to bear in mind that the only input differences between the two scenarios are demand projections and that all other technology options and potentials are the same. In this case, due to the higher demand projection in Dem2009, the model brings gas CCS online in 2030, whereas in Dem2010, gas CCS only comes online in 2050.

4.3 Marginal Abatement Cost

To compare the marginal cost of abatement for both model scenarios, the shadow price of CO_2 constraint was extracted from the model and compared. The TIMES model is formulated as a linear programming

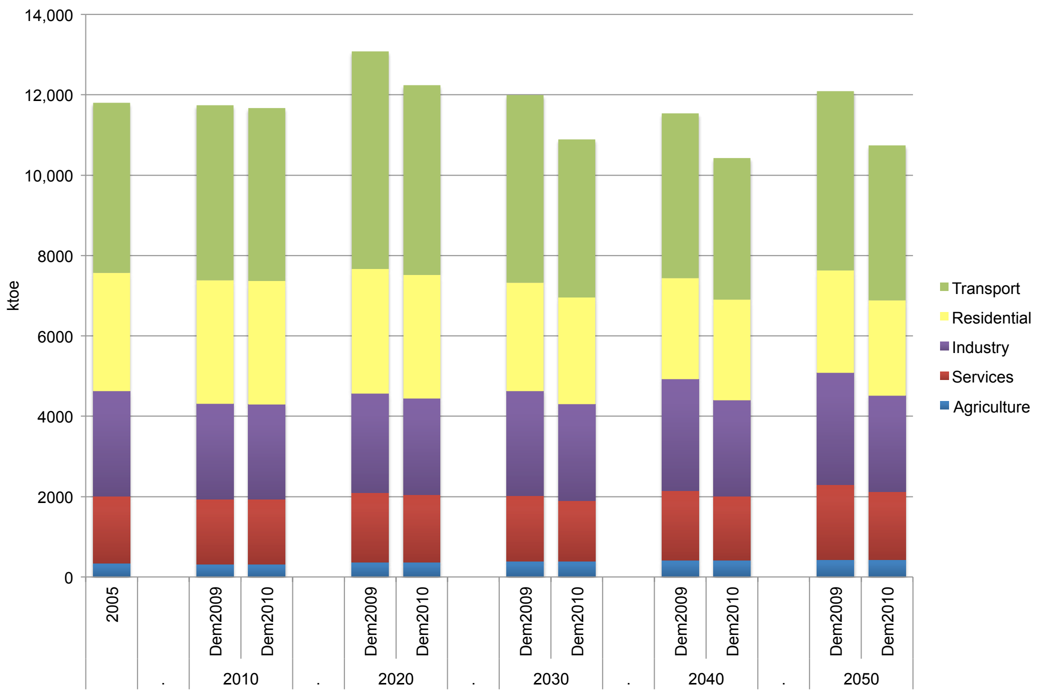

Figure 4.3. Final energy consumption by sector.

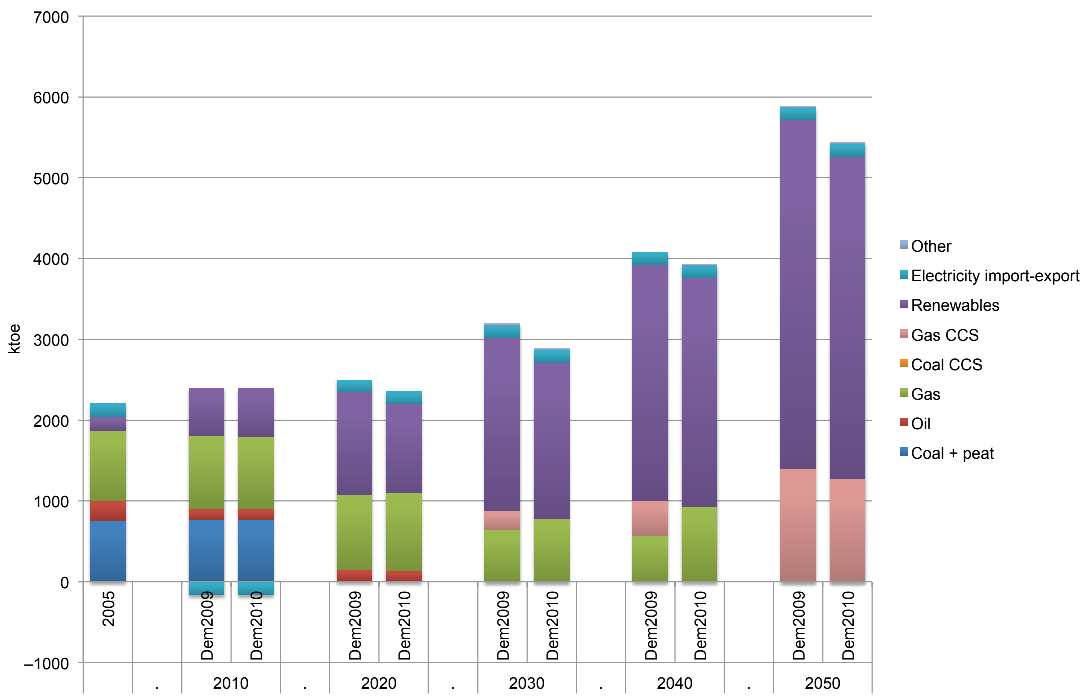

Figure 4.4. Electricity consumption by source.

problem. The solution of a linear programming model consists of a primal and dual solution. The primal solution of a TIMES model (or of Irish TIMES) provides the optimal values for the decision variables of the primal problem (e.g. energy flows and installed capacity) while the dual solution provides the marginal costs that are assigned to each constraint of the primal problem (e.g. CO_2 upper target).

Table 4.1 compares the CO_2 marginal costs for the two demand scenarios. The Dem2009 scenario based on high economic driver growth shows higher CO_2 marginal costs in particular for periods 2020 (about 50%

more than Dem2010) and 2050 (about 32% more than Dem2010). The difference in the CO_2 marginal price is due to the different demand and, consequently, the different technology and fuel mix by sector.

4.4 Economic Impact

The energy system costs and the investment costs associated with the different economic recovery pathways is also an output of the Irish TIMES model. In this way, the model can be used to test different economy recovery speeds and the effect on demand evolution and the associated impact on the energy sector and costs. The system cost is the sum of all the annual investment, activity, flow (including import/export prices) and fixed operating and maintenance costs. The investment cost is the cost due to the new capacities installed in the model for each technology (e.g. new power plants, new cars or residential boilers). It is clear that the system and investment costs for the Dem2010 scenario are lower than costs in the Dem2009 scenario. The difference between Dem2009 and Dem2010 system cost in 2020 is 13% and in 2050 it is 18%, while the difference in the investment costs is 14% and 21%, respectively (see Table 4.2).

4.5 Conclusions

The impact of the economic recession on energy consumption could potentially create distortions in the policies that each European country should apply to achieve the 2020 target and long-term targets on GHG. The links between economic recovery, energy service demand, energy consumption, CO_2 emissions and price, and system costs are extremely important to identify and policymakers should be aware of these linkages and their impacts. The appropriate policies should be adopted to achieve GHG reduction targets.

Between 2005 and 2050, the average GDP growth rate for Ireland is predicted to be 2.22% in the 2009 forecasts and 1.7% in the 2010 forecasts. The impact of these different economic activity forecasts on the energy service demands was an average growth of 0.43% and 0.08% in the “other industrial sectors”, 1.7% and 1.1%, for transport passenger demand, 1.9% and 1.6% for freight transport, and 1.04% and 0.81% for the service sector for the 2009 forecast (Dem2009) and 2010 forecast (Dem2010), respectively. The forecast impact of the difference in economic activity for residential and agriculture sectors was minor.

The energy service demand drives the model solution in terms of flows, emissions, installed capacity and system cost. The final predicted energy consumption average growth between 2005 and 2050 in the Dem2009 scenario was 0.05%, although, in the same period for the Dem2010 scenario, energy consumption was predicted to fall by 0.21% with the same CO_2 emissions level (due to the target imposed in the model) and a CO_2 price for the Dem2009 scenario of €76/tonne in 2020 and €2255/ton in 2050 and €51/tonne and €1674/tonne in the Dem2010 scenario.

The total system cost of Dem2009 is about 10% higher than the total system cost in the Dem2010 scenario with a difference in the investment costs between Dem2009 and Dem2010 of a 13% increase in 2020 and an 18% increase in 2050.

Table 4.1. CO_2 marginal price in euros per tonne

	2020	2030	2040	2050
Dem2009	76	274	275	2255
Dem2010	41	263	221	1674

Table 4.2. System and investments costs difference between Dem2009 and Dem2010

	2010	2020	2030	2040	2050
Systems	1%	13%	18%	19%	18%
Investments	2%	14%	18%	18%	21%

5 Energy Security – Constrained Oil Supply Scenario for Ireland

Ireland imports 88% of its energy requirements. Oil makes up 59% of total final energy consumption (TFC) (Figure 5.1). Import dependency, low fuel diversity and volatile prices leave Ireland vulnerable in terms of energy security. This work models energy security scenarios for Ireland using long-term macroeconomic forecasts to 2050, with oil production and price scenarios from the International Monetary Fund (IMF), within the Irish TIMES energy systems model. The analysis focuses on developing a least-cost optimum energy system for Ireland under two scenarios of constrained oil supply (one with 0.8% annual import growth and another with a 2% annual import decline) and subsequent sustained long-term price shocks to oil and gas imports. The results point to gas becoming the dominant fuel source for Ireland, at 54% TFC in 2020, supplanting oil from reference projections of 57% to 10.8% TFC. In 2012, the cost of net oil imports was €3.6 billion per annum (2.26% GDP). The modelled high oil and gas price scenarios show an additional annual cost in comparison to a reference of between €2.9 billion and €7.5 billion per annum by 2020 (1.9% to 4.9% of GDP). Investment and ramifications for energy security are discussed. The full details of this research are described by Glynn *et al.* (2014).

5.1 International Monetary Fund Supply Scenario Inputs

The scenario inputs specific to this work are based on recent work within the research department of the IMF. The IMF first published oil sector research using their Global Integrated Monetary and Fiscal (GIMF) model in a chapter titled, "Oil Scarcity, Growth, and Global

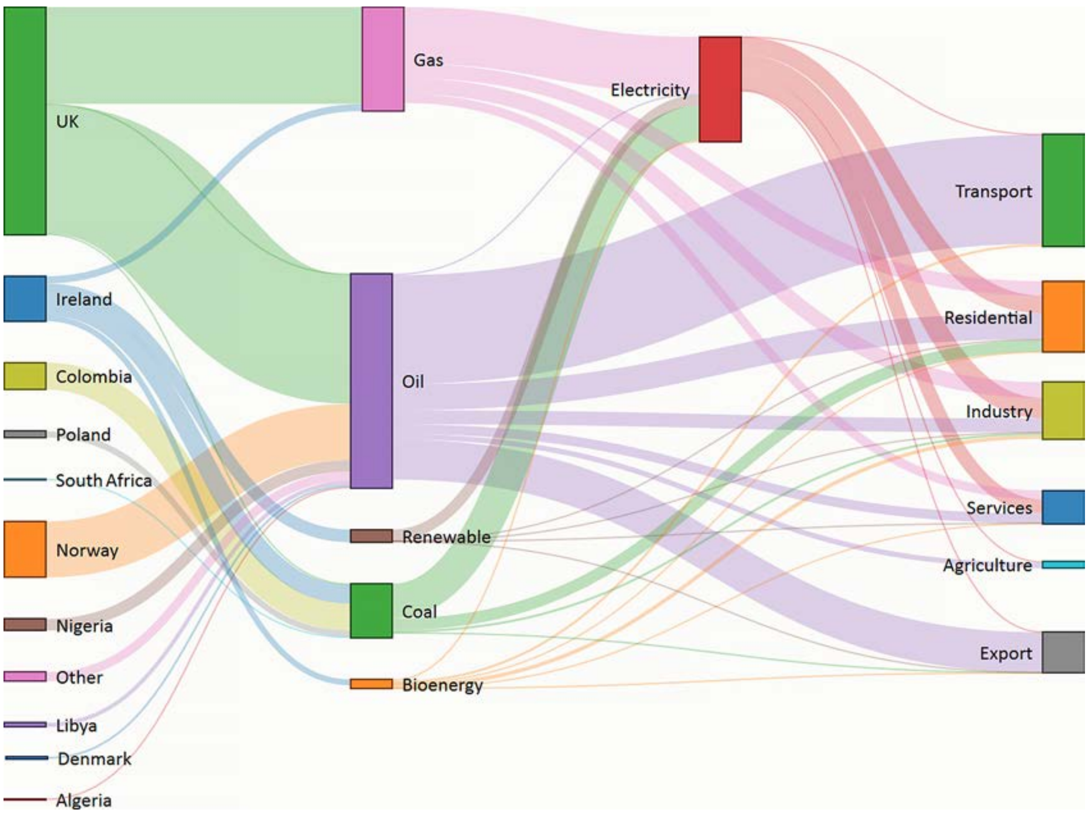

Figure 5.1. Ireland's present energy system energy flow 2011. Primary energy flows from energy sources on the left to sectorial final consumption on the right. Data sources: Sustainable Energy Authority of Ireland and IEA.

Imbalances", within their 2011 World Economic Outlook (International Monetary Fund, 2011). The model investigates the effects of oil supply, price, substitutability and oil-derived productivity upon the global and regional economies. They developed four scenarios, a benchmark (IMF1), an upside efficiency scenario (IMF2) with greater substitution away from oil, a downside productivity scenario (IMF3) where oil has a greater role in economic production and a downside scenario (IMF4) where there is a greater decline in oil production compared with the benchmark scenario.

The benchmark scenario considered the effect of a slowing of the growth rate of global oil production, to a rate of increases of only 0.8% per annum in comparison to the historical 1.8% per annum. This knowledge is reflected in market realisation that supply will not automatically meet demand as has been historically assumed. This realisation results in an immediate price shock resulting in a 63% increase, reflecting the relatively low, short-term price elasticity. Demand destruction and comparably larger medium-term price elasticities enable fuel substitution and the stabilisation of the rate of price increase by year three on a new, higher long-term price trajectory. An upside efficiency scenario investigates the effect of greater technological substitutability away from oil. A productivity scenario investigates benchmark substitutability, but includes increased levels of productivity and an increase of the cost share of oil historical levels of 5% to 25% of cost share of production. The IMF considered a final fourth scenario of equivalent substitutability of the benchmark scenario, but where global oil supply declines at 3.8% in comparison to the benchmark, or 2% in gross terms. This effect again takes the shape of a market realisation of declining oil production at 2% per annum, and an immediate price spike of 240% in year one. Medium-term fuel substitution leads to a slowing of the rate of price increase by year three at a 286% real price increase, growing to 487% real price increase by year 10. The "peak" scenario (IMF4) and the benchmark scenario (IMF1) results show world oil supply and resultant price increases of 350% and 90% respectively within 5 years and are outlined in Figure 5.2. While these outputs may appear divergent and extreme, they are based on conservative assumptions of maintaining a 0.8% growth in oil production to a gross 2% oil production decline rate, while others expect decline rates of between 3% and 5%. The benchmark and peak scenario IMF outputs are the starting point for this investigation and, while the Irish TIMES model is calibrated to the current Irish energy system, the outputs should be seen as exploratory scenarios rather than forecasts given macroeconomic uncertainty.

5.2 Results

The methodological approach combines Irish TIMES, the Irish energy systems model, with the IMF's research department's oil price and supply scenario projections

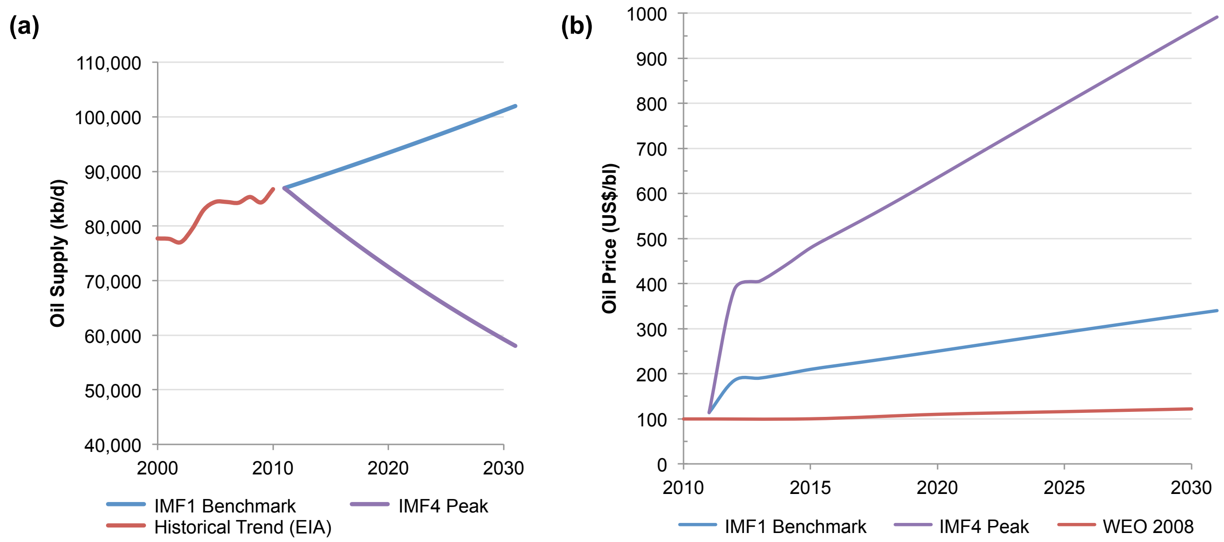

Figure 5.2. International Monetary Fund global integrated monetary and fiscal model outputs showing (a) extrapolated world oil supply in kilobarrels/day (kb/d) and (b) resultant prices by year in US$ per barrel (US$/bl). Reprinted from Glynn *et al.* (2014) with permission from Elsevier.

for constrained global oil supply. These projections are based on the IMF's in-house global dynamic stochastic general equilibrium model (GIMF) for scenarios of increasing price volatility and supply contraction. This work focuses on the Irish calibrated reference energy system, combined with the IMF benchmark and downside (peak) scenarios, disaggregated into two oil import volume constrained scenarios and three detailed price-constrained scenarios. The impact on emissions is not examined.

In 2003, the cost of net oil imports to Ireland was €1.46 billion (1.0% GDP) per annum. In 2012, the cost of net oil imports was €3.6 billion (2.26% GDP) per annum (Central Statistics Office of Ireland, 2013). The Eurozone debt crisis has had a detrimental effect on the value of the euro and the subsequent ability to trade and import commodities denominated in US dollars. The annual average Brent oil price for 2011 and 2012 respectively were €79.9 per barrel and €87.1 per barrel, which represents a 9% increase year-on-year and a 34% increase since the dollar spot price maximum in 2008.

In the possible scenario where global oil supply remains in its current stagnated state with minimal supply growth, the benchmark scenario energy system pathway outlines a least-cost energy system with an additional annual cost of €2.9 billion by 2020 (1.9% of GDP), in comparison to the reference case. The worse-case scenario, in which global oil supply begins to contract at 2% per annum and the subsequent price increases instigate a process of rapid fuel substitution and demand destruction, shows a least-cost energy system for an additional cost of €7.5 billion per annum by 2020 (an additional 4.9% of GDP). An annual cost of this magnitude could potentially undermine the ability of the economy to grow; however, as this is the least-cost solution for this scenario, continuing the current energy mix consumption trend would be more costly.

In the scenario where gas prices remain indexed to oil prices and global oil production remains stagnant, gas would be used as a transition fuel until 2020. This is a useful outcome: both costs-bench and bench plus gas scenarios show similar energy systems to 2020. Beyond 2020, a greater divergence occurs, where penetration of renewable energy sources increases and, most noticeably, biofuel imports substitute for natural gas imports in the transport and industry sectors.

6 How Can We Integrate Agriculture and Energy Modelling?

Agriculture is responsible for approximately 33% of anthropogenic GHG emissions in Ireland (and 25% globally). This highlights the importance of the agricultural sector in Ireland's mitigation challenge. The work described here developed and tested a methodology for integrating agricultural systems modelling and energy systems modelling. The goal was to extend the Irish TIMES energy systems modelling approach by incorporating agriculture in order to provide richer insights into the dynamics and interactions between the two (for example in competition for land use). This shortened version of the previously published paper (Chiodi *et al*., 2015) summarises the methodology used, and also presents indicative results to illustrate the approach and provide initial insights.

6.1 The AGRI-TIMES Module

This work developed a TIMES module for the agriculture system (Agri-TIMES) to be used in conjunction with a full energy system model (Irish TIMES). The Irish agriculture system has been characterised and modelled in a simplified way in terms of supply commodities (land and water), production (e.g. animal storage, processing and production), and service demands (e.g. litres of milk). Abatement measures include extended grazing, manure management and dietary supplements. This approach draws on data from the FAPRI-Ireland and FLAGGS models.

6.2 Results

The results for two scenarios are shown in Table 6.1, comparing 50% and 60% GHG emissions reduction targets by 2050. The results are illustrative of the methodology rather than providing robust guidance for the national mitigation plan. The results show that, to achieve GHG emissions targets of between 50% and 60% below 1990 levels (GHG-50 and GHG-60) at least cost, the energy system would be subject to steep reductions (75–87%) in emissions, while non-energy sectors (notably agriculture) contribute partially (reductions of 17–25% in emissions). Compared with the corresponding emissions reductions at EU level (presented in the EU Low Carbon Roadmap), this work shows that energy results are aligned with the EU emissions reductions. For agriculture however, the EU Roadmap target of a 42–49% reduction in emissions relative to 1990 levels appears not to be applicable to Ireland. This contrasts the constraints facing mitigation in agriculture in Ireland with those in the EU as a whole.

Table 6.1. GHG sectoral changes (relative to 1990) for the GHG-50 and GHG-60 scenarios

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

7 Beyond Ireland – Impacts of National Renewable Energy Actions Plans on the North-west European Electricity Market

This work builds a comprehensive north-west European electricity market model for the year 2020 and uses it to quantify the impacts of ambitious national renewable electricity targets. The geographical coverage of the model comprises Belgium, France, Germany, Great Britain, Ireland, Luxembourg and the Netherlands. The model simulates the electricity market operation for the entire region at a half-hourly resolution and produces results in terms of electricity prices, cross-border flows, emissions and associated total system costs. The impact of two carbon price scenarios was examined within the model. The results highlight the importance of integrated modelling of interconnected regions, as cross-border power flows play a significant role in market dynamics, especially in the presence of geographically dispersed variable renewable energy generation sources such as wind and solar energy. The results suggest that, based on these national plans, congestion will be present on a number of key lines at long periods during the year. The full details of this research are described by Deane *et al*. (2015b).

7.1 Introduction

The creation of a European internal electricity market is a priority of the EU. Since 1996, with the introduction of the "First Legislative Package" in the internal energy market (Directives 96/92/EC and 98/30/EC), there has been a move towards electricity market integration between national markets with a focus on common rules for generation, transmission and distribution of electricity. Despite two EU Directives in 2009 (Directives 2009/72/EC and 2009/73/EC)[9] and the creation of the Council of European Energy Regulators (CEER), the Directorate-General for Competition report on energy sector inquiry (EC, 2007) found inefficiencies impeding a European internal electricity market. Issues highlighted included a high degree of market concentration, vertical integration, insufficient interconnecting infrastructure between nations and insufficient incentives to improve this, as well as incompatible market design. Furthermore, a lack of simplified and standardised regulations has been identified as a barrier to a European internal market.

This chapter describes the development of (to the authors' knowledge) the first detailed electricity market model for the year 2020 for the north-west European region, which includes Belgium, France, Germany, Great Britain, Ireland, Luxembourg and the Netherlands. Renewable energy capacities are aligned in the model to National Renewable Energy Actions Plans (NREAP) submitted by each country to the EU. The goal of the work is to develop (and make freely available) a comprehensive database of electricity power plants in north-west Europe to improve the understanding of the development of regional markets within the EU. In addition, the database and model were used to determine the impacts of renewable energy targets on electricity prices and regional flows within the study area.

7.2 Data Sources

A number of publicly available sources were drawn upon to gather the large amount of information required to develop the 2020 north-west Europe electricity model. These sources can primarily be divided into power plant technical data, renewable energy installed capacities, projected interconnection capacity between each country and load profiles.

In all, the current model and database contains over 900 individual power plants. Information on power plant capacity and type were taken from Transmission Systems Operators (TSOs), regulators, generation adequacy reports and individual company websites. In cases where a generation adequacy report provided information only as far as 2018, it was assumed that this thermal capacity was unchanged for 2020. A breakdown by primary fuel type for each country is provided in Table 7.1 for installed MW capacities and number of thermal power plants.

9 The First Legislative Package was adopted in 1996 and was replaced by the Second Legislative Package in 2003. There has since been a Third Legislative Package, which was adopted in 2009.

Some jurisdictions, such as the All Island[10] (AI) system, provide very detailed information concerning power plant technical characteristics and, where possible, direct information on thermal generation type is used; however, in most countries, detailed information is not available and has to be inferred from the best available sources. Each power plant in the model is described by a maximum capacity, a minimum stable level, start costs, minimum up and minimum down time and, where applicable, ramp rates. Average heat rates are used to describe the efficiency of each power plant. The efficiency of each plant is inferred from the fuel type, size and, where possible, the age of the plant. Information from the IEA-ETSAP technology database is used to approximate the average efficiency of each plant type by country. Generation plants that are predicted to come online between 2012 and 2020 are generally assumed to have the maximum efficiency for that plant type. Natural gas plants that are less than 100 MW in capacity are assumed to be open cycle gas turbines, whereas plants with a higher capacity than this are assumed to be CCGTs, unless specific information shows otherwise. Coal plants in the UK are also assumed to have limitations on the annual number of running hours and this is reflected in the estimation of the maximum annual capacity factors of 38%. These assumptions aim to capture the impact of the Large Combustion Plant Directive (2001/80/EC) and the Industrial Emissions Directive (2010/75/EU). Pumped storage plants are modelled as individual units (38 plants) with a pumping efficiency of 75% in all cases. All units are also assumed to operate on a daily cycle where the storage reservoir is forced to return to its initial level at the end of each day. This is potentially a restrictive operational rule and further research will look at the impact of relaxing this constraint.

Transmission within each country is ignored and a "copper plate" assumption is made. Interconnection between each country is included with values for 2020 sourced from ENTSO-E's Ten Year Network Development Plan (ENTSO-E, 2014) and from regional TSOs. Figure 7.1 shows the MW interconnection capacities assumed between each country for the target year 2020.

7.3 Results

The PLEXOS model was populated with individual unit characteristics and technical details. A number of simulations were undertaken to determine the resultant flows of electricity and market prices (as represented by shadow prices) of electricity under a number of carbon price assumptions, namely €20 and €45 per tonne. In PLEXOS, shadow prices are automatically determined as part of the solution to the optimisation problem. The price reported represents the shadow price of the constraint that matches supply and demand. This can be considered as the change in the objective function for an incremental change in demand.

France is a significant net exporter of low-cost electricity and its high degree of interconnection to other regions makes it attractive as an export market. However, as shown in Figure 7.2, there are long periods of

10 The All Island System refers to the power system of both Northern and Republic of Ireland. The system is currently operated as the Single Electricity Market.

Table 7.1. Installed thermal capacity (MW) and number of thermal plants in each country for 2020

Country	AI	UK	FR	DE	BE	NL
Capacity (MW)						
Coal	855	21,384	2935	49,610	470	6652
Gas	4320	49,622	10,606	27,955	11,000	22,919
Nuclear	0	6078	64,670	8052	5060	504
Number of thermal power plants						
Coal	3	13	5	141	2	10
Gas	24	76	26	249	69	66
Nuclear[a]	0	5	58	6	6	1

[a]Information on German nuclear 2020 capacity and phase out was taken from the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. For the UK, information was taken from the Department of Energy and Climate Change.

AI, All Island; BE, Belgium; DE, Germany; FR, France; NL, the Netherlands; UK, United Kingdom.

Figure 7.1. Projected interconnection between each country for 2020. Reprinted from Deane *et al.* (2015) with permission from Elsevier.

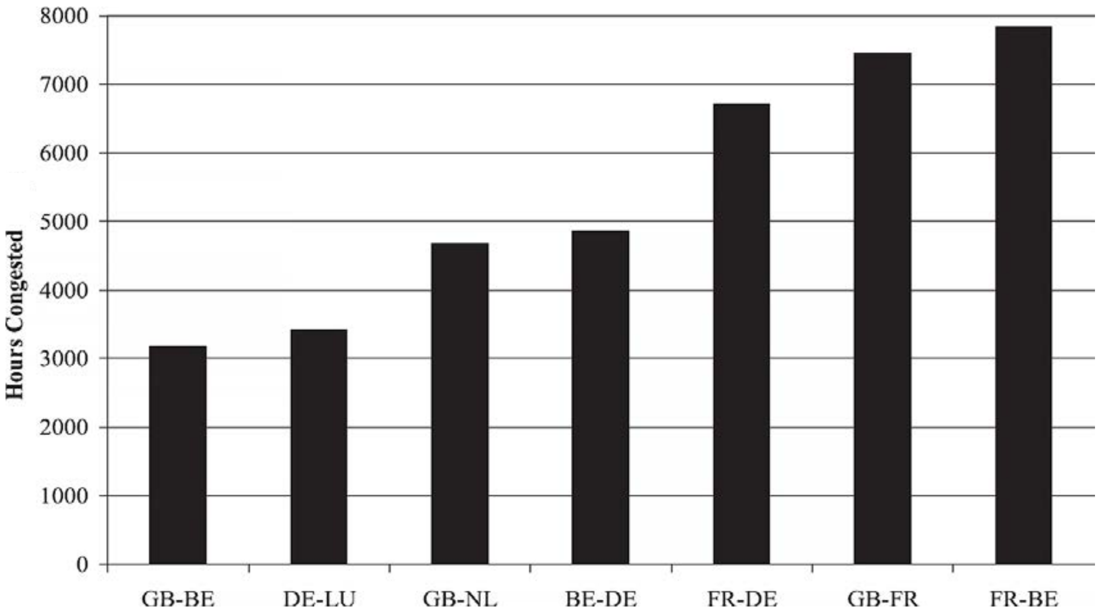

Figure 7.2. Congestion time in hours for electricity interconnector lines for European countries. BE, Belgium; DE, Germany; FR, France; GB, Great Britain; LU, Luxembourg; NL, the Netherlands. Reprinted from Deane *et al.* (2015) with permission from Elsevier.

congestion (i.e. when the line flow is at the maximum possible flow) predicted for the interconnector lines, particularly from France, as power is wheeled through Belgium into the UK or into the Netherlands and on to Germany. The level of congestion places strong limitations on the ability of the system to move electricity around efficiently. The impact of a higher carbon price tends to reduce imports and exports of electricity across most countries; Germany is an exception to this trend as a higher carbon price drives an increase in imports, particularly from France. This is accompanied by a reduction in exports from Germany, particularly to the Netherlands, which reduces imports and generates more from local gas-fired generation. The UK also

reduces imports from France and Belgium in favour of CCGT generation, which is brought into favour by a higher carbon price.

Annual CO_2 emissions for each region are presented in Table 7.2. Germany and the UK, with a high portion of coal-fired generation, are the largest absolute emitters in the region. Interestingly, the CO_2 emissions in Belgium increase significantly at the higher carbon tax level, linked to the greater amount of exports. The inclusion of an extra €25 of carbon tax is predicted to reduce emissions by approximately 50 MT.

7.4 Conclusion

The presented analysis describes and details the development of a 2020 electricity market model calibrated to each country's NREAP projections for the north-west region of Europe. The focus of individual NREAPs is generally limited to impacts at a Member State level. The value of this work is assessing the impacts at a regional and inter-Member State level. The results highlight the importance of integrated modelling of interconnected regions, as cross-border power flows play a significant role in market dynamics, especially in the presence of geographically dispersed variable renewable energy generation sources such as wind and solar energy. Flows on the interconnectors are an important aspect of any future EU market and the results here shows that congestion will be present on a number of key lines over long periods during the year. This is especially true for France and its neighbouring regions, as low-cost nuclear and renewable electricity will flow to regions with higher prices. The wheeling of power through Belgium and the Netherlands into either the UK or Germany is also seen periodically.

The work also highlights the contribution that integrated modelling can make to policy decisions by providing insight into the impact of varying levels of carbon pricing and, in particular, how this level of pricing impacts on total generation costs and emissions reductions in each specific country.

Regional market prices, as inferred from the shadow price of electricity, are naturally seen to be lowest in regions with strong nuclear (such as France) or renewable energy capacity (such as Ireland). The impact of a higher carbon price has a lower impact on these regions. The carbon intensity of the full power system as presented here is expected to be approximately 236 g CO_2/kWh for a carbon price of €20 per tonne that reduces to 206 g CO_2/kWh for an increased carbon price of €45 per tonne. Germany, with its legacy of coal-fired generation, and the UK are the largest emitters in absolute terms.

This work presents the first important step in the analysis of regional market integration in the EU. Further work will focus on the areas where increased interconnection would have the most beneficial impacts under a range of carbon scenarios and market structures within the study region.

Table 7.2. Annual CO_2 emissions for each country from the electricity sector

Country	CO_2 emissions for €20 per tonne	CO_2 emissions for €45 per tonne
AI	13,292,776	8,409,913
BE	3,879,131	7,736,829
DE	236,575,446	197,255,119
FR	5,313,165	1,882,753
GB	97,804,477	96,148,749
LU	220,357	217,730
NL	52,659,860	45,214,760
Total	409,745,212	356,865,853

AI, All Island; BE, Belgium; DE, Germany; FR, France; GB, Great Britain; LU, Luxembourg; NL, the Netherlands.

8 Conclusions and Future Research

Irish TIMES is Ireland's only fully integrated long-term energy systems model and the model is unique in its ability to provide cross-sectoral evidenced-based analysis for climate and energy policy. This report outlines research outputs from the EPA-funded Phase II of the Irish TIMES Project. The project has made a number of important diverse contributions to national and international research, reflecting the complexity and interdependency of energy and climate policy. The project has developed improved methodologies and techniques for linking and coupling models to develop robust policy evidence for a transition to a low carbon future and has also delivered direct model improvements for the integration of agriculture and economic feedback into the decision process.

The key recommendations from this research project centre on the further development of the multi-modelling approach that was developed this project to other aspects of energy systems modelling in order to gain the following:

- An improved understanding of the interactions between the energy system and the economy (in order to approach questions, such as what are the economic impacts of different mitigation ambition levels). This can be done by incorporating price response within the Irish TIMES model (i.e. elastic demand), by hard linking Irish TIMES to a simplified macro-economic model (the MACRO model) and by soft-linking Irish TIMES to a more detailed macro-economic model (e.g. ESRI's HERMES model)
- An improved understanding of the respective roles of energy and agriculture in GHG emissions abatement, by soft-linking the Irish TIMES model with FAPRI-Ireland (a macro-level agricultural model of Ireland) and FLAGGS (a farm level agricultural model of Ireland). This will provide insights into combined mitigation pathways and enable an analysis of land use competition.
- An improved understanding of the role of increased integration of Ireland's energy system with other EU energy markets. This can be done by expanding the electricity dispatch modelling to integrated electricity and gas modelling and by developing EU-wide models. This will enable analysis of increased electricity and gas infrastructure development (including interconnection to France, further gas infrastructure, etc.). In addition, the role of imported bioenergy to meet future energy needs in transport and heat should also be explored from the perspective of the sustainability of mitigation pathways.

Within the context of Irish legislation for action on climate change, it is also important that the modelling capacity developed through this project should be utilised to inform (1) government decisions regarding national policy and (2) Ireland's negotiating position within the context of the EU climate and energy policy framework. An important first step has been taken in this regard: UCC and ESRI were commissioned to provide technical advice and guidance on the development of a low carbon roadmap for Ireland with the aim of achieving transition to a low carbon, climate resilient and environmentally sustainable economy in the period up to and including the year 2050. The UCC/ESRI report on a *Low Carbon Energy Roadmap for Ireland*[11] (Deane *et al.*, 2013) builds on the research carried out in the Irish TIMES research project and applies it directly to inform policy decisions.

11 http://www.environ.ie/en/Publications/Environment/ClimateChange/FileDownLoad,41727,en.pdf

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Abbreviations

AI	All Island
ASHP	Air source heat pumps
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
ESRI	Economic and Social Research Institute
ETS	(EU) Emissions Trading Scheme
ETSAP	Energy Technology Systems Analysis Program
GDP	Gross domestic product
GHG	Greenhouse gas
GIMF	Global Integrated Monetary and Fiscal (model)
IEA	International Energy Agency
IMF	International Monetary Fund
ktoe	Kilotonnes of oil equivalent
LOLE	Loss of load expectation
NREAP	National Renewable Energy Actions Plan
SPF	Seasonal performance factor
TFC	Total final energy consumption
TIMES	The Integrated Markal-Efom System
TSO	Transmission systems operator
UCC	University College Cork

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- An Oifig um Cosaint Raideolaíoch
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Irish TIMES Energy Systems Model Phase 2

Authors: Paul Deane, Alessandro Chiodi and Brian Ó Gallachóir

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Irish TIMES is Ireland's only fully integrated long term energy systems model, projecting energy scenarios out to 2050. The model is unique in its ability to provide cross sectoral evidence based analysis for climate and energy policy. The Phase 2 project linked Irish TIMES with other models to examine, inter alia, electricity market, and agricultural landuse interactions.

Identifying Pressures

The Irish TIMES Phase II project identifies pressure points and challenges for Ireland in meeting greenhouse gas emission reduction targets while also addressing other policy goals such as energy efficiency and renewable energy targets. It makes an important contribution to Ireland's technical capability to quantifying the challenges of moving to a low carbon economy. It also makes valuable contributions to the international collaborative research effort in TIMES energy systems modelling (used in over 70 countries to inform policy decisions) co-ordinated by the IEA ETSAP activity.

Informing Policy

Projected scenarios offer insights to key technologies and strategies to reduce emissions in the short and longterm out to 2050. Analysis addresses key policy questions ensuring the research directly supports policy makers. It is shown that a multi model approach to testing scenarios greatly improves the technical robustness of results from the model. Results highlight that cross border power flows play a more significant role in market dynamics especially in the presence of geographically dispersed variable renewable generation sources such as wind and solar. This is important from a policy making perspective as poor model based evidence for example, based on an isolated national system, can lead to poorly informed policy decisions.

Developing Solutions

Modelling results show that electrification of residential heating may rise by the year 2020 in order for Ireland to meet its non-ETS emission reduction target in a cost optimal fashion and that greater electrification of existing oil fired central heating systems through ASHP technology should warrant further investigation. Results also point to gas (both renewable and natural gas) becoming the dominant fuel source for Ireland to 2050. In this particular analysis it was shown that technical solutions in agriculture may contribute with some emissions reductions – however these reductions represent less than a 20% reduction relative to 1990 levels – while the bulk of cost optimal emissions reductions remain in the energy related sectors. Comparing with the findings of the EU roadmap the results indicated that in the case of Ireland an 80% to 95% GHG emissions reduction by 2050 would be very challenging without also reducing activity levels of the agriculture sector.

EPA Research: McCumiskey House, Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

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