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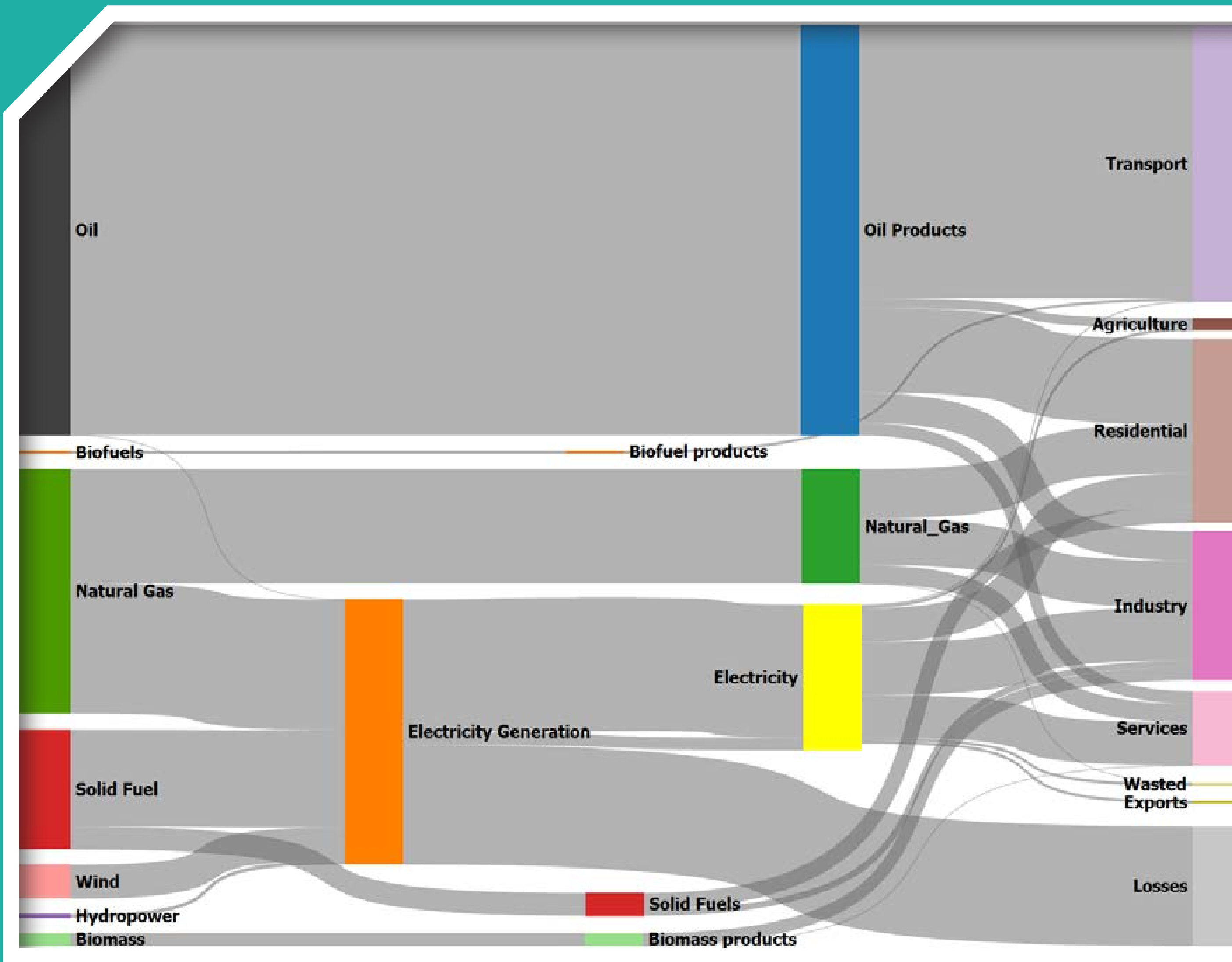
Report No.349

# Develop a LEAP GHG Ireland Analytical Tool for 2050

Authors: Tomás Mac Uidhir, Fionn Rogan and Brian Ó Gallachóir

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**EPA RESEARCH PROGRAMME 2014–2020**

# Develop a LEAP GHG Ireland Analytical Tool for 2050

## (2016-CCRP-MS.34)

## EPA Research Report

A copy of the end-of-project technical report is available on request from the EPA

Prepared for the Environmental Protection Agency

by


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This report is based on research carried out/data from 2015 to 2019. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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# Executive Summary

This report describes a greenhouse gas (GHG) emissions model of Ireland's energy and agriculture sectors, which were responsible for approximately 61 million tonnes (Mt) of GHG emissions in 2017.[1] The Low Emissions Analysis Platform (LEAP) software was used to build the LEAP Ireland 2050 model, which simulates the development of future possible decarbonisation pathways for Ireland. To date, Irish decarbonisation policy has been successful in reducing emissions in electricity generation (accounting for approximately 18% of total emissions in 2017). However, we also need emission reductions in heating, transport and agriculture if Ireland is to fulfil its obligations under EU effort-sharing agreements and the Paris Agreement. The LEAP Ireland 2050 model includes all emission-generating sectors of the economy, including agriculture, enabling analysis of how decarbonisation plans for each sector can contribute to reducing the overall annual total of 61 Mt of GHG emissions. At present the model accounts for approximately 95% of all GHG emissions in Ireland.

The LEAP Ireland 2050 model enables the development of policy scenarios, focusing on the effects of individual (and groups of) policy measures on emissions growth. This complements the Irish TIMES model of Ireland's energy system, whose key strength is in exploring least-cost technology roadmaps. Within this project, we also explored the policy implications of existing mitigation policy measures through an ex-post analysis of residential retrofitting supports and a range of ex-ante scenarios that consider all sectors. The ex-post analysis of residential retrofitting showed how an additional 86% of energy savings (643 gigawatt hours (GWh)/annum) might have been achieved through alternative retrofit choices that are currently available within the retrofit programme. Achieving these additional energy savings would require additional effort and incur increased costs. The total cost of the grant scheme increases from €130 million to €169 million in the alternative retrofit scenario, i.e. a 30% increase. Additionally, cost is not evenly distributed among all building types, with detached dwellings and apartments witnessing an 83% and a 41% increase, respectively, and terraced homes reducing in cost by 18.6% (Mac Uidhir *et al.*, 2019a).

In order to inform the Climate Action Plan, we used LEAP Ireland 2050 to investigate the impact of key ambitions related to large-scale residential retrofitting and high penetration of electric vehicles (EVs) into private passenger transport. These scenarios compare the impacts of early and delayed target compliance for the period 2021–2030. Scenario results for this ex-ante analysis show that there is a potential additional 2 Mt carbon dioxide equivalents ($CO_2$eq) (1.2 Mt $CO_2$eq from electric vehicle diffusion and 0.8 Mt $CO_2$eq from residential retrofitting) emission reduction possible in the early action scenario, relative to the delayed scenario. The results highlight the need for robust policy implementation pathways to accompany high-level end-year targets. LEAP Ireland 2050 will be used to support the Irish Government's Climate Action Modelling Group as it develops the evidence base of policy measures for Ireland to transition to a zero-carbon economy by 2050.

The LEAP Ireland 2050 model presents a complete GHG-accounting tool for emissions arising from transport, buildings, industry, agriculture and electricity generation. The model can incorporate both top-down and bottom-up modelling methodologies, depending on what is appropriate for each sector, and data availability. Bottom-up energy modelling methods focus on aggregating the emissions of individual technologies that deliver specific energy services, e.g. a private passenger vehicle. This approach factors in the energy performance and usage of each technology and sums across all technologies to estimate total energy demand. By contrast, top-down modelling methods combine aggregate variables appropriate to each sector (such as gross domestic product or gross value added) with energy intensity to estimate future energy demand.

1 Sources include energy industries, residential, manufacturing combustion, commercial services, public services, transport, industrial process, fluorinated gases, agriculture and waste.

This project assembles a number of subsectoral models into a single coherent economy-wide modelling framework. Detailed modelling structures have been carefully chosen to reflect the best available data for each sector, providing for scenario analysis across a range of sector-specific policy pathways. Effective model integration necessitated the development of the Application Script Editing Tool, a new model creation tool that was required to create complex model topologies and incorporate sector-specific data.

A number of sector-specific models were leveraged to better represent that sector in a single coherent LEAP Ireland model. The transport sector has been developed to capture stock turnover and large volumes of imports, while also accounting for vehicles' engine size, fuel type and vintage. The residential sector utilises nine distinct building archetypes to represent national housing stock. Residential energy demand for space/water heating and lighting was obtained from a detailed analysis of the Sustainable Energy Authority of Ireland's Building Energy Rating database. Commercial services are represented by 109 archetypes across a range of building types, heating fuels and building condition indicators, while public services are simulated using a top-down methodology linking economic growth with energy intensity. Industry is disaggregated by Statistical Classification of Economic Activities in the European Community categories and includes detailed end-use estimates for each subsector. The implications of the methodology used to estimate end uses within each subsector is also explored for future model development. Agriculture is divided into energy and non-energy demand. Agricultural energy demand captures consumption of oil and electricity in the sector, while non-energy demand is represented by GHG emissions associated with livestock, pasture and tillage. A simplified model of electricity generation uses PLEXOS Ireland electricity modelling outputs and aggregates based on plant fuel and heat rate. Generation types include oil, natural gas, coal, peat, wind and solar power.

# 1 Introduction

There is an urgent need for all countries to decarbonise their energy systems if the world is to limit global warming to well below 2°C, as specified in the Paris Agreement (UNFCCC, 2019). Energy systems tend to get locked into particular configurations owing to their complexity, size and institutional/societal inertia. This makes them difficult to change over short periods of time (Unruh, 2000). Owing to these difficulties, analysts and policymakers have made use of energy system models to improve understanding and aid in the decision-making process for long-term energy planning, helping to guide and inform the development of energy and climate policy in many countries (Strachan *et al*., 2009). A range of energy models are available according to different jurisdictions of analysis (i.e. by region or country, or global), research questions, environmental concerns, levels of computing power available and the available human capacity to conduct the energy modelling.

As computing power has grown in capacity and availability (Khaitan and Gupta, 2012), energy models have grown in capability, complexity and extent (Bale *et al*., 2015), particularly in the industrialised world. Ireland presents its own particular challenges relating to its greenhouse gas (GHG) emission profiles, climate policy and decarbonisation pathways. In 2017 Ireland's emissions stood at 13.3 $tCO_2eq$/capita, 51% greater than the European Union (EU) average for the same year (Eurostat, 2019). A dispersed population and increasing trends in the level of urban sprawl present particular challenges to the reduction of residential and transport energy demand (Ahrens and Lyons, 2019). In addition, Ireland's sectoral share of greenhouse gas (GHG) emissions from agriculture, approximately 33% of total emissions (EPA, 2019), is substantially above the EU average of 9.8% (EEA, 2019). This large share of agricultural emissions is due to the scale of agri-food production in Ireland, as, despite production systems already functioning at the higher end of efficiency per unit of production, Ireland has the highest national proportion of agriculture emissions in the EU.

Ireland has been unable to break the link between economic growth and increasing GHG emissions over the past two decades. In 2018, both primary and final energy demand continued to grow in line with the economic recovery. This growth is driven primarily by growth in transport and heat demand (SEAI, 2019a). Following the economic recession of 2007–08, emissions were seen to fall in residential heating and transport (private and freight). Improved energy efficiency (EE) of residential dwellings owing to retrofitting and improved engine efficiency (EU, 2009a) have played a role in delivering this reduction; however, the policy-driven contribution to this reduction has been overestimated. Dennehy *et al*. (2019) quantify the impact of the economic recession on dwelling energy demand, highlighting that retrofitting played a relatively minor role in reduced consumption in the post-recession period. Similarly, demand shifts within the transport sector can be attributed to changes in economic activity and the prioritisation of private over public transportation modes (O'Mahony *et al*., 2012). Recent years have witnessed a growing trend in the size and type of private vehicles purchased (Ó Gallachóir *et al*., 2009; SEAI, 2019a), resulting in a resurgence in transport emissions as the Irish economy has recovered (CCAC, 2018).

Ireland's progress towards achieving climate targets has been poor. While Ireland is world leading in terms of integrating variable renewable electricity into a synchronous power system, progress in terms of energy efficiency and renewable energy in transport has been slow, and renewable energy use in heating has been largely stagnant. In addition, the cattle herd has increased to allow the expansion of meat and dairy exports (DAFM, 2015).

Understanding the slow progress towards 2020 targets across EE, renewable energy sources (RES) shares and GHG reductions requires an awareness of Ireland's climate and energy policy in recent years. The Energy White Paper (EWP) (DCENR, 2015) was intended to encapsulate a complete policy framework to guide climate actions within the energy sector. The

EWP leveraged the technical analysis provided in the Low Carbon Roadmap (Deane *et al*., 2013) to outline policy objectives for the period 2015–2030. The EWP provided an overview of targets set in the National Energy Efficiency Action Plan (NEEAP) (DCENR, 2009) and National Renewable Energy Action Plan (NREAP) but failed to provide robust future targets for the period 2015–2030 across key sectors.

The National Mitigation Plan (DCCAE, 2017a) provides a starting point in the quantification of the steps required to deliver a decarbonisation pathway from a policy perspective. This document outlines headline targets across all economic sectors, with specific policy targets relating to renewable electricity supply, sustainable transport, residential retrofitting and agricultural emissions. In 2018, the draft National Energy and Climate Plan (NECP) (Government of Ireland, 2018) provided an overview of existing climate policy actions and planned future policy contained within the National Development Plan (NDP) (DPER, 2018). The 2019 Climate Action Plan (CAP) presents a culmination of all previous climate policy and seeks to increase ambition and deliver rapid reductions in GHG emissions across all sectors between 2020 and 2030 (Government of Ireland, 2019). While the CAP sets ambitious targets and is strong on governance, it contains challenging policy targets within passenger transport and residential energy demand. These measures are particularly challenging as they are decentralised demand-side measures, which will require significant effort on the part of significant numbers of individuals.

The complex history of climate policy highlights Ireland's need to develop sustainable policy pathways that deliver a decarbonised society in the medium (2030) and long terms (2050). Ireland's record as a climate "laggard" has not been significantly influenced by national policy or broader EU climate policy (Torney and O'Gorman, 2019). At present, Ireland's goal of achieving a net-zero carbon society by 2050 will require strong governance and a significant transition to a low-carbon trajectory by 2030. The CAP sets ambitious targets for the introduction of electric vehicles (EVs) and retrofitting of the existing building stock. The CAP includes increasing shares of renewable sources in electricity generation and liquid biofuels but does not set significant ambitions for renewable gaseous fuels. As Ireland approaches the end of 2020, there will be a need to purchase carbon credits from other EU Member States to bridge the gap between progress to date and GHG reduction targets. There is a need to closely monitor progress towards the emissions reduction ambitions of the CAP, underpinned by evidence-based policy support. This will involve assessing whether or not the individual policy measures are delivering emissions savings as expected and developing additional policy measures where necessary to compensate for existing measures that are not delivering. The goal of the Plan is to put in place an equitable and sustainable pathway to achieve mandatory emissions reduction targets in the period 2020–2030, and to provide a trajectory towards a net-zero 2050.

There is an ongoing need in Ireland to provide this evidence-based policy support and aid in the decarbonisation of the whole Irish energy system, including the non-energy agricultural emissions. This need represents a requirement for a new GHG emissions model for Ireland that can consider complex policy questions relating to renewable heating and transport – using a coherent set of transparent modelling assumptions across all sectors.

This project develops a GHG emissions model to 2050 for Ireland using the Low Emissions Analysis Platform (LEAP). The project involved multiple stakeholder engagement at all stages, including with government departments, the Sustainable Energy Authority of Ireland (SEAI), the Environmental Protection Agency (EPA), Teagasc and the Climate Change Advisory Council. The objective is to provide a detailed bottom-up simulation model of all economic sectors that can be utilised to provide an evidence base for robust policy pathway support. The model (LEAP Ireland 2050) captures GHG emissions associated with industry, transport, residential, services, agriculture and electricity generation. The model structure is dictated by the best available data and reflects the need to be able to answer relevant policy pathway questions within each sector. The LEAP Ireland 2050 model and associated scenario analysis are the key deliverables of this project and are provided with this report. Scenario analysis is dictated by current/expected national policy and the LEAP Ireland 2050 tool serves as the modelling framework to assess the implications for GHG emissions in Ireland, relative to a projected reference scenario.[2] Table 1.1 shows some of the key scenarios investigated using the LEAP Ireland 2050 model.

A key modelling output of this project is the evaluation of some existing policies and the quantification of the impact on GHG emissions in Ireland, owing to different future possible implementation policy pathways. Future modelling scenarios are focused on delivering key residential retrofitting and electric vehicle (EV) targets for 2030.

This project is delivered across five work packages (WPs). WP1 is defined as project management and coordination. WP2 includes a review of national and international best practice within inventory and projection systems. WP3 includes an ex-ante and ex-post assessment of mitigation measures to date. WP4 develops and tests the analytical LEAP Ireland 2050 tool, and WP5 is defined as dissemination and engagement. The report is structured as follows: Chapter 2 provides an overview of Ireland's EU and national policy targets for 2020 and 2030, including progress to date and a discussion on expected challenges. Chapter 3 discusses the modelling methodologies used in each sector of the LEAP Ireland 2050 model, describes key assumptions within each scenario and also provides key modelling results relating to policy levers highlighted in Table 1.1. Chapter 4 provides project outputs. Conclusions and recommendations are provided in Chapters 5 and 6.

**Table 1.1. Scenario analysis key targets: National Development Plan and Climate Action Plan**

| Policy | Sector | Subsector | Target | Description |
|---|---|---|---|---|
| NDP | Transport | Private passenger transport | 500,000 EVs | Deliver 500,000 electric vehicles by 2030, including additional charging infrastructure |
| | | | Non-zero emissions vehicle ban | No new non-zero emission vehicles sold post 2030 |
| | Residential | Existing dwellings | 45,000 dwellings per annum | Retrofit 45,000 dwellings per annum to minimum B standard (≤125 kWh/m$^2$ per annum) |
| CAP | Transport | Private passenger transport | 840,000 EVs | Deliver 840,000 electric vehicles by 2030: 550,000 BEVs and 290,000 PHEVs, including additional charging infrastructure |
| | | | Non-zero emissions vehicle ban | No new non-zero emission vehicles sold post 2030 |
| | Residential | Existing dwellings | 500,000 dwellings (including 400,000 heat pumps) | Deliver 500,000 residential retrofits to minimum B2 standard (≤100 kWh/m$^2$ per annum) and install at least 400,000 electric heat pumps |

**BEV, battery electric vehicle; PHEV, plug-in hybrid electric vehicle.**

2 The reference scenario is not directly comparable with the EPA's official national inventory and forecast, as the methodological developments of the two forecasts may vary. Work is ongoing to provide a consistent EPA reference scenario that would be directly comparable. The EPA reference scenario is produced using the macro demand projections formulated by the Economic and Social Research Institute (ESRI). SEAI's energy models simulate the impact of policies on the macro demand and then the energy projections go to the EPA, which quantifies the emissions forecast.

# 2 Background

## 2.1 Policy Context

In 2009 the EU agreed a target to reduce GHG levels by 20% by the year 2020, relative to 1990 levels. Two key policy instruments were established to deliver this goal. The Emissions Trading Scheme (ETS) was developed for large point source emissions (electrical power plants and large industry). This established a target to achieve a 21% reduction in ETS emissions by 2020 relative to 2005 levels. The Effort Sharing Decision (ESD) (EU, 2009b) focused on non-ETS emissions, setting a 10% reduction target for these emissions relative to 2005 levels. Within the ESD, Member States agreed mandatory national targets based on relative wealth, gross domestic product (GDP) per capita, in the range of ±20%, relative to 2005 levels. Ireland received the most ambitious target of 20% non-ETS GHG reduction by 2020, alongside Denmark and Luxembourg, owing to their relatively high GDP per capita in 2005.

In 2009 the EU agreed and published the EU Renewable Energy Directive (EU, 2009c), which requires the publication of NREAP reports every 2 years. These NREAP reports track progress to date and indicate compliance with EU targets. Ireland's most recent NREAP report was published in 2018 (DCCAE, 2018). Ireland's RES target is a 16% share of gross final consumption to be delivered from renewable sources across renewable electricity generation (RES-E), heat (RES-H) and transport (RES-T). To meet the mandatory 16% RES target, Ireland set modal targets as follows: 40% RES-E, 12% RES-H and 10% RES-T, the sum of which equates to a total RES target of 16%. Recent publications from SEAI project a final RES share between 12.3% and 13.2% across a range of scenarios that consider multiple factors including fuel price (SEAI, 2019b). These scenarios are consistent with data provided as part of the draft NECP.

In 2012 the EU established the Energy Efficiency Directive (EU, 2012), which requires the publication of NEEAPs every 3 years. Ireland's most recent NEEAP report was produced in 2017 (DCCAE, 2017b) and tracks progress towards achieving Ireland's energy efficiency target of a 20% energy saving, measured against the average energy consumption for the period 2001–2005. At present Ireland is expected to achieve a 16.2% reduction by 2020, owing to energy efficiency improvements (DCCAE, 2017b). In 2018, the regulation on the governance of the energy union and climate action entered into force. This regulation requires that EU Member States produce a NECP. Ireland published its first draft NECP in December 2018. The NECP process replaces the NEEAP documentation and comprises energy and climate policies at date of publication, feeding into the national CAP (Government of Ireland, 2019).

The 2014 EU climate and energy framework provides for high-level EU-wide climate targets covering the period 2021–2030. The EU has agreed a 40% GHG reduction target, relative to 1990 levels, a reduction in energy demand through delivering an EE target of 32.5% and an increased overall RES share of 32% by 2030. In 2018 the EU adopted the Effort Sharing Regulation (ESR) (EC, 2016), providing a framework that adequately distributes the overarching GHG target between ETS and non-ETS sectors. Overall, non-ETS sector targets a 30% GHG reduction, relative to 2005 levels, with Member States allocated 2030 targets of between 0% and 40% reduction, based on relative wealth. The ETS sector targets a 43% GHG reduction by 2030, relative to 2005 levels. Beyond 2030, the European Green Deal (EGD) (EC, 2019) provides a pathway for net-zero GHG emissions by 2050. The EGD aims to decouple economic growth from GHG emissions and provide an equitable transition to a sustainable economy in 2050. The EGD also provides for a revision of the current 2030 GHG target with a view to increasing it to between 50% and 55%, relative to 1990 levels, in a responsible manner. This includes the potential for new sectors to be included in the ETS scheme and an upward revision of 2030 Member State GHG targets. At present, 2030 targets for Ireland include reducing GHG emissions by 30%, relative to 2005 levels (EC, 2016).

Ireland has produced multiple policy documents during the period of analysis that seek to outline policy measures intended to address these shortfalls and indicate increased future ambition in the medium term (2030) and long term (2050); notably, the NDP (DPER, 2018) and the more recent CAP. These policy documents outline measures across all sectors of the economy, i.e. transport, residential, services, industry, power generation and agriculture.

Ireland's 2014 national policy position remains an 80% reduction in energy-related $CO_2$ emissions across electricity generation, built environment and transport by 2050, relative to 1990 levels (Government of Ireland, 2014). The 2014 national policy position also states that the low-carbon transition will be guided by an approach to carbon neutrality in agriculture, land use and forestry that does not compromise capacity for sustainable food production. The CAP increases this ambition and commits to the evaluation of the necessary changes (policies) that would be required to achieve net-zero emissions by 2050. While the CAP intends to put Ireland on a net-zero 2050 trajectory by 2030, much work is needed to realise this goal.

While other energy models, e.g. Irish TIMES (Ó Gallachóir *et al*., 2012), have provided useful insight into cost-optimal climate targets, the LEAP Ireland 2050 model can contribute to the policy discussion in a different manner. The LEAP simulation model can function as a policy pathway tool, providing the necessary steps required to reach a cost-optimal target. In its current format the LEAP Ireland 2050 model provides a useful tool that can be used to understand the impacts on energy demand and GHG emissions owing to increases within residential retrofitting, commercial building retrofits, diffusion of EVs, modal shift within transport and increasing livestock output. The accessible nature of the LEAP model lends itself well to bridging the gap between energy analysts and policymakers going forward. Limited capacity to model detailed dispatch of electricity generators remains beyond the scope of the model. The absence of Irish-specific industry end-use data serves to highlight the value in gathering detailed survey data that can feed into simulation models and aid in guiding sector-specific policies going forward.

## 2.2 Model Rationale

### *2.2.1 Modelling context*

Energy modelling encompasses a broad range of tools, each of which contains specific strengths and weaknesses. Each model is designed to address a specific modelling need/research question. This section provides a brief overview of the range of models and the associated methodologies/sectors utilised within this project. Sector-specific models are used to provide in-depth analysis of energy use in the residential and private passenger transport sectors. The Archetype Dwelling Energy Model (ArDEM-SQL) (Dineen and Ó Gallachóir, 2011) utilises the Building Energy Rating (BER) database as inputs to produce a flexible archetype demand profile for residential dwellings in Ireland. The ArDEM-SQL tool is explored in more detail in section 3.2.1. The CarSTOCK model is an Excel-based, techno-economic private car simulation model that contains granular detail relating to the final stock, energy consumption and emissions of the Irish private car sector (Daly and Ó Gallachóir, 2011). The gas and electricity markets are modelled in high spatial and temporal resolution using the PLEXOS Ireland model (Deane *et al*., 2012). The Agri-TIMES model (Chiodi *et al*., 2016), designed specifically for the agriculture sector, was also utilised in the development of non-energy agricultural emissions for this LEAP project. Irish TIMES is a least-cost optimisation model that considers future energy system configurations under a range of policy constraints. The multi-model approach of utilising different energy system models to interrogate results provides useful insights into the technical feasibility of cost-optimal results and climate policy implementation pathways. The PLEXOS Ireland and Irish TIMES models have been previously soft-linked using this multi-model approach (Deane *et al*., 2017), improving the temporal resolution of 12 time slices in TIMES to 30-minute time resolution dispatch modelling from PLEXOS. A pre-existing LEAP demand simulation tool with projections for the period 2013–2020 already exists (Rogan *et al*., 2014). This older tool contains energy demand scenarios with some detailed subsectoral descriptions; however, this older model does not contain emission factors and considers energy demand only.

The integration of multiple subsectoral models into LEAP improves problems associated with model development. Historically, this has resulted in sectoral simulation models remaining siloed from one another, impacting on the relative value of individual model outputs that might otherwise operate using different key assumption and drivers. In addition, an integrated simulation model provides insights into the interaction effect associated with different policies, across sectors and the entire energy system. This aids in understanding and balancing out over/underachievement in different sectors.

### *2.2.2 National modelling context*

National modelling is conducted across a range of organisations including research institutions, utilities and government authorities. The nature and scope of each organisation's modelling activity also varies significantly based on requirement, e.g. econometric projections, detailed subsector-specific policy simulations. MaREI is an Science Foundation Ireland research centre for energy, climate and marine research and innovation coordinated by the Environmental Research Institute (ERI) at University College Cork (UCC). Within MaREI, energy modelling research is undertaken by UCC's Energy Policy and Modelling Group (EPMG) using three main models (TIMES, PLEXOS, LEAP), described in section 2.2.1, each functioning to answer different types of research questions and modelling needs. The Energy Institute within University College Dublin (UCD) produces many bespoke modelling tools focusing on different areas of the economy. The main SFI-funded research programme within the UCD Energy Institute is the Energy Systems Integration Partnership Programme (ESIPP),[3] which is designed to consider all aspects of energy systems through academic and industrial collaborations with multiple stakeholders.[4] The Economic and Social Research Institute (ESRI) has developed the Ireland Environment, Energy and Economy model (I3E[5]). The I3E model is a computable general equilibrium (CGE) model that describes the relationship between energy inputs and environmental impacts. Teagasc's farm-level policy model, FAPRI-Ireland,[6] examines the farm-level effects of agricultural policy reform in terms of the implications for farm numbers, farm incomes, farming intensity and diversification, sustainability and the general viability of farm households. The SEAI utilises multiple sector-specific policy simulation models designed to address energy efficiency, bioheat, transport and RES-E.
In the context of SEAI's National Energy Modelling Framework (NEMF), ESRI/UCC models provide energy demand forecasts and are combined with SEAI's sectoral simulation tools to produce an "energy scenario tool" that outputs primary and final energy demand by sector and fuel. These scenario results are then provided as official national energy projections to EPA and the Department of Communications, Climate Action and Environment (DCCAE) as required.[7]

### *2.2.3 Why LEAP?*

There are a number of energy system models available worldwide, each offering its own distinct advantages and disadvantages. Many off-the-shelf modelling tools can achieve similar results to LEAP. This prompts the question of why LEAP is used to construct a GHG emissions model for Ireland. Owing to the number of different available models, a complete review of all alternative modelling tools is beyond the scope of this report. A comprehensive review of different modelling tools is completed in Connolly *et al.* (2010). LEAP is developed and maintained by the Stockholm Environment Institute (SEI). The software is used by academic institutions, consulting companies and government agencies in more than 190 countries. LEAP was used in the development of 32 individual Intended Nationally Determined Contributions (INDC) as part of the Paris Agreement in 2015. The software is available to download online (Heaps, 2016) and made freely available to students; there is a paid licensing structure for the purposes of academic research and private consultancy based on the number of users per licence (SEI, 2020). LEAP provides a sufficiently flexible modelling framework that can combine both bottom-up and top-down

3 https://energyinstitute.ucd.ie/wp-content/uploads/2019/08/UCD-Energy-Institute-and-Climate-Action-Plan-2019.pdf (accessed 15 May 2020).

4 Dublin City University, Economic and Social Research Institute, National University of Ireland Galway, Trinity College Dublin, Allied Irish Banks, EirGrid, Ervia, ESB Energy, SSE and Glen Dimplex.

5 https://www.esri.ie/events/launch-of-the-new-ireland-environment-energy-and-economy-i3e-model (accessed 15 May 2020).

6 https://www.teagasc.ie/media/website/publications/2014/6104_FAPRI_Policy_Model.pdf (accessed 15 May 2020).

7 http://www.epa.ie/pubs/reports/air/airemissions/ghgprojections2017-2035/SEAI2018EnergyProjections31May18.pdf (accessed 7 May 2020).

methodologies in a single energy system model that inherently uses consistent key assumptions. While many other simulation modelling tools are focused on supply-side management, LEAP offers a comprehensive method for conducting both supply- and demand-side analyses. Comprehensive scenario analysis techniques within LEAP provide for additional modelling insights and the exploration of different policy pathways. LEAP also supports an active user community where modelling methodologies are exchanged. The accessibility of the LEAP tool means it is useful to both energy analysts and decision-makers. Figure 2.1 illustrates LEAP's position within the context of other simulation modelling tools. This also highlights the additional functionality offered by the newly developed Application Script Editing Tool (ASET) in the specific context of this project.

LEAP does not consider consumers as individual agents; however, it does model the impacts of consumer behaviour by analysing uptake rates of different technologies, e.g. significant EV diffusion and deep retrofitting ambition. In this manner LEAP can analyse the deployment of different technologies and the impact on climate policy targets. The detailed bottom-up design methodology facilitates further insight into policy implementation pathways and disaggregated sectoral carbon budgets in the short, medium and long term. These pathways aid in providing more clarity on the short-term feasibility of 2030 CAP policy targets and the potential for further deep decarbonisation in the long term (2050). The integrated simulation approach can also enhance the process of annual GHG accounting and progress reporting requirements within CAP.

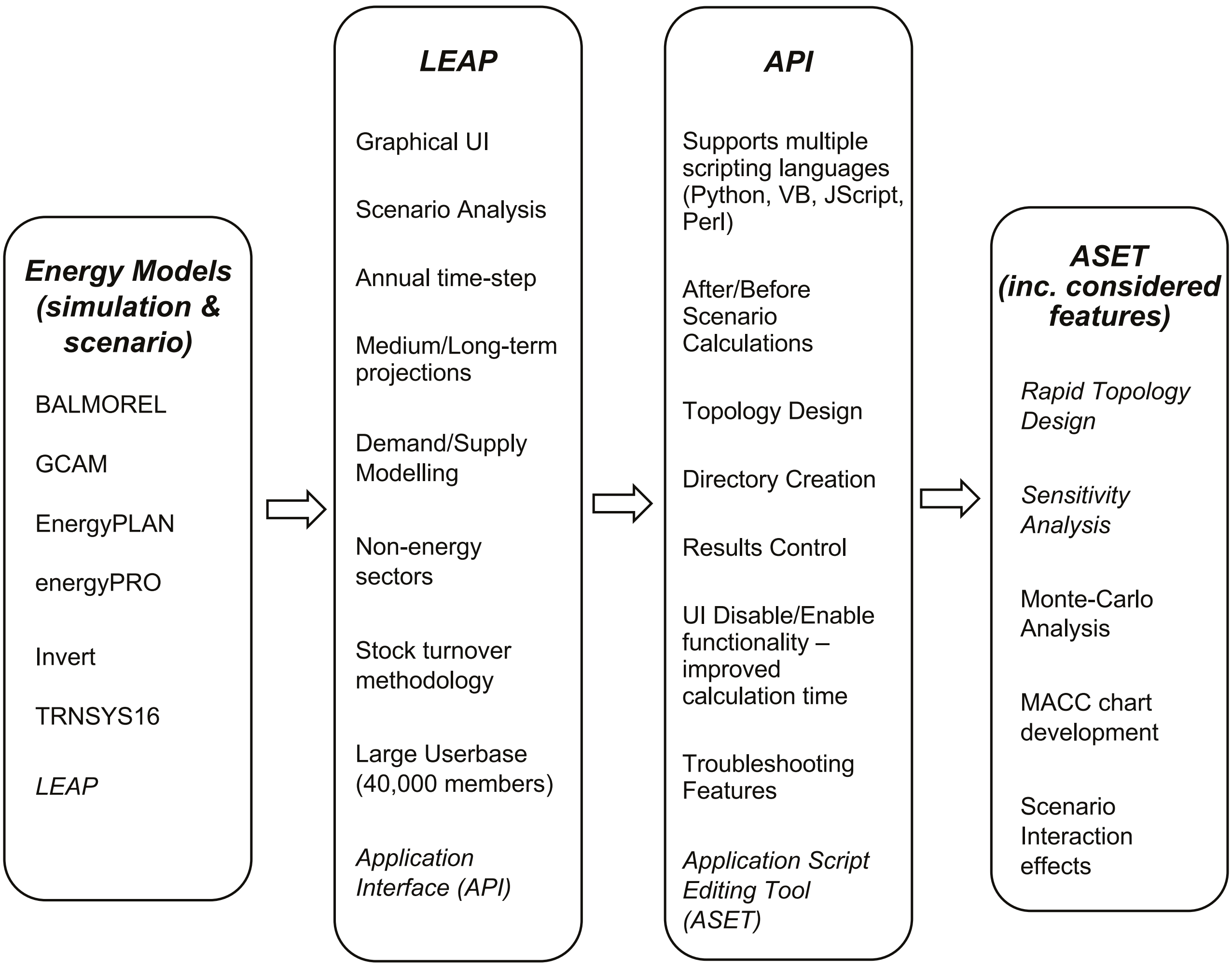


**Figure 2.1. Simulation and scenario modelling tools and the Application Script Editing Tool (ASET). API, application programming interface; MACC, marginal abatement cost curve; UI, user interface.**

# 3 LEAP Ireland 2050 Model

This section describes the LEAP Ireland 2050 model delivered as part of this project. Each sector is described individually, indicating sector-specific input data sources and specific policy levers that are applicable to each sector. While individual references are embedded in text, Table A2.1 contains an overview of the data sources that underpin the LEAP Ireland 2050 model. Typical outputs for all sectors include final energy demand (flexible units) and emissions ($CO_2$eq). The reference scenario is presented, including the CAP EV and retrofitting scenarios. The model uses historical base-year data for 2016 and includes projections for each subsequent year to 2050.

## 3.1 Demand Model Structure

LEAP models are designed with a hierarchical tree structure that defines the sectoral definitions for each demand category. The LEAP demand structure for the LEAP Ireland 2050 model is shown in Figure 3.1. This figure provides a broad overview of the model; it represents the main sectoral descriptions and illustrates the logical order for the organisation of the data. Sections 3.2–3.7 provide modelling approaches utilised for each subsector within the complete LEAP Ireland 2050 model. This also includes detailed model topologies, data sources, modelling assumptions and data inputs.

## 3.2 Residential Sector

The LEAP residential sector demand is defined by three different end uses: space heating, water heating, and lighting and appliances, as they apply to existing and new dwellings. Existing dwellings are defined as all permanently occupied residential dwellings completed earlier than 2017. Each end use is further described by nine unique building archetypes. These include building type, detached, terraced, apartment and energy efficiency classification, divided into three categories (low, medium and high) based on the BER groupings AB, CD and EFG.

This sector's structure is designed to consider retrofitting policy in detail – hence the model topology is focused on the existing building stock. Fuels delivering space/water heating include electric heat pump, coal, natural gas, solid fuels and kerosene. While new dwellings are also included in the model, their energy efficiency ratings preclude the need for retrofitting. This implies a pool of potential dwellings that can be retrofitted over time. There is an applied

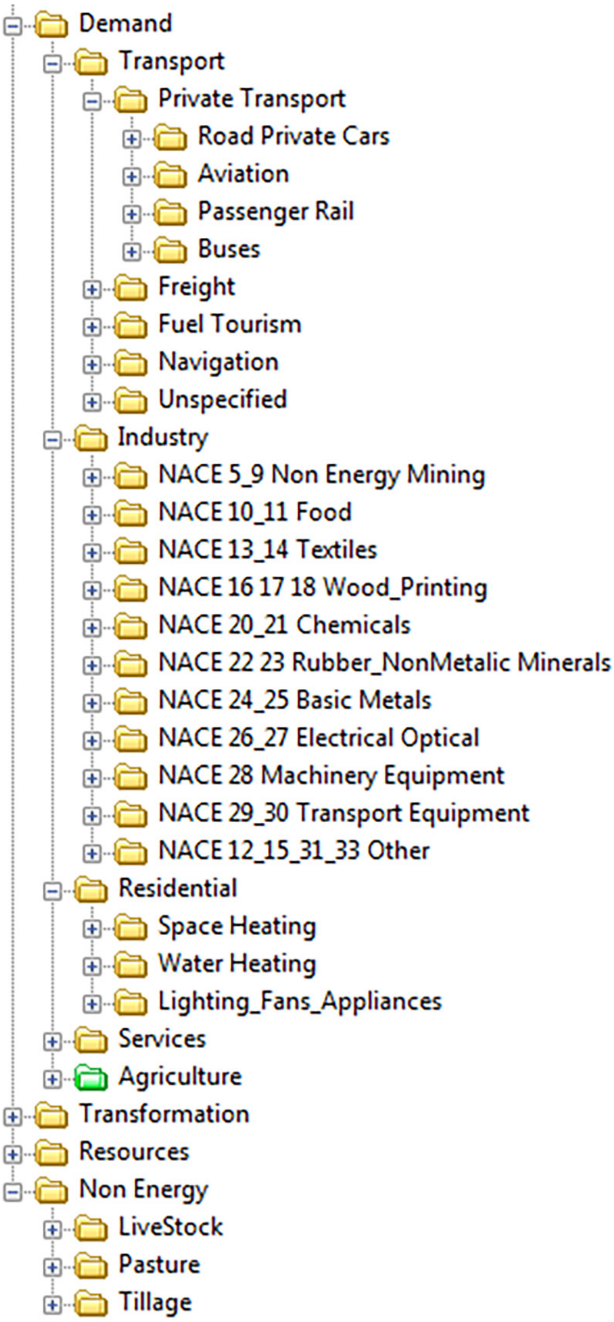


**Figure 3.1. LEAP Ireland 2050: demand model topology.**

obsolescence rate of 0.35% per annum to the existing building stock.

Key inputs include the number of archetypes available for retrofitting and the energy intensity of each archetype. Data are supplied from the Central Statistics Office (CSO, 2016) and SEAI's BER database (SEAI, 2019c). Energy intensity within this sector is represented by an aggregated energy efficiency rating for each archetype and end use. Figure 3.2 shows the final model structure for the residential sector.

### *3.2.1 Residential demand calculation*

The energy intensity ratings are provided exogenously from a separate bottom-up residential model, the ArDEM-SQL (Mac Uidhir *et al*., 2019a). This model contains detailed building fabric information for each archetype, which can be modified to capture the extent of retrofitting works required to improve building energy efficiency to minimum efficiency standards.

ArDEM-SQL is a new modelling tool that was developed as part of this research project but is based on the ArDEM model by Dineen *et al.* (2015).

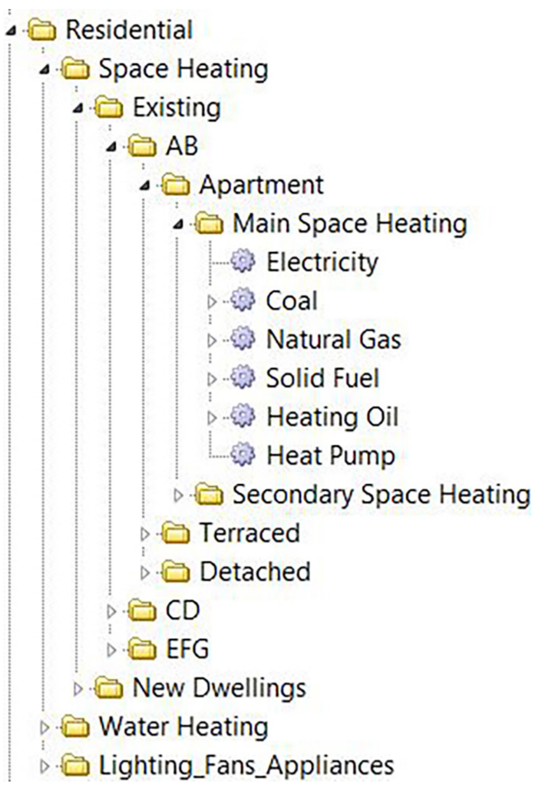


**Figure 3.2. LEAP Ireland 2050: residential model topology.**

The original ArDEM model is a simulation model built on the IS EN 13790 – Dwelling Energy Assessment Protocol (DEAP) – (SEAI, 2008) providing calculation methods for annual energy consumption for space/water heating, ventilation and lighting for Ireland (Dineen *et al*., 2015). Input data is gathered from each individual dwelling's BER assessment and includes detailed information relating to:

- dwelling type, size and geometry;
- thermal insulation properties of building fabrics;
- dwelling ventilation characteristics;
- heating system efficiency and control characteristics;
- solar gains through glazing;
- fuels used to provide space/water heating, ventilation and lighting.

A separate journal publication completed as part of this project includes a copy of all supplementary BER database inputs used as part of this analysis (Mac Uidhir *et al*., 2019b). A set of calculations process the data relating to building fabrics and characteristics for each of the building archetypes. The model:

- uses average occupancy based on floor area;
- sets target internal temperatures for living/non-living spaces;
- sets monthly average external temperatures;
- calculates total primary and final energy demand by space, water heating, pumps and fans.

The model assumes a target internal temperature of 21°C for living areas and 18°C for the rest of the dwelling. External temperatures are provided as monthly mean temperatures (Met Éireann, 2019). See Table 3.1 for a complete list of all temperatures utilised.

ArDEM-SQL energy intensity is then utilised within LEAP using a simplified energy demand calculation for each archetype dwelling and end use, provided in equation 3.1:

$$D_T = \sum_{k=1}^{n} \left(A_k I_k\right) \quad (3.1)$$

where $D_T$ = end-use energy demand, $n$ = total number of archetypes, $A_k$ = frequency of each archetype and $I_k$ = energy intensity of each archetype.

The total number of archetype dwellings included in the base year is shown in Table 3.2.

**Table 3.1. Monthly mean external temperatures (°C)**

| Month | Value (°C) |
|---|---|
| January | 5.3 |
| February | 5.5 |
| March | 7.0 |
| April | 8.3 |
| May | 11.0 |
| June | 13.5 |
| July | 15.5 |
| August | 15.2 |
| September | 13.3 |
| October | 10.4 |
| November | 7.5 |
| December | 6.0 |

**Table 3.2. LEAP Ireland 2050: dwelling archetype frequency, base year**

| Building archetype | Number of dwellings |
|---|---|
| Detached AB | 88,507 |
| Terraced AB | 71,823 |
| Apartment AB | 32,690 |
| Detached CD | 433,748 |
| Terraced CD | 481,653 |
| Apartment CD | 95,819 |
| Detached EFG | 226,738 |
| Terraced EFG | 218,824 |
| Apartment EFG | 47,863 |

## 3.3 Services Sector

The services sector is subdivided into commercial/public services. Lack of access to granular public services data required the use of a simple top-down methodology that associates an energy intensity with economic activity within the sector. Total energy demand, measured in kilotonnes of oil equivalent (ktoe), was provided from historical SEAI energy balances (SEAI, 2019d). Figure 3.3 shows total public service energy demand for the period 1995–2016, by fuel type. Recent economic activity was provided by the CSO, measured as gross value added (million euros) within Statistical Classification of Economic Activities in the European Community (NACE) classifications O.84, P.85, QA.86, QB.87–88 and R.90–93 (CSO, 2019).

A new dataset provided by SEAI for the commercial services sector disaggregates energy demand into 109 distinct building archetypes (SEAI, 2016). These archetypes include building type (hotel, office, restaurant/public house, retail and warehouse), size (small/large), heating fuel (natural gas, electricity, oil) and building fabric condition (windows, walls). Figure 3.4 shows the final model structure for the services sector.

## 3.4 Transport

The transport sector is described by the following subsectors: private transport, freight, fuel tourism and navigation. Detailed subsectoral models provide input data for these subsectors. Private transport contains the most granular data and is further disaggregated into road private cars, aviation, passenger rail and buses. Figure 3.5 shows the final transport model structure as seen in LEAP. Road private cars describes vehicles across a range of 25 vintages, fuel types (petrol, diesel, electric, compressed natural gas (CNG), hybrid and plug-in hybrid electric) and engine sizes (< 900 cc, 901–1200 cc, 1201–1500 cc, 1501–1700 cc, 1701–1900 cc, 1901–2100 cc and > 2100 cc). Data for private passenger transport is supplied from the sector-specific CarSTOCK model (Daly and Ó Gallachóir, 2011). The CarSTOCK model is a techno-economic simulation model used to calculate future stock, energy consumption and emissions for private passenger transport in Ireland. The model includes estimates of vehicle stock, lifetime and average annual mileage, disaggregated by fuel type and engine size over a 25-year period. Figure 3.6 shows a detailed breakdown of the model topology utilised within LEAP to support this data.

Data relating to freight, navigation and fuel tourism is supplied by the CSO. Freight data includes the total tonne-km activity of vehicles, subdivided in weight classes and economic sectors. Navigation data is provided as total energy consumption with no further level of disaggregation. Fuel tourism data are provided in the form of total energy consumption and the historical price differential between the euro and the pound sterling. Fuel tourism is defined by the ratio of the pound to the euro as this was found to be a strong driver of cross-border fuel consumption and purchasing. Figure 3.7 shows the link between energy demand (ktoe) and exchange ratio (pound/euro) (XE, 2019). No attempt was made to estimate future differences in the exchange rate and therefore fuel tourism remains constant at approximately 162 ktoe

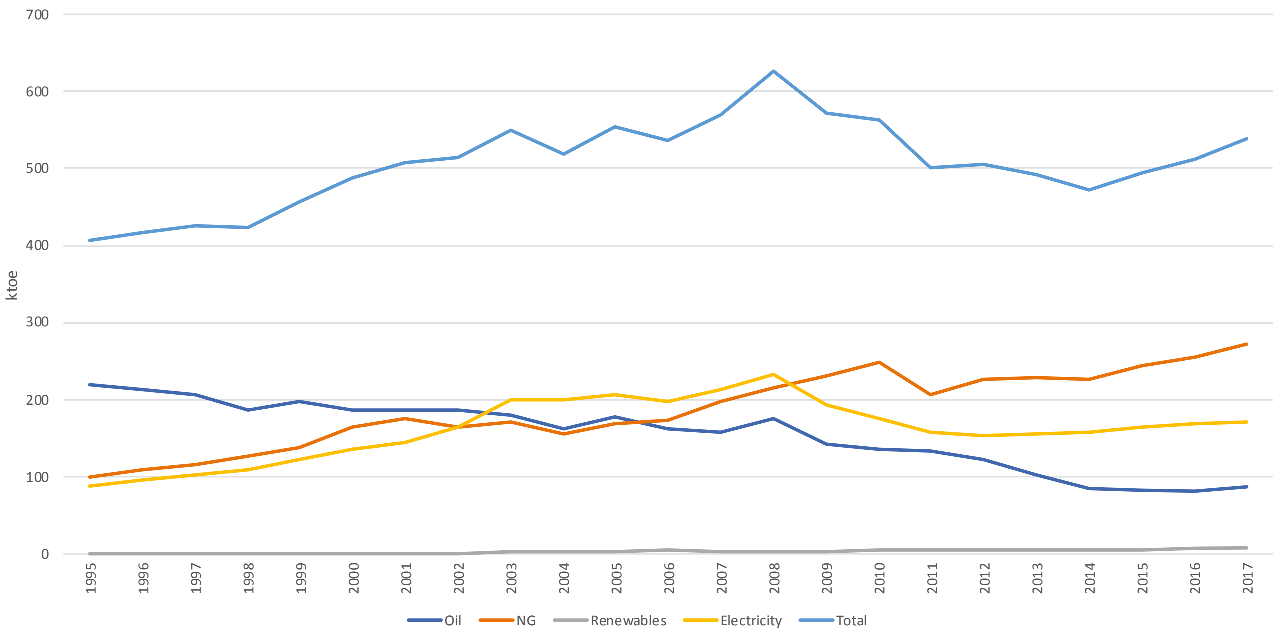


**Figure 3.3. Public services energy demand by fuel type.**

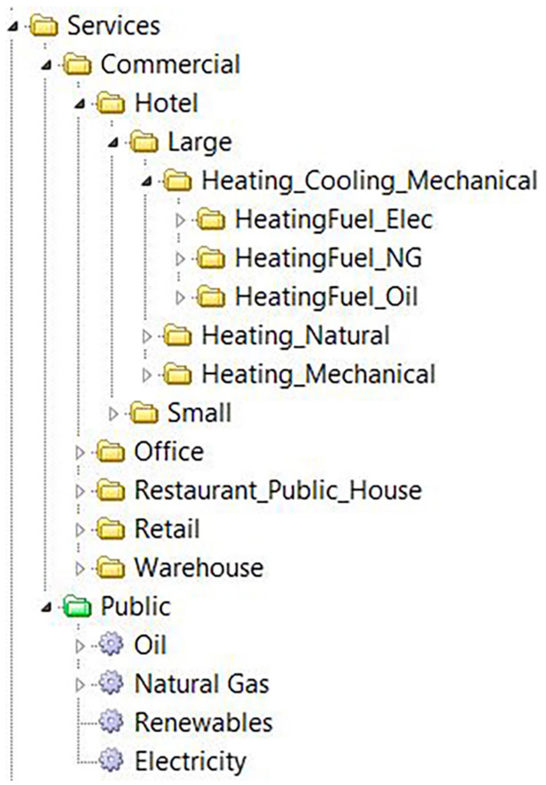


**Figure 3.4. LEAP Ireland 2050: services model topology.**

post 2016; this compares with SEAI's figure of 184 ktoe in 2018 (SEAI, 2019a).

Table 3.3 contains key model input data for each subsector in the transport section of the model. The model is designed to consider energy consumption

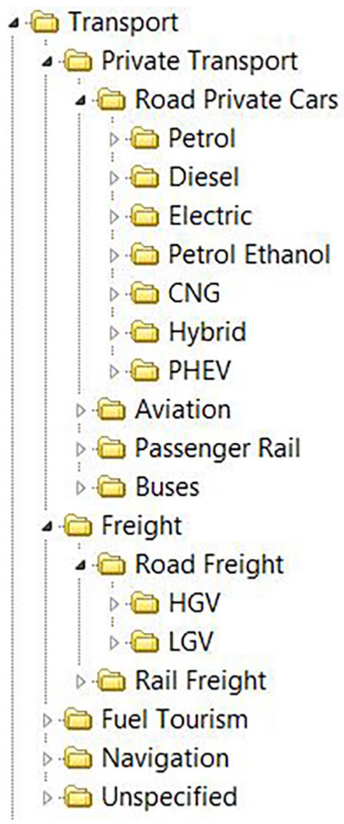


**Figure 3.5. LEAP Ireland 2050: transport model topology.**

across public and private transport modes. The transport sector is designed to consider policy levers such as the introduction of EVs, increased penetration of biofuels and modal shift to other forms of public transport.

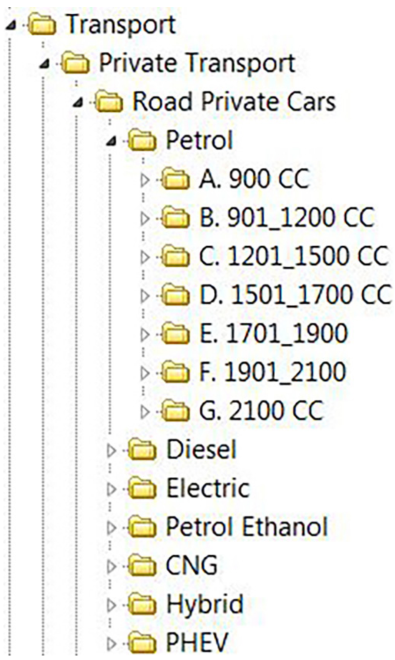


**Figure 3.6. LEAP Ireland 2050: private passenger transport model topology.**

## 3.5 Agriculture

The agricultural sector includes energy and non-energy emissions. Energy-related demand is defined by electricity and oil consumption, with activity measured by agricultural output at basic prices (million euros). Data are supplied by the CSO. Non-energy-related activity is disaggregated into livestock (dairy/non-dairy cattle, sheep, pigs and poultry), and pasture and tillage (pulses, potatoes, sugar beet, barley, oats and wheat). The energy intensity and activity figures for livestock/tillage are provided exogenously from a separate sector-specific Agri-TIMES model (Chiodi *et al*., 2016) that was developed by UCC and Teagasc. Livestock activity is measured as total number of each livestock category stated and emission intensity for each type is estimated for biogenic methane ($CH_4$) and nitrous oxide ($N_2O$). Figure 3.8 shows the final model structure for the non-energy agriculture sector.

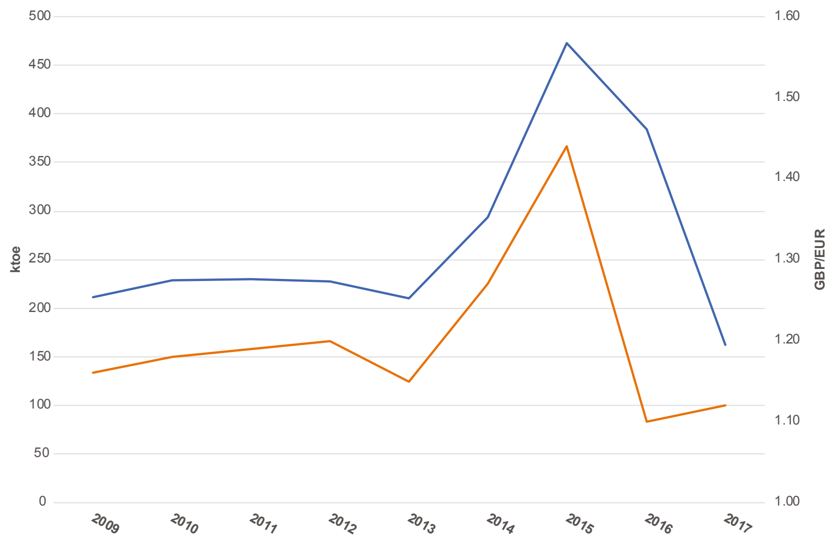


**Figure 3.7. Transport fuel tourism and projected energy demand.**

**Table 3.3. LEAP Ireland 2050: transport model drivers**

| Subsector | Activity driver | Intensity driver |
|---|---|---|
| Road private cars | Vehicle-km | MJ/Veh-km |
| Aviation | N/A | ktoe |
| Passenger rail | Passenger-km | MJ/Pass-km |
| Buses | Passenger-km | MJ/Pass-km |
| Heavy goods vehicles | Tonne-km | MJ/Tonne-km |
| Light goods vehicles | Vehicle-km | MJ/Veh-km |
| Rail freight | Tonne-km | MJ/Tonne-km |
| Fuel tourism | N/A | ktoe |
| Navigation | N/A | ktoe |

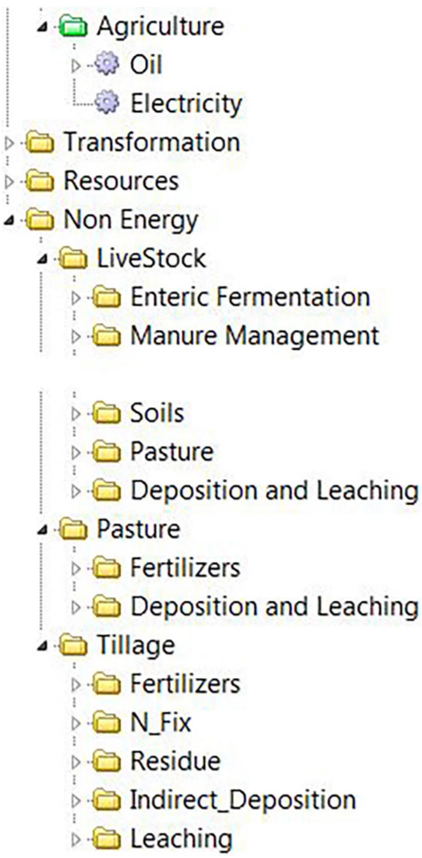


**Figure 3.8. LEAP Ireland 2050: agriculture model topology.**

Table 3.4 provides base-year data for non-energy agricultural activity. This includes livestock figures and tonnage of various crops.

## 3.6 Industry

The industry sector is disaggregated into associated NACE Rev.2 subsectors. These include:

- NACE 5–9: Non-Energy Mining;
- NACE 10–11: Food;
- NACE 13–14: Textiles;
- NACE 16–18: Wood Products and Printing;
- NACE 20–21: Chemical;
- NACE 22–23: Rubber and Non-Metallic;
- NACE 24–25: Basic Metals;
- NACE 26–27: Electrical and Optical;
- NACE 28: Machinery and Equipment;
- NACE 29–30: Transport Equipment;
- NACE 31–33: Other Activity.

Activity drivers are supplied by the CSO [national income and expenditure report, subsectoral gross value added (GVA); CSO, 2019]. Each subsector has a derived energy intensity by dividing sector-specific energy consumption, taken from the national energy balance, by the activity variable, sectoral GVA (million euro) at constant prices. A best-fit curve of energy intensity is then generated using these historical data and used to estimate future energy intensity for each subsector. Figure 3.9 provides an example of this energy intensity calculation for the non-metallic minerals industry subsector; here, a log curve was found to best represent the historical data, with a coefficient of determination ($R^2$ value) of 0.86, seen in the figure.

**Table 3.4. LEAP Ireland 2050: agriculture base-year inputs**

| Process | Type | Unit | 2016 |
|---|---|---|---|
| Cattle | Dairy | Mhead | 1.1 |
| Cattle | Non-dairy | Mhead | 5.7 |
| Sheep | – | Mhead | 5.5 |
| Pigs | – | Mhead | 1.8 |
| Poultry | – | Mhead | 17.1 |
| Other | – | Mhead | 0.1 |
| Tillage | Pulses | Mtonnes | 0.0 |
| | Potatoes | Mtonnes | 0.4 |
| | Sugarbeet | Mtonnes | 0.0 |
| | Barley | Mtonnes | 1.4 |
| | Oats | Mtonnes | 0.2 |
| | Wheat | Mtonnes | 0.9 |

The industry sector leverages UK Department of Business, Energy and Industrial Strategy data (UKBEIS, 2019) to provide an initial estimate for end-use processes including high/low temperature processes, drying and separation, motors, compressed air, lighting, refrigeration, space heating and other. End-use percentage estimates are applied and energy use is normalised to the Irish energy balance to ensure consistency. Fuel use within each energy end use is delivered through various fuel types (electricity, natural gas, oil, coal and biomass). Figure 3.10 shows the final model structure for the industry sector. The inclusion of end-use demands allows an initial estimate of how energy is being used within industry. This methodology highlights the potential value associated with capturing this level of data specifically for Ireland.

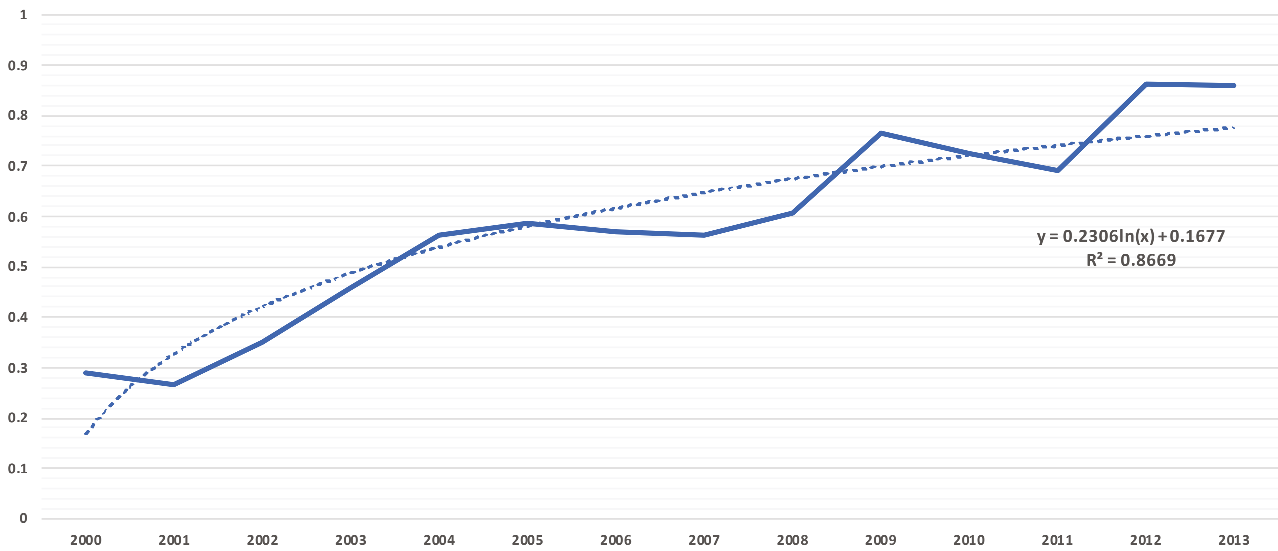


**Figure 3.9. Historical energy intensity: industry – other non-metallic mineral products.**

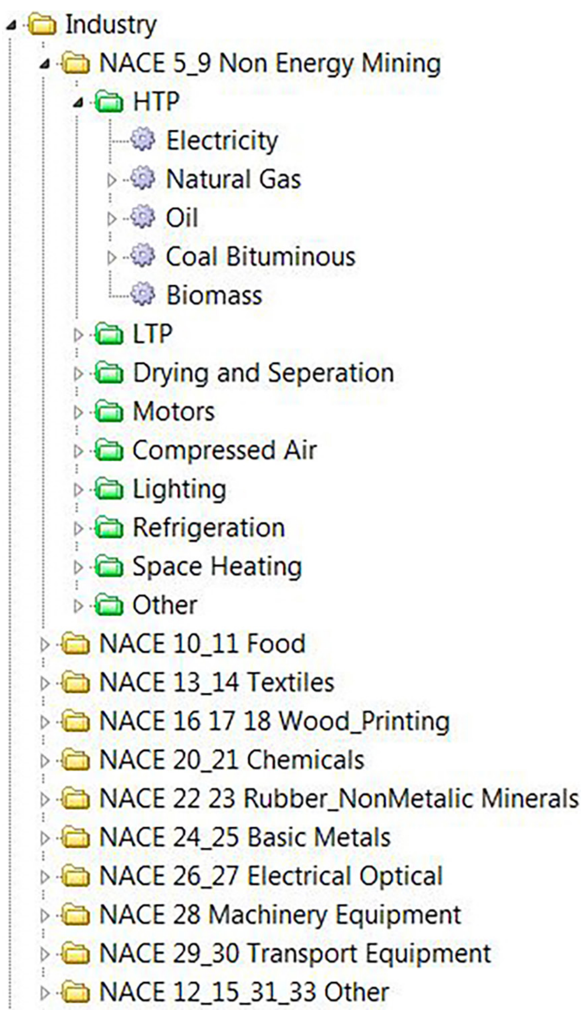


**Figure 3.10. LEAP Ireland 2050: industry model topology.**

## 3.7 Electricity Generation

The electricity generation sector is represented using simplified electricity generation profiles. Baseline data are supplied using the sector-specific PLEXOS Ireland model and generation units are aggregated by generation fuel and plant efficiency (measured by plant heat rate GJ/MWh). Projected electricity demand is generated endogenously based on sectoral demand projection and emissions are calculated using LEAP's built-in "running cost" dispatch rule. Generation types range in efficiency and fuel type (oil, natural gas, coal, peat, on/offshore wind and solar). Figure 3.11 shows the final model structure for the electricity generation sector. Table 3.5 contains 2016 base-year data for electricity generation modules as they appear in LEAP. Wind profiles are utilised within LEAP to determine the availability of wind resources at any given time. The wind availability is subdivided into 103 distinct time slices, represented by week of the year and weekday/weekend. Figure 3.12 shows the availability of the wind profile for each time slice used in this LEAP model.

## 3.8 2030 Scenario Analysis

This section presents the key modelling assumptions and results of the scenario analysis for the LEAP Ireland 2050 GHG reference scenario, EV diffusion and residential retrofitting scenarios. These additional scenarios were chosen because two ambitious targets within the 2019 CAP include the penetration

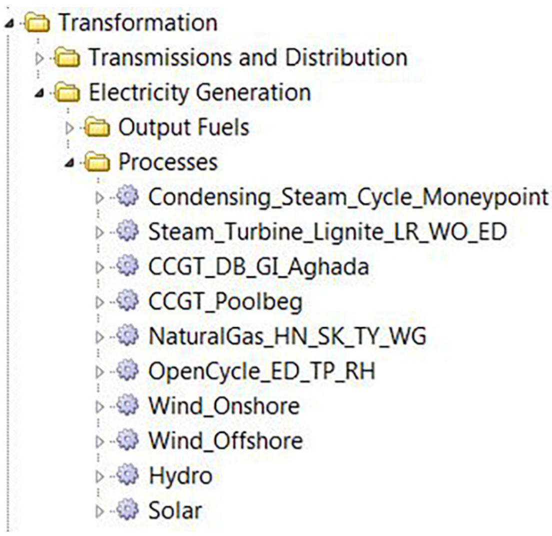


**Figure 3.11. LEAP Ireland 2050: electricity generation model topology.**

**Table 3.5. LEAP Ireland 2050: electricity generation base-year data**

| Electricity-generating process | Exogenous capacity (MW) | Historical production (GWh) | Heat rate (GJ/MWh) |
|---|---|---|---|
| Condensing_steam_cycle_moneypoint | 855 | 6190 | 9.92 |
| Steam_turbine_lignite_lr_wo_ed | 350.6 | 589.1 | 9.57 |
| Ccgt_db_gi_aghada | 1331 | 6952.4 | 6.18 |
| Ccgt_poolbeg | 512 | 2797.6 | 7.12 |
| Naturalgas_hn_sk_ty_wg | 1762 | 4106.1 | 6.5 |
| Opencycle_ed_tp_rh | 324 | 15.28 | 11.23 |
| Wind_onshore | 2377 | 6338.4 | 3.6 |
| Wind_offshore | 25 | 75 | 3.6 |
| Hydro | 216 | 687.2 | 3.6 |
| Solar | 0 | 0 | 3.6 |

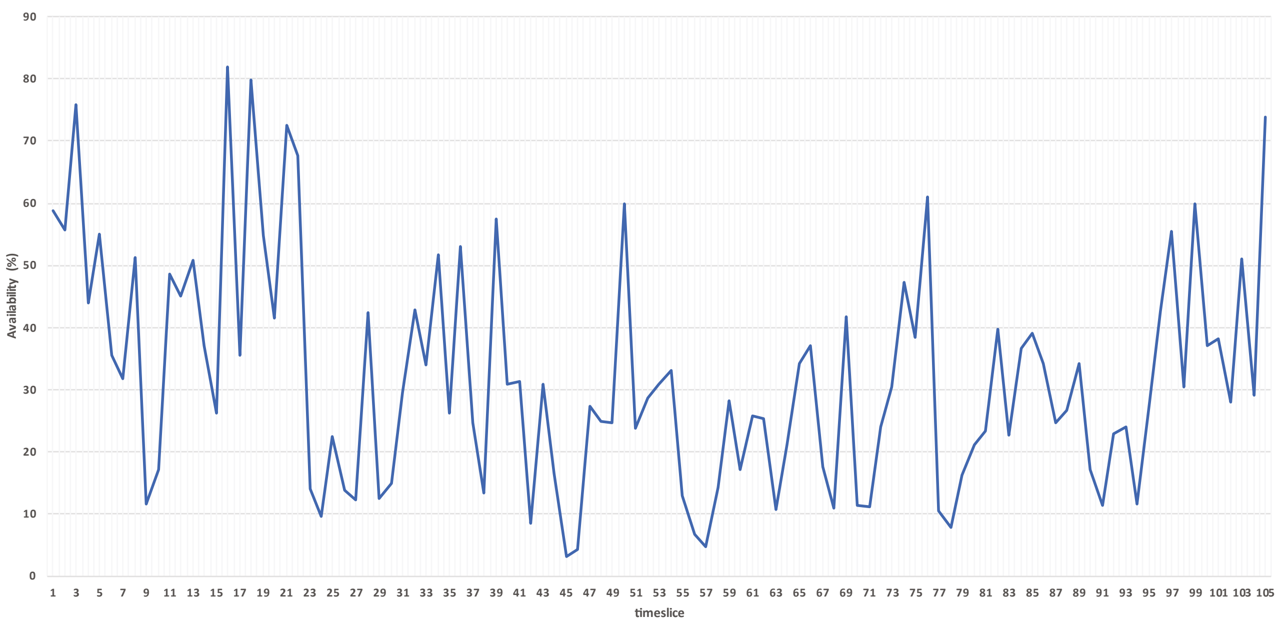


**Figure 3.12. LEAP Ireland 2050: electricity generation wind profile and time slices.**

of 840,000[8] EVs into the private passenger transport sector and the retrofitting of 500,000 residential dwellings (including 400,000 heat pumps). While every effort has been made to include an inventory of all national emissions, the model does not currently account for combined heat and power, waste emissions and fluorinated gases (F-gases). Results for the energy demand and emissions reference scenario are shown for the period 2016–2050. However, the EV and retrofitting diffusion scenarios include a 2030 time horizon, as this is the CAP target implementation year.

### *3.8.1 Reference*

The reference scenario is a projection of current policies, coupled with market trends and econometric projections. The reference scenario is not designed as a forecast of what is likely to happen in the future, instead providing a counterfactual scenario with which other policy scenarios can be compared. The reference scenario results are presented in terms of final projected energy demand (million GJ) and emissions (Mt $CO_2$eq), by subsector. The reference scenario includes only policies that were in place up to the end of 2019, e.g. 2013 building regulations, current low uptake of EVs (reaching 37,000 EVs and 23,000 PHEVs by 2030 in the reference scenario) and minimal deep retrofitting (achieving approximately 60 deep retrofits per annum in the reference scenario). Figure 3.13 shows the results for final energy demand in the reference scenario, reaching 155 TWh by 2050, while Figure 3.14 shows the projected emissions associated with all sectors (including non-energy agricultural emissions) reaching 63 Mt $CO_2$ by 2050. Econometric projections (GVA/population growth) are consistent across all scenarios and based on figures provided by the ESRI.

The residential sector contains a granular level of detail regarding dwelling energy demand. As described in section 3.2, residential energy demand is described by several defining characteristics: building type, service demand (space/water heating, lighting and appliances), fuel type and BER grade. Figure 3.15 highlights the granularity within the results. The largest energy demand shown in Figure 3.15 consists of space heating demand for terraced and detached CD/EFG dwellings.

The transport sector also consists of a detailed bottom-up design. Figure 3.16 shows the transport energy demand results at an aggregated level. Figure 3.17 presents an additional layer of granular

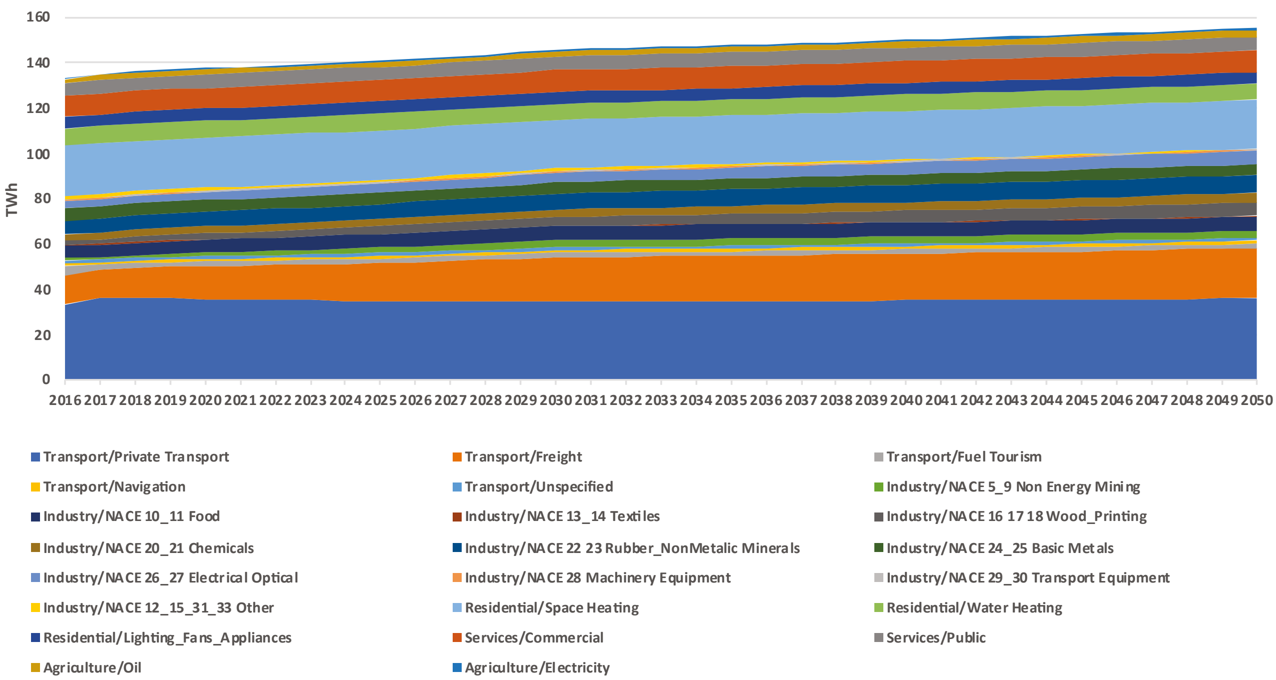


**Figure 3.13. LEAP Ireland 2050: reference scenario energy demand (TWh).**

8 840,000 EVs are described by 550,000 battery electric vehicles and 290,000 plug-in hybrid electric vehicles.

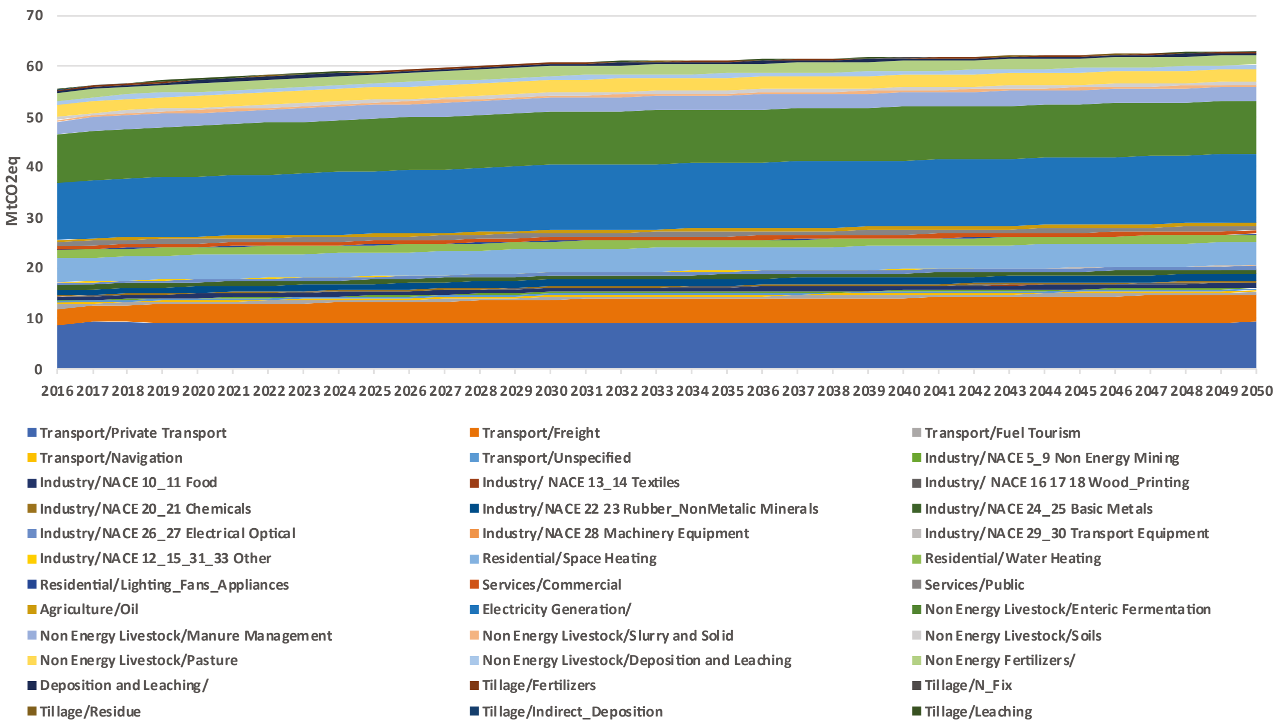


**Figure 3.14. LEAP Ireland 2050: reference scenario emissions (Mt $CO_2$ eq).**

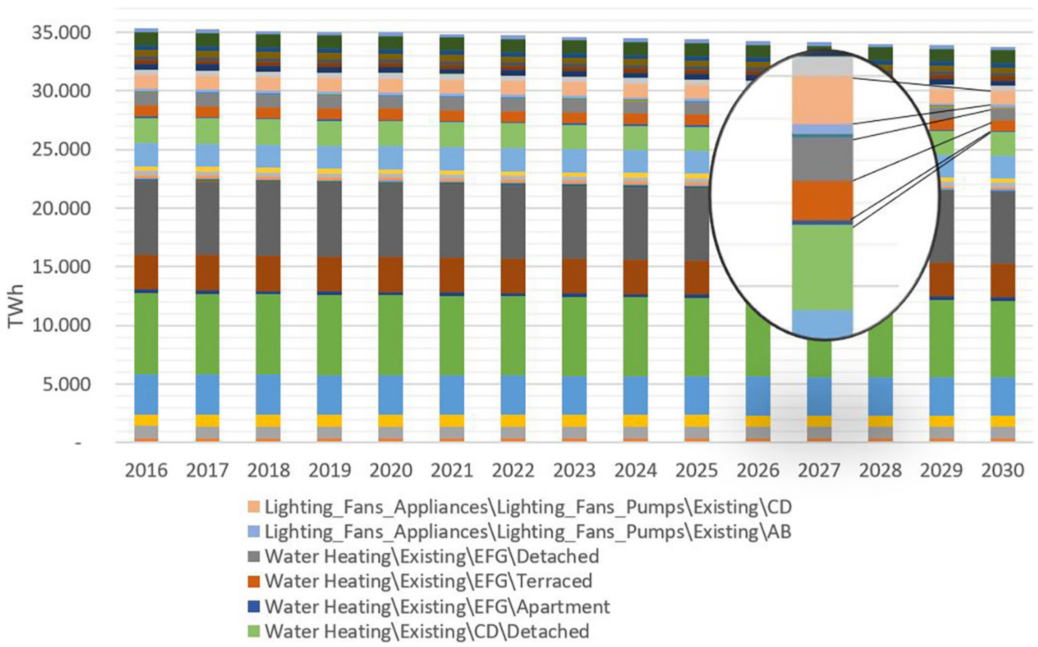


**Figure 3.15. Residential energy demand – granular detail.**

detail available within the demand results; transport subsectors include road private cars (various fuel types), freight (LGV/HGV), aviation (domestic/ international), buses, rail, navigation and fuel tourism.

Road private cars can be further disaggregated by fuel type (petrol, diesel, CNG, electricity, hybrid), engine size (<900 cc, 901–1200 cc, 1201–1500 cc, 1501–1700 cc, 1701–1900 cc, 1901–2100 cc and >2100 cc) and vintage (25 years). Figure 3.18 shows the level of bottom-up granular detail available within the LEAP: road private car demand transport sector. The figure highlights the demand (TWh) for diesel vehicles with an engine size of F1901–2100 cc, with vintages of 3–7 years.

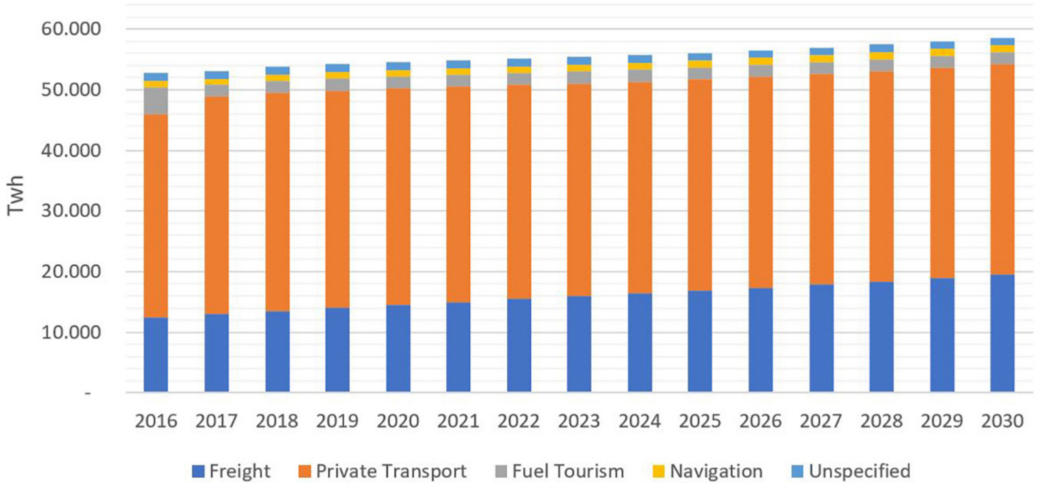


**Figure 3.16. LEAP Ireland 2050: transport energy demand – aggregated subsectors.**

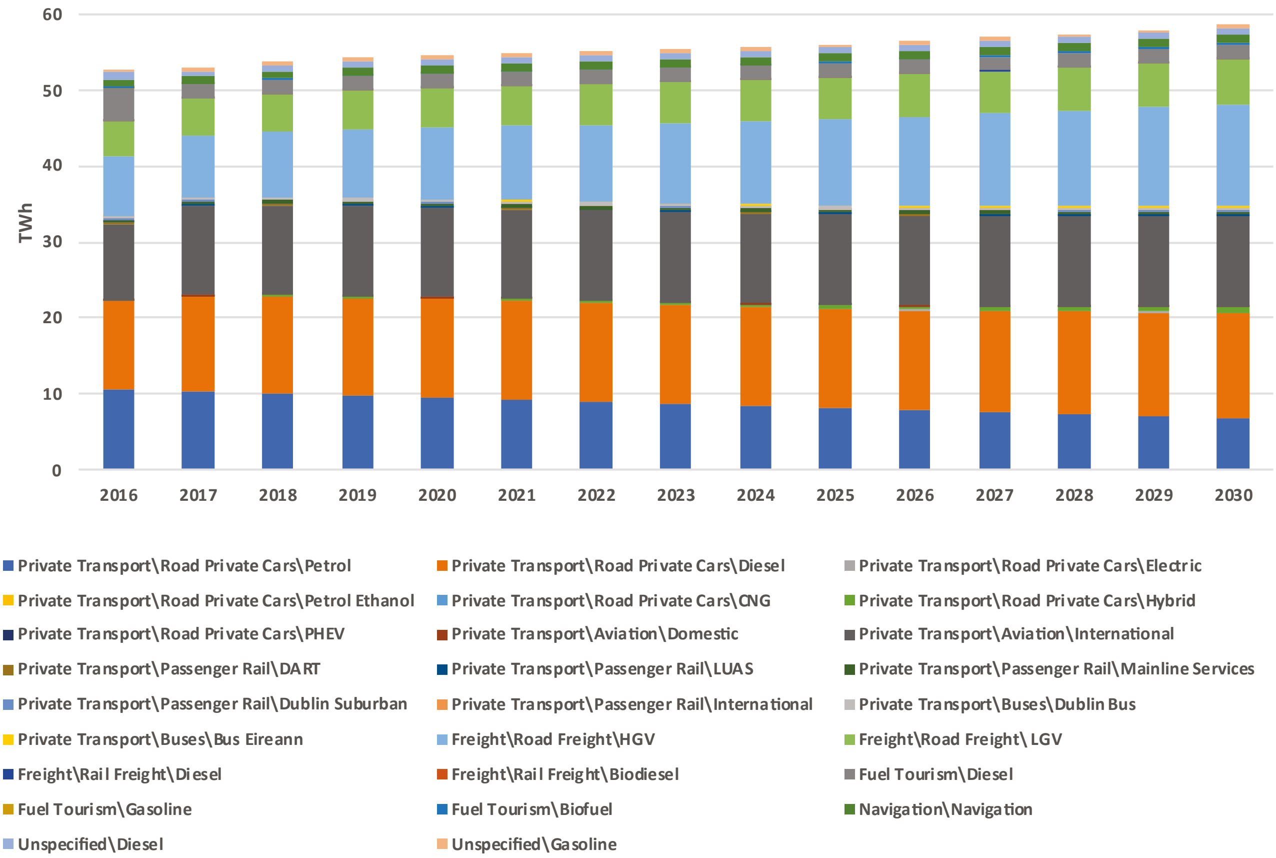


**Figure 3.17. LEAP Ireland 2050: transport demand – disaggregated granular detail.**

### *3.8.2 CAP electric vehicle penetration*

The CAP EV penetration scenario investigates the impact of achieving the target 840,000 EVs in the private passenger transport sector by 2030. Cumulative emissions reductions shown in Figure 3.19 equate to approximately 7 Mt $CO_2$eq over the period 2020–2030. This scenario includes no sales of any petrol/diesel vehicles within private passenger transport by 2030. A third scenario explores the potential for emissions reduction and EV penetration using historical EV diffusion data from Norway as a proxy for understanding what we might expect if Ireland were to follow a world-leading example. The EV Norway scenario projects Ireland seeing approximately 200,000 EVs on the road by 2030, with

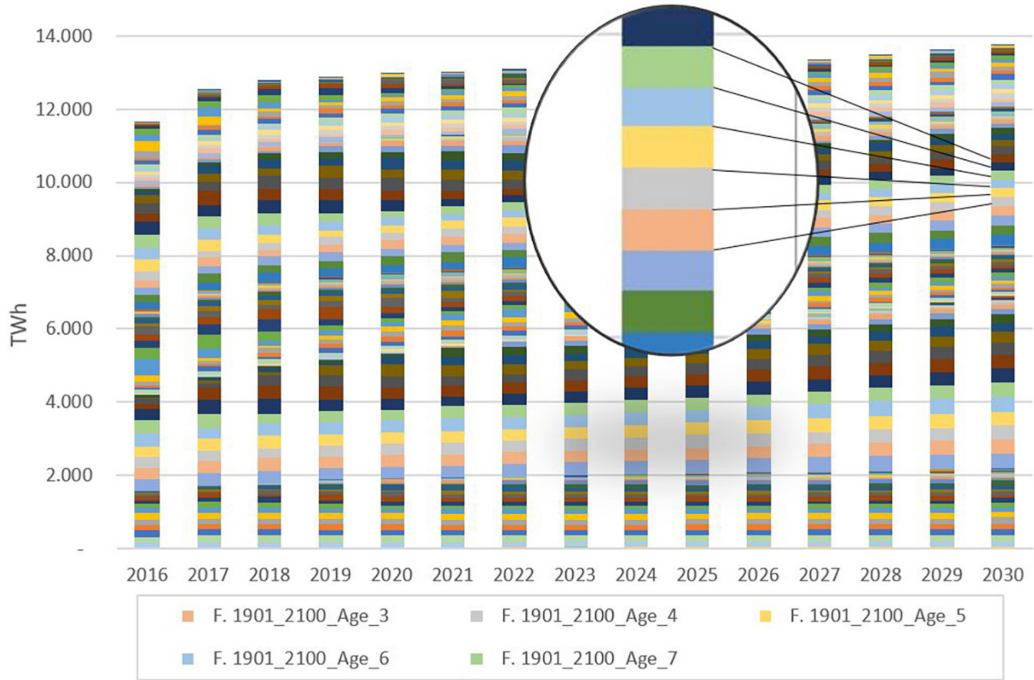


**Figure 3.18. Private passenger transport energy demand: road private vehicles – granular detail including vehicle vintage.**

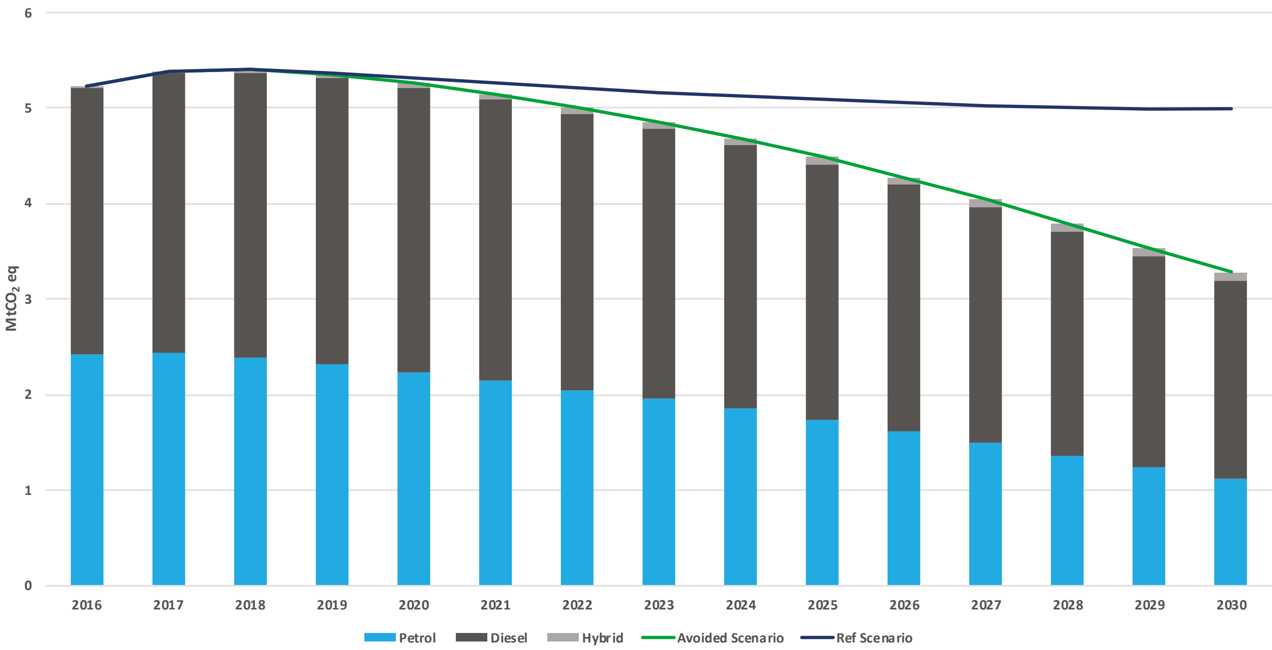


**Figure 3.19. LEAP Ireland 2050 CAP electric vehicle penetration scenario (to 2030).**

a cumulative emissions reduction of 0.6 Mt $CO_2$eq. Figure 3.20 shows the cumulative emissions reduction associated with achieving the 200,000 EVs by 2030. The EV Norway scenario highlights the challenge associated with delivering 840,000 private passenger EVs and shows the importance of understanding pathways of headline end-of-period targets.

The added advantage associated with using LEAP Ireland 2050 to conduct this type of technology diffusion scenario analysis is the quantification of the number of EVs entering the system in each year. In addition, this method quantifies the number and type (fuel, engine size) of vehicles removed from the system. Figure 3.21 shows the number of EVs [battery

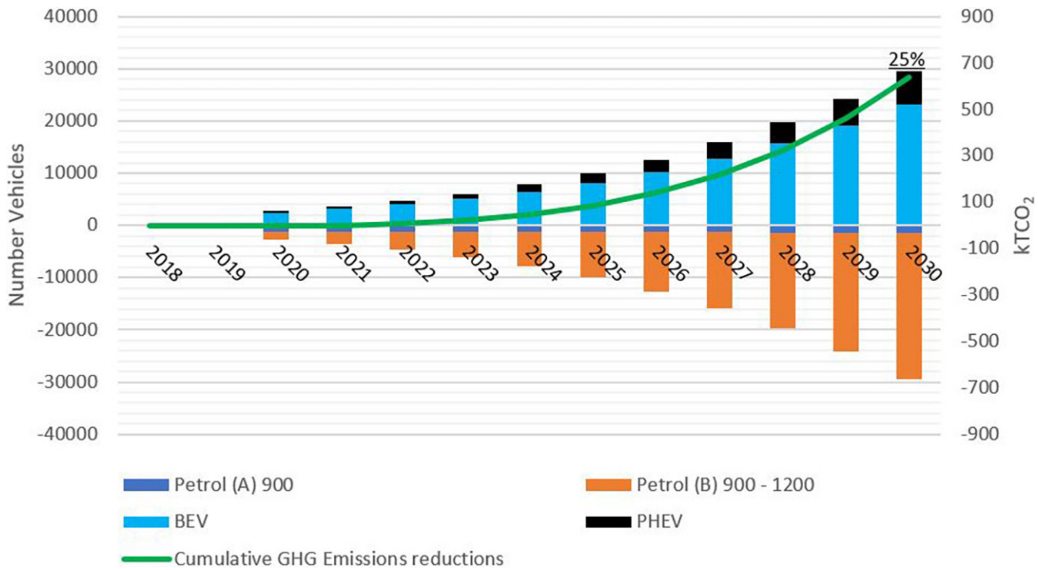


**Figure 3.20. Electric vehicle EV Norway scenario, vehicle sales and cumulative emissions reduction (kt $CO_2$).**

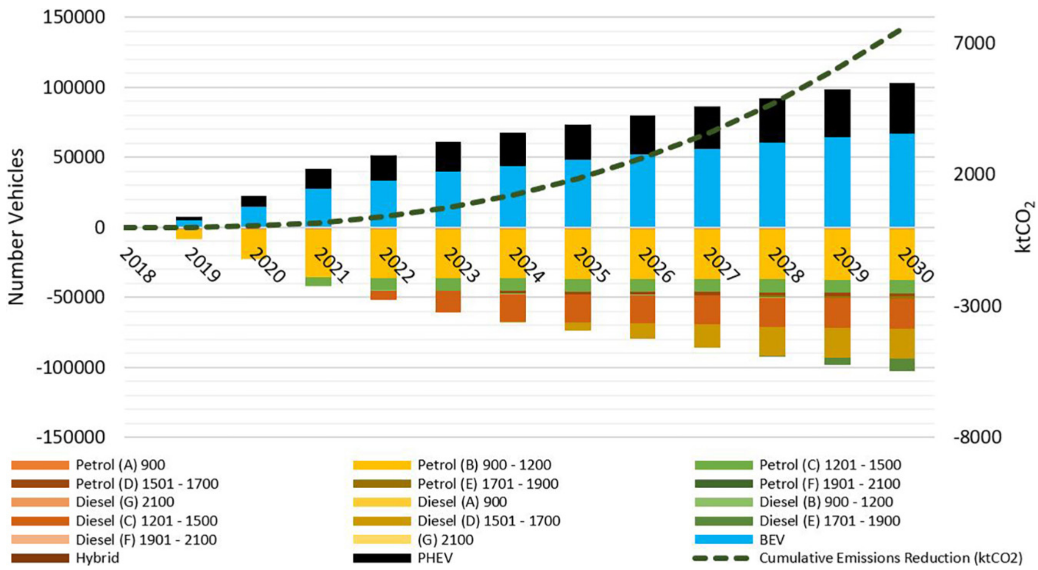


**Figure 3.21. Electric vehicle early action target compliance, vehicle sales and cumulative emissions reduction (kt $CO_2$).**

electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)] introduced in each year and the number of internal combustion engine (ICE) vehicles removed for this scenario (by type). ICE removal is based on removing the smallest capacity engines first, i.e. < 900 cc, and moving up through larger capacity engines as the requirement for larger numbers of replacements is needed (Xing *et al.*, 2019).

An alternative target-compliant “late-adopter” scenario was also developed to quantify the impact of achieving the CAP target of 840,000 vehicles with a different diffusion rate of BEVs and PHEVs. Figure 3.22 shows the alternative scenario results, with the number of EVs cumulatively achieving the CAP target by 2030. The cumulative emissions reduction for this scenario equates to 6.3 Mt $CO_2$eq between 2020 and 2030.

### *3.8.3 CAP residential retrofitting*

The CAP residential retrofitting scenario investigates the impact of achieving 500,000 residential retrofits to an average AB BER standard across apartments

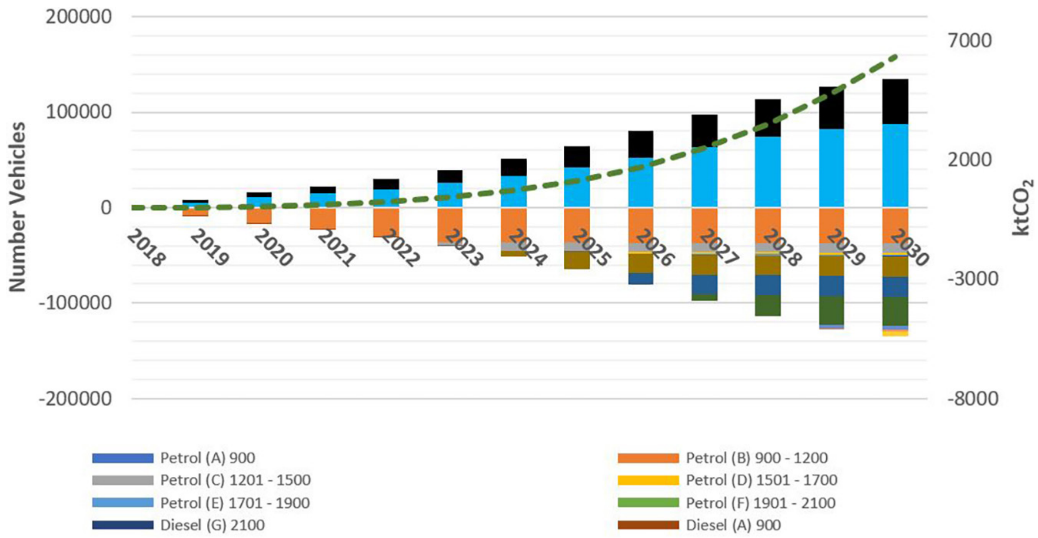


**Figure 3.22. Electric vehicle delayed action target compliance, vehicle sales and cumulative emissions reduction (kt $CO_2$).**

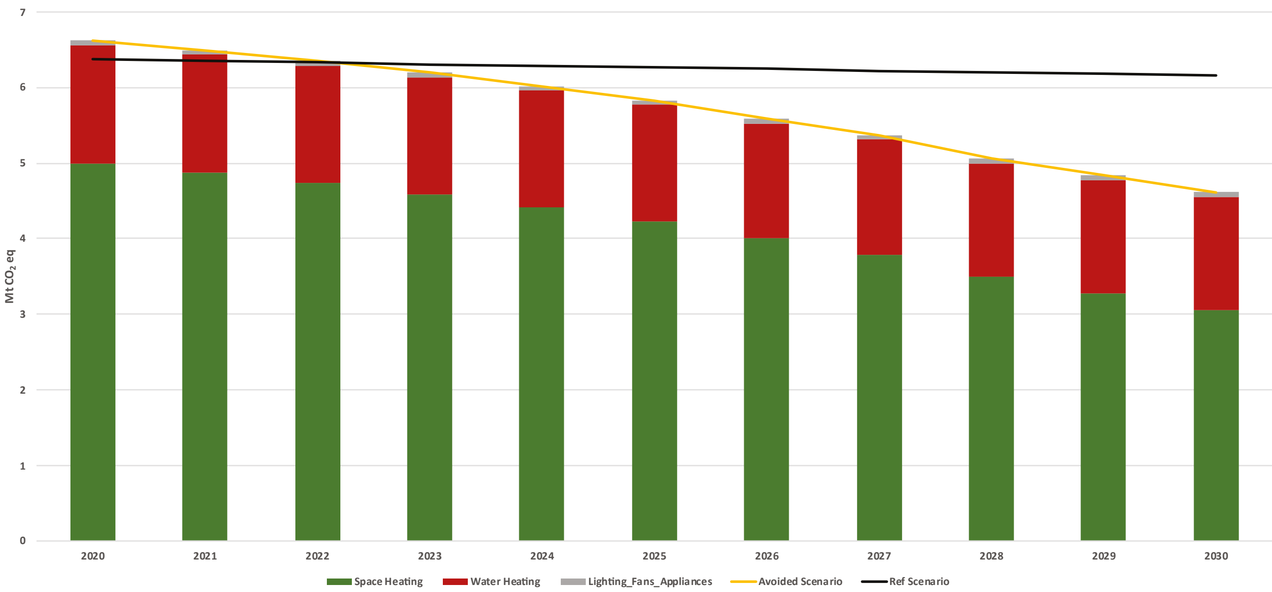


**Figure 3.23. LEAP Ireland 2050 CAP residential retrofitting scenario (to 2030).**

and terraced and detached dwellings. The scenario includes an even distribution of 400,000 heat pumps across terraced and detached dwellings, post retrofit. Cumulative emissions reductions shown in Figure 3.23 equate to approximately 6 Mt $CO_2$eq over the period 2020–2030. This scenario only investigates the potential cumulative emissions reduction associated with achieving the CAP retrofitting target. Importantly, it does not examine the feasibility of achieving this target and implicitly assumes that it is possible to reach 500,000 dwelling retrofits by 2030. Figure 3.24 assumes a significant increase of approximately 20,000 deep retrofits per annum in 2020, rising to over 70,000 per annum by 2030. This contrasts with the approximately 200 deep retrofits estimated to have been completed in 2019, highlighting the scale of the challenge associated with delivering the CAP deep-retrofitting target.

The LEAP model also quantifies the number and type of dwellings retrofitted in this baseline reference scenario (by defined archetype – see section 3.2). Figure 3.24 shows the number and type of dwellings retrofitted in each year between 2020 and 2030.

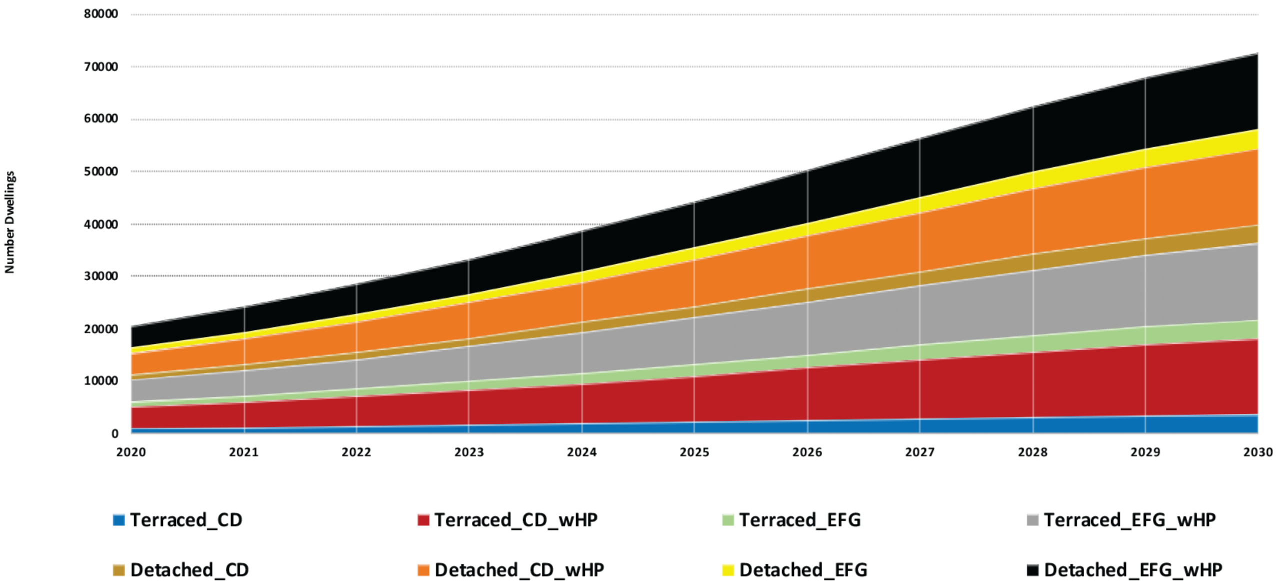


**Figure 3.24. Residential retrofit CAP scenario – number of dwellings retrofitted per annum by archetype.**

# 4 Project Outputs

This project has resulted in several significant outputs, including the LEAP Ireland 2050 model, four peer-reviewed journal papers, a PhD thesis and five peer-reviewed conference papers across multiple national/international LEAP collaborations.

## 4.1 LEAP Ireland 2050

The LEAP Ireland 2050 model remains a core deliverable from this research project. This new simulation tool accounts for energy- and non-energy-related GHG emissions in Ireland across industry, transport, residential, services, agriculture and electricity generation. The model structure chosen for each sector was dictated by the best available data and reflects the need to answer relevant policy pathway questions within each sector. Chapter 3 provides a detailed description of the modelling structure and data sources that underpin the new LEAP Ireland 2050 model. This new model facilitated the ex-post evaluation of existing policy and ex-ante evaluation of future policy, the results of which are explored in Chapter 5.

## 4.2 Abstracts of the Peer-reviewed Publications

Tomás Mac Uidhir, Fionn Rogan, Matthew Collins, John Curtis and Brian Ó Gallachóir. Improving energy savings from a residential retrofit policy: a new model to inform better retrofit decisions. *Energy and Buildings* 29: 105247. https://doi.org/10.1016/j.enbuild.2019.109656. Reproduced under the terms and conditions of the Creative Commons attribution licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

> Retrofitting is one of the most important policy measures for timely decarbonisation of the residential sector due to slow turnover of the housing stock. Ireland is an interesting case study given the high reliance on oil as a fuel, the dispersed pattern of residential housing and the relatively poor energy efficiency performance of the existing housing stock. Decarbonising residential space and water heating has proved challenging in the Irish context. These energy service demands are generally inflexible and resilient to reduction due to a range of considerations including external weather conditions, fuel price and the rebound effect. This paper examines and challenges the suitability of popular retrofit combinations as they apply to nine distinct building archetypes in Ireland's housing stock portfolio. An archetype simulation model is used to evaluate the potential for improved energy efficiency gains within the existing retrofit program. We introduce a new methodology that provides insights into sub-optimal retrofit choices. The five most common retrofit combinations are simulated for each of the nine archetypes. The results show that the alternative retrofit combination differs by archetype and that additional energy efficiency gains of up to 86% can be achieved due to alternative retrofit choices. We believe there is room to improve building energy efficiency standards in Ireland through the implementation of a bespoke building retrofit grant scheme which delivers better informed retrofit choices and more effectively considers the pre-existing condition of a building as part of the initial application process. The implications of this analysis are explored and insights for policy are also provided.

Tomás Mac Uidhir, Fionn Rogan, Matthew Collins, John Curtis and Brian Ó Gallachóir. Residential stock data and dataset on energy efficiency characteristics of residential building fabrics in Ireland. *Data in Brief* 29: 105247. https://doi.org/10.1016/j.dib.2020.105247. Reproduced under the terms and conditions of the Creative Commons attribution licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

> These data support the research article "Improving energy savings from a residential retrofit policy: a new model to inform better retrofit decisions" – (Mac Uidhir *et al*., 2019) This article presents 3 data sources which are utilised in conjunction with a detailed

energy system model of the residential sector to explore policy pathways for residential retrofitting. Data is collected from the Central Statistics Office (CSO) and the Sustainable Energy Authority of Ireland (SEAI). The first SEAI dataset is compiled for Ireland in compliance with the EU Energy Performance of Buildings Directive (EPBD). Data is collected using the Dwelling Energy Assessment Procedure (DEAP). DEAP is used to produce energy performance certificates known as Building Energy Ratings (BER). A BER indicates a building's energy performance across a 15-point energy efficiency scale, rated alphabetically from A1 to G, in units of kWh/$m^2$ year. A BER is required for new buildings and the rent or sale of existing dwellings – therefore the database has consistently grown in size since its inception in 2006. The BER database contains 735,906 records of individual dwellings. The database includes detailed building fabric information across a range of different building types, year of construction, Main/Secondary space/water heating fuels, heating system efficiency, ventilation method and structure type (Insulated concrete form, Masonry, Timber or Steel Frame). The second SEAI dataset (PWBER) contains aggregated pre and post BER information for a sample of 112,007 dwellings retrofitted during the period 2010–2015; this database contains mean energy efficiency improvement (kWh/$m^2$ year) for a range of retrofit combinations as they apply to nine distinct building archetypes. The third CSO dataset is compiled from census data, representing the frequency of building types by year of construction.

Tomás Mac Uidhir, Fionn Rogan and Brian Ó Gallachóir. The diffusion of innovation within policy – a new model to investigate the impact of carbon budgets on climate policy. *Energy Policy* (in preparation).

This paper presents a national energy demand and emissions model for Ireland. The model is developed using the Long-range Energy Alternative Planning system, applying a bottom-up methodology which contains sufficient detail to provide insights into the impact of policy pathways applied to national climate policy. The study focuses on two key national policies, (1) the introduction of 840,000 electric vehicles and (2) the retrofitting of 500,000 residential dwellings by 2030. Each policy explores the effect on cumulative greenhouse gas emissions between early and delayed target compliance scenarios, for the period 2021–2030. While providing a policy pathway with annual implementation targets, this study also highlights the advantages associated with early action with respect to delivering end year 2030 targets. Cumulatively, early action can deliver an additional 19.6% (1.14 Mt $CO_2$eq) reduction within private passenger transport and an additional 9.6% (0.82 Mt $CO_2$eq) within residential retrofitting. This study highlights the vital need to progress the policy narrative to include implementation pathways and carbon budgets, not just final year headline targets. The results include detailed information on the type of residential dwellings retrofitted in each year, and the number, age and engine size of dwellings displaced by electric vehicles.

Tomás Mac Uidhir , Fionn Rogan, Paul Deane, James Glynn, Charles Heaps and Brian Ó Gallachóir. Understanding energy modelling limitations – unlocking advanced simulation modelling applications using a simple accessible tool.

The characteristics of energy modelling tools consist of a wide range of component attribute categorisations. The nature of policy question which can be assessed is defined by these attributes and includes the model purpose, analytical approach (top-down/bottom-up) and data requirements. Recent developments have witnessed a shift to a bottom-up approach to energy demand and emissions modelling (e.g. Kyoto Protocol, NDCs) – this change has prompted a need for new modelling techniques and features to aid in the development of robust evidence-based policy support. This paper introduces the Application Script Editing Tool (ASET), a new modelling tool which leverages a simple coding framework to enable (i) a new method of producing energy system model topology using the Low Emissions Analysis Platform (LEAP) and (ii) facilitate complex scenario and sensitivity analysis of key model assumptions. This new framework is designed to support accessibility, compatibility and usability, with the aim of unlocking the underutilised Application Interface within LEAP. The advantages associated with developing a simulation model using ASET are explored and a case study of the added benefits "associated" within transportation energy modelling is provided.

This paper provides an overview of energy system modelling categorisations and explores the complete range of current application interface commands which exists within the application interface and provides suggestions for developing other modelling tools.

## 4.3 Abstract of the PhD Thesis

All countries must decarbonise their energy systems if global warming is to remain below 2°C, as stipulated in the now ratified Paris Agreement. The EU has ambitious decarbonisation targets for 2020/2030 and 2050. Improving energy efficiency and reducing demand form two key pillars designed to achieve these goals. In 2009 the European Union (EU) established the Effort Sharing Decision (ESD), which set individual Member State greenhouse gas (GHG) emission reduction targets for transport, built environment, agriculture and waste. Ireland is currently not on course to achieve its 2020 target of 20% reduction, relative to 2005 levels. In 2012 the EU established the Energy Efficiency Directive, which set an EU-wide target of 20% energy savings as a direct result of energy efficiency measures, relative to average final energy consumption for the period 2001–2005.

Energy systems are comprised of many overlapping elements interacting between different economic sectors. Policy narratives tend to focus on the decarbonisation pathways/technologies which ultimately apply to cleaner electricity generation, e.g. electrification of heat and transport, and ever-increasing penetration of wind turbines for electricity generation. Owing to their size, institutional inertia and their complex structure, these energy systems tend to get locked into particular configurations which make them difficult to change. While analysts and policymakers have usefully exploited energy models to improve our understanding of these complex interactions, there is an on-going need to improve the evidence base underpinning key policy decisions. Various energy system modelling tools exist which vary according to different jurisdictions of analysis (i.e. by region, country, or global), questions that analysts seek to answer, the interactions between human earth systems and levels of computing power available.

The main aim of this thesis is to establish the methodological framework necessary to answer complex policy pathway questions for Ireland. The first part of this thesis seeks to improve the capacity within the national modelling framework and provide more granular detail within key sectors such as private passenger transport, residential, commercial services and industry. This section will introduce new model development techniques which are utilised in the creation of detailed bottom-up subsectors. The second part of this thesis utilises the improved modelling capacity to conduct an ex-post analysis of existing retrofit supports, seeking to find ways in which the existing policy could be improved. Finally, the improved modelling capacity and lessons learned are applied to an ex-ante evaluation of the potential for increased GHG reductions over the period 2020–2030 for Ireland.

The main contribution of this thesis is the improved model development capacity within the Low Emissions Analysis Platform (LEAP), the evaluation of key existing policy and the development of an improved modelling framework which improves the evidence base for future policy pathway development.

## 4.4 Conference Proceedings/ Presentations

- A multi-model approach to provide insight into energy efficiency gains in industry. European Council for an Energy Efficient Economy (ECEEE) – Industrial Energy Efficiency conference. Berlin, 2016.
- Better Energy Homes Scheme with Archetype Dwelling Energy Model (ArDEM). ESRI-UCC-MaREI energy research conference. Dublin, 2016.
- SEI summer internship and the Application Script Editing Tool (ASET). SEI LEAP internship – model development techniques presentation. Boston, 2017.
- Policy pathways for Ireland – how much energy efficiency is residential retrofitting delivering? ESRI-UCC-MaREI energy research: climate action conference. Dublin, 2019.
- LEAP 2050 GHG Model Development. EPA-UCC-MaREI energy research workshop – LEAP assessment. UCC, 2019.

## 4.5 Review of National and International Best Practice

A literature review on inventories and projections gathered materials from various guidelines developed by the European Commission Directorate-General for Climate Change (DG CLIMA), Intergovernmental Panel on Climate Change (IPCC), World Resources Institute (WRI), United Nations Environment Programme (UNEP), United Nations Human Settlement Programme (UN-Habitat), World Bank, Local Governments for Sustainability (ICLEI) and Covenant of Mayors on GHG emission inventory and projection and its application at national and local spatial scales (Table 4.1).

Based on this literature review, a list of criteria for evaluating country inventories and projections was developed (Table 4.2).

The main output from this review was a set of policy criteria that could be the basis for a template for evaluating different countries' approaches to GHG inventories and projections. Further study could be useful to evaluate practices and give deeper insights into the different scenario approaches employed to develop emissions projections. These criteria and template could also be a basis for international comparative analysis and contain the potential for critiquing Ireland's national practice in the context of international best practice, notwithstanding the challenges of data gathering that such an undertaking would probably present.

**Table 4.1. List of documents reviewed as part of phase 1 of the review framework to evaluate GHG emission projections**

| Organisation | Guidelines | Reference |
|---|---|---|
| Covenant of Mayors for Climate and Energy initiative | How To Develop A Sustainable Energy Action Plan (SEAP) – Guidebook | Covenant of Mayors, 2010 |
| Directorate-General for Climate Change | Draft GHG Projection Guideline Part A: General Guidance | DG CLIMA, 2012a |
| | Draft GHG Projection Guideline Part B: Sectoral Guidance | DG CLIMA, 2012b |
| Intergovernmental Panel for Climate Change | 1996 IPCC Guidelines for National Greenhouse Gas Inventories | Houghton *et al.*, 1996 |
| | Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories | IPCC, 2000 |
| | Good Practice Guidance for Land Use, Land-Use Change and Forestry | IPCC, 2003 |
| | 2006 IPCC Guidelines for National Greenhouse Gas Inventories | IPCC, 2006 |
| Local Governments for Sustainability | International Local Government GHG Emissions Analysis Protocol (IEAP) | ICLEI, 2009 |
| UN Environment Programme, UN-Habitat, World Bank and Cities Alliance | International Framework for Reporting Greenhouse Gas Emissions from Cities | UNEP *et al.*, 2012 |
| World Resources Institute | GHG Protocol Mitigation Accounting Initiative | WRI, 2012 |

**Table 4.2. Criteria for sectoral-level assessment of greenhouse gas emission inventories and projections**

| Category | Criteria |
|---|---|
| Quality of submission | Completeness |
| | Comparability |
| | Consistency |
| Data | Data sources |
| Modelling approaches | Key parameters |
| | Key categories |
| | Model |
| | Method |
| Policies and measures | Type of policies and measures |
| | Status of policies and measures |
| Transparency | Transparency of method |
| | Role and responsibility |

# 5 Conclusions

This section outlines the key conclusions, as they apply to the five work packages that define the research project. The LEAP modelling software was found to function effectively as a robust simulation modelling tool that could adequately model a complex energy system while simultaneously communicating results in an accessible form. While the key focus of the project remained the completion of the LEAP Ireland 2050 model, additional tools, e.g. ArDEM-SQL, ASET and the marginal abatement cost curve (MACC) tool, emerged as important features during the project. The LEAP model, including these additional tools, have aided in delivering a robust GHG simulation tool for Ireland, the completion of ex-post and ex-ante evaluations of key climate policy, and the dissemination and engagement with key stakeholders within the climate policy space. These outcomes align with the work packages defined at the start of this project and are explored in more detail within this section.

## 5.1 Ex-post Analysis

The ex-post analysis of residential retrofitting (2010–2015) served to highlight policy recommendations and ways to deliver improved outcomes in future policy formation. Switching future grants to an output-based system (i.e. a grant for achieving specified levels of energy savings) as opposed to a grant for the installation of specific retrofit measures (i.e. insulation) could pivot homeowners' perspective towards energy savings and away from specific retrofit measures. The ArDEM-SQL tool developed as part of this work could usefully inform homeowners seeking to maximise energy savings and policymakers in setting grant values for achieving specified levels of energy savings. Prioritising alternative, archetype-focused retrofit activity, while maintaining the total number of retrofits completed, estimates an energy savings potential of 1389 GWh, realising an additional 643 GWh or an 86% additional energy savings potential per annum, relative to those in the actual retrofits which were conducted during the period 2010–2015 (Figure 5.1). The additional 86% annual energy savings was estimated to cost an additional 30% (to the grant provider), relative to the baseline cost. This analysis formed the basis of an open access journal article published in *Energy and Buildings* (Mac Uidhir *et al*., 2019a) and further detailed analysis is available there.

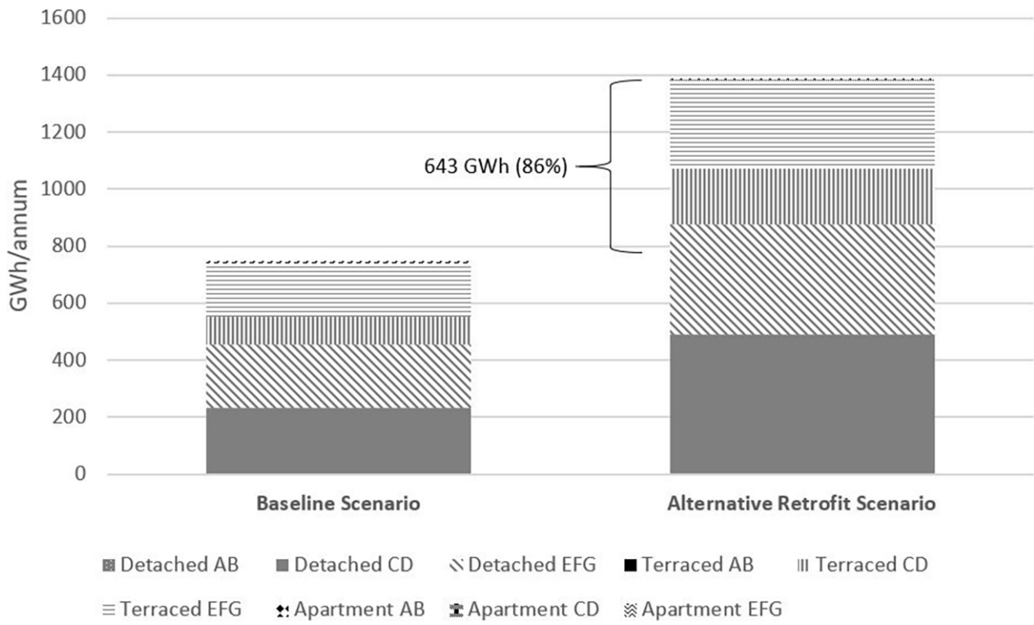


**Figure 5.1. Estimated energy savings (baseline versus alternative retrofit scenario). Reproduced from Mac Uidhir *et al*. (2019a) under the terms and conditions of the Creative Commons attribution licence CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).**

## 5.2 Ex-ante Analysis

The ex-ante evaluation of key climate policies within CAP was facilitated by the completion of the LEAP Ireland 2050 simulation model. This analysis examined the impact of introducing 840,000 private passenger EVs and 500,000 residential retrofits by 2030. In addition to quantifying the emissions reduction associated with ambitious EV targets, this analysis also considered their feasibility by comparing Ireland's targets with those of international case studies, concluding that delivering 840,000 EVs by 2030 would require an unprecedented effort in such a short time horizon. This analysis formed the basis of a journal article, "Exploring EV diffusion and residential retrofitting using a new model to investigate the impact of climate policy on carbon budgets", which is currently being finalised for submission to *Energy and Climate Change*. This ex-ante analysis highlighted the importance of simulating technology diffusion pathways to aid in understanding the impact on carbon budgets. Distinct CAP-compliant, early/late diffusion scenarios for EVs and residential retrofitting showed there was an additional 2.15 Mt $CO_2$eq potential abatement possible based solely on the diffusion pathway followed, when early action is prioritised. Early versus delayed action can deliver an additional 20.9% (1.33 Mt $CO_2$eq) reduction within private passenger transport and an additional 9.6% (0.82 Mt $CO_2$eq) within the residential sector, between 2021 and 2030.

At present the CAP EV target, deep retrofitting and installation of heat pumps are all included as discrete policy scenarios in the LEAP Ireland 2050 model. Within the LEAP CAP-compliant EV scenario, projected emissions within private vehicles reach 3.96 Mt $CO_2$eq in 2030. This figure is approximately equivalent to the "required" range provided within CAP (3–4 Mt $CO_2$eq by 2030; Government of Ireland, 2019). Similarly, the LEAP deep-retrofit scenario projects emissions within the residential built environment as 4.4 Mt $CO_2$eq by 2030. This figure is approximately 10% above the upper bound of the CAP range of 3–4 Mt $CO_2$eq by 2030. While it is a useful calibration exercise to compare results between LEAP and the CAP for one individual year (2030), LEAP adds value as it shows the pathway (2020–2030) that delivers this 2030 target, allowing for a deeper understanding of carbon budgets for the analysis period across private passenger transport and residential retrofitting. Significantly, it is not immediately apparent what simulation pathway is included within the CAP analysis and hence it is not possible to compare carbon budget analyses between the two figures.

## 5.3 Future of LEAP Ireland

This report has outlined a range of policy pathways to 2030 and 2050, reflecting the focus to date of Irish climate policy. Action 1 of the CAP (launched in June 2019) focuses on climate policy targets for 2050, namely what would be required to increase decarbonisation ambition from the current target of an 80% reduction in energy-related $CO_2$ emissions (and carbon neutrality in land use) to a new target of net-zero GHG emissions (covering both energy and land use) (DCCAE, 2019). This increased ambition should reflect the need to realise a transition that accounts for all GHG emissions in the long term. The requisite analysis to evaluate this proposal is being marshalled by the Climate Action Modelling Group (CAMG) as chaired by DCCAE. An expanded version of the model described in this report will be used to contribute to the evidence base for this proposed increase in climate policy ambition.

The LEAP Ireland 2050 model will extend the policy pathways analysis beyond 2030 to be an operational modelling tool for scenario analysis that can inform Ireland's energy and climate action policy to 2050. The model will be continuously improved to incorporate new information and requirements (relating to, for example, new insights on citizen uptake of new technologies and practices, effectiveness of policy measures, and behavioural and societal change); and incorporating ongoing updates of fuel prices, energy technologies, and imported and indigenous energy resources. The model will improve the evidence basis available to policymakers on the role and effectiveness of policy measures in delivering improvements in energy efficiency, renewable energy and GHG emissions reductions. It will help increase the understanding of the effectiveness of policy measures in delivery of agreed targets, including within the non-ETS sectors of car transport, freight and residential energy efficiency, as well as economy-wide efficiency measures. Lastly, it will contribute to the development of energy policy roadmaps through combining energy systems optimisation and simulation modelling.

## 5.4 Model Dissemination

The LEAP Ireland 2050 model will be maintained within the EPMG within UCC. The tool will be hosted online and accessible via the MaREI datahub.[9] Access to the LEAP model will be subject to a Creative Commons licence. The tool requires a licensed version of the Low Emissions Analysis Platform system software to be utilised successfully. Details on available licensing structures are available from the Stockholm Energy Institute (SEI, 2019).

9 https://www.marei.ie/data-hub/ (accessed 14 May 2020).

# 6 Recommendations

This section outlines the recommendations that have been identified throughout this research project. The LEAP Ireland 2050 model has been designed to function as a robust policy simulation tool that can adequately model the impact of climate-related policies and effectively communicate the results to policymakers. The project outlined five key work packages, including project management (WP1), review of national and international best practice (WP2), ex-ante and ex-post analysis (WP3), development of an analytical GHG tool (WP4) and dissemination of results (WP5).

WP2 focused on an assessment of current models and data sources used within Ireland's inventory and projection systems, including a critique of national practice in the context of international best practice. WP3 focused on conducting ex-post and ex-ante analysis of key climate-related policies. In practice, this required the development of a new simulation tool (ArDEM-SQL) and was delivered in the form of an ex-post analysis of residential retrofit programmes (2010–2015) (Mac Uidhir *et al.*, 2019a). Completing WP3, ex-ante analysis, required the completion of WP4, i.e. the LEAP Ireland 2050 simulation model. WP4 presented challenges with respect to data gathering and technical modelling, explored in more detail within this section. Once the LEAP Ireland 2050 model was completed, an ex-ante evaluation of key policies within CAP was conducted. WP5 was delivered through engagement and dissemination of results throughout the research project in the form of conferences and workshops in Ireland and abroad.

While every effort was made to identify all available data sources as part of WP4, there were difficulties identifying granular data for industry and public services. Chapter 3 describes the best available data and methods implemented to gain some insight into these sectors; the illustrated advantages associated with gathering these data stand as useful recommendations in the absence of the actual data. There is a need to continually update and improve the LEAP Ireland 2050 model as new data are made available. These knowledge gaps and recommendations can help to define future areas of research related to the LEAP Ireland 2050 model. The recommendations in sections 6.1–6.3 relate to WP4 and the ongoing improvement of the LEAP Ireland 2050 model. Sections 6.4 and 6.5 relate to recommendations associated with WP3 and WP5, respectively.

## 6.1 Data Gaps

This project has highlighted data gaps within certain subsectors. There is a need for more robust data gathering within the industrial sector – in line with the superimposed UK Department of Energy and Climate Change (DECC) data utilised within this project. This would allow for sector-specific energy efficiency measures that target individual subsectors by NACE category. At present the data gathered within the business energy use survey do not allow this type of analysis. Public services would also benefit from additional data-gathering activity as energy end use within this sector is not transparent. An in-depth survey of residential appliance energy use would also provide useful data for future research. It would be useful if these data were linked directly with the information already contained within the BER database. These data would aid in a deeper understanding of appliance energy use, applied to distinct archetypes already in use within LEAP. Improved data collection across all sectors would facilitate the use of 'tagging' functionality in LEAP, which would allow for disaggregation between ETS and non-ETS activity; this should be considered on any new model development.

## 6.2 Extending LEAP Model to Include Air Pollutants

LEAP includes integrated support to analyse the effect of policies and measures on air pollutants. These factors have not been considered as part of this project and it is recommended that they are included in future iterations of the LEAP modelling framework in Ireland.

## 6.3 Extending LEAP Model to Include Costs

LEAP should be extended to include costs for all technologies. At present, basic fuel prices are included in the model for the purpose of successfully modelling electricity generation profiles. A complete set of costs would allow the LEAP Ireland 2050 model to utilise the LEAP marginal abatement cost curve tool developed within UCC.

## 6.4 Extend the Range of Policies Simulated within LEAP

While the scope of any research project is naturally limited by data availability, LEAP should continue to extend the range of policy measures simulated as data gathering is continually improved. Extending the scope of policy measures will allow more in-depth ex-post and ex-ante evaluations of key climate policies in line with WP3.

## 6.5 Improve Dissemination and Engagement

This research project has successfully facilitated and participated in ongoing dissemination and engagement in the form of national/international conferences, workshops and stakeholder meetings. Improving the frequency and nature of future engagements should be pursued to ensure robust simulation models are consistently utilised to underpin future climate policy discussions in Ireland.

## 6.6 Policy Recommendations

Improving the energy efficiency of residential dwellings will play a key role in delivering Ireland's energy efficiency and GHG emissions reduction targets in 2020 and beyond to 2030. At present, more than 80% of residential dwellings have a BER of C or worse. Ireland's Climate Action Plan 2019 (Government of Ireland, 2019) aims to achieve 500,000 retrofits to a B2 standard by 2030, including the installation of 400,000 heat pumps in existing buildings. Currently, 23,000 dwellings are retrofitted per annum. This highlights the scale of the challenge with respect to delivering meaningful retrofits that achieve minimum energy savings at a scale not previously undertaken in Ireland. ArDEM-SQL and the new LEAP Ireland 2050 model provide a methodological foundation to assess the effectiveness of potential retrofit combinations to aid in designing alternative archetype retrofit schemes that are output based, i.e. grants that are paid for achieving verified savings per unit grant, in place of the current measure-based grant system.

The retrofitting and EV diffusion pathway analysis raises the question of the adequacy of setting end-year policy targets, if the aim is to maximise emissions reductions over the whole analysis period. The LEAP model provides a platform that can explore the impact of different policy pathways across residential, transport, industry, services, agriculture and electricity generation. The examples explored serve to highlight the added benefits of early adoption, especially within energy efficiency measures. This project finds that end-year targets, while perhaps a useful starting point, provide little insight into implementation pathways. Policymakers should utilise the methodology established here to explore the feasibility of different diffusion pathways, establishing a range of favourable policy outcomes, prior to announcing end-year targets.

The tool presented here would be useful to policymakers in understanding the impact of potential policies in terms of a carbon budget over the period 2021–2030. Importantly, this tool provides a framework to "monitor the progress of the State in reducing Greenhouse Gas emissions" as outlined in the CAP (Government of Ireland, 2019).

In theory, policies achieve maximum benefits as a result of early action; in practice, policymakers contend with a broad range of concerns regarding which policies to prioritise. Future work within residential retrofitting could consider additional co-benefits of the effects on GHG reductions of retrofitting the least energy-efficient dwellings only. Future scenario analysis within the transport sector could include the impact of modal shift within private passenger transport, as high rates of EV penetration provide a simplified view of climate policy and ignore other important areas of concern such as congestion issues and broader health benefits.

The range of policy scenarios in LEAP should be expanded to include more CAP measures. This will aid in providing robust evidence-based policy support to the CAMG and enhance the process of annual progress reporting as required within

CAP. While ex-ante evaluation of future climate policies is necessary, it is also important to prioritise further ex-post analyses of past climate policy. This retrospective look at progress to date will aid in understanding which areas of policy have been successful and can be replicated going forward. Continued integration of multiple models into the LEAP framework will deliver consistency across modelling assumptions and remove siloed analyses. LEAP can enhance our understanding of implementation pathways, improving the current approach of providing end-of-period policy targets and instead deliver insights into carbon budgets in the medium/long term across all sectors.

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# Abbreviations

| | |
|---|---|
| **ArDEM-SQL** | Archetype Dwelling Energy Model |
| **ASET** | Application Script Editing Tool |
| **BER** | Building Energy Rating |
| **BEV** | Battery electric vehicle |
| **CAP** | Climate Action Plan |
| **CNG** | Compressed natural gas |
| **$CO_2$eq** | Carbon dioxide equivalents |
| **CSO** | Central Statistics Office |
| **DCCAE** | Department of Communications, Climate Action and Environment |
| **DEAP** | Dwelling Energy Assessment Protocol |
| **DECC** | UK Department of Energy and Climate Change |
| **EPA** | Environmental Protection Agency |
| **EPMG** | Energy Policy and Modelling Group |
| **ESD** | Effort Sharing Decision |
| **ESRI** | Economic and Social Research Institute |
| **ETS** | Emissions Trading Scheme |
| **EU** | European Union |
| **EV** | Electric vehicle |
| **EWP** | Energy White Paper |
| **GDP** | Gross domestic product |
| **GHG** | Greenhouse gas |
| **GWh** | Gigawatt hours |
| **ICE** | Internal combustion engine |
| **ktoe** | Kilotonnes of oil equivalent |
| **LEAP** | Low Emissions Analysis Platform |
| **MaREI** | Research Centre for Energy, Climate and Marine |
| **Mt** | Million metric tonnes |
| **NACE** | Statistical Classification of Economic Activities in the European Community |
| **NDP** | National Development Plan |
| **NECP** | National Energy and Climate Plan |
| **NEEAP** | National Energy Efficiency Action Plan |
| **NREAP** | National Renewable Energy Action Plan |
| **PHEVs** | Plug-in electric hybrid vehicles |
| **RES** | Renewable energy sources |
| **RES-E** | Electricity from renewable energy sources |
| **RES-H** | Heat from renewable energy sources |
| **RES-T** | Transport from renewable energy sources |
| **SEAI** | Sustainable Energy Authority of Ireland |
| **SEI** | Stockholm Environmental Institute |
| **UCC** | University College Cork |
| **UCD** | University College Dublin |

# Appendix 1 Additional Project Outputs

## Application Script Editing Tool

This project required the development of new modelling tools to create, modify and update the LEAP model topology. The Application Script Editing Tool (ASET) was developed within UCC and in conjunction with the SEI–LEAP application development team. This development took place during a 3-month internship with SEI and resulted in the development of the standalone ASET tool. The ASET tool allows for the rapid development of new model structures and insertion/updating of data expression, and enables sensitivity analysis within LEAP in a manner that was not previously possible. The development of the ASET scripting methodology also unlocked the ability to conduct other forms of analysis within LEAP, e.g. the production of marginal abatement cost curves within LEAP. Figure A1.1 shows the Excel interface designed within ASET used to generate new model topologies.

Figure A1.2 shows the Excel userform developed within ASET that enables sensitivity analysis within LEAP. This userform allows the user to identify key assumptions within the model and set a new maximum, minimum and step interval. The scripts generated by ASET are executed against a chosen LEAP model and provide a standardised range of outputs in line with any favourite charts as defined by the user within the LEAP graphical interface.

In addition to aiding in the construction of the LEAP Ireland 2050 model, the ASET tool was also utilised in the development of other regional and national models as part of MEngSc theses within UCC, shown below:

- Mario P. Castaneda, 2017. Energy Consumption and Green-House Gases Emission Model for Vietnam using LEAP-ASET.
- Yoga Bagus Wicaksono, 2017. Energy Consumption Model of Jakarta Transportation System: Passenger Road Transport.

## Marginal Abatement Cost Curve Tool

A script was developed for the LEAP API to generate a MACC. Figure A1.3 shows a MACC compiled from 20 measures outlined within the National Mitigation Plan (DCCAE, 2017a) MACC. These measures were chosen owing to data availability and represent a total abatement potential of 28 $MtCO_2$. Data on emissions mitigation associated with policies were gathered and rendered into a MACC format using the data visualisation software Tableau. The MACC tool is also available online.[10]

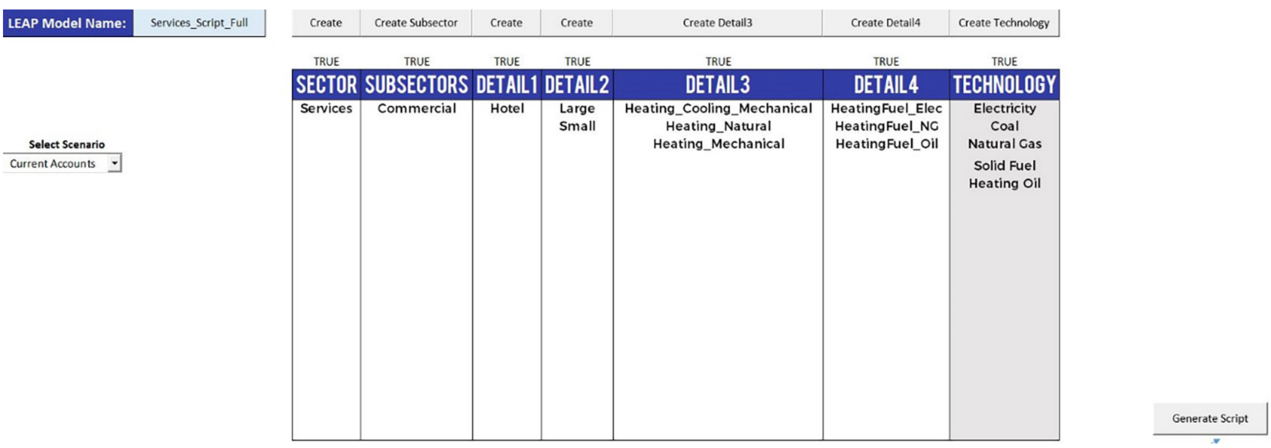


**Figure A1.1. Application Script Editing Tool: model topology creation interface.**

10 https://public.tableau.com/profile/ember.doyle#!/vizhome/MACCv1/Story1 (accessed 1 May 2019).

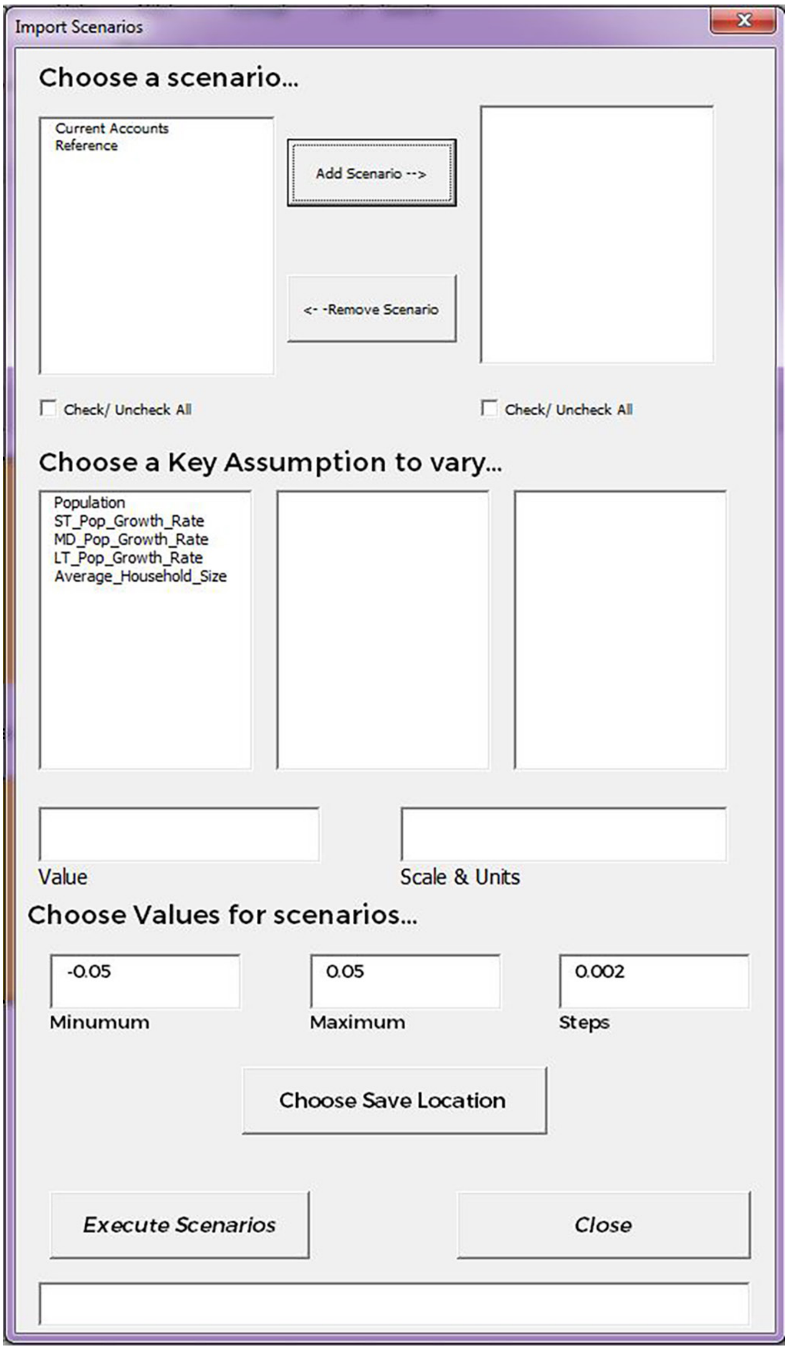


**Figure A1.2. Application Script Editing Tool: sensitivity analysis user interface.**

## Vietnam Ireland Bilateral Education Exchange Programme

In addition to the internal LEAP modelling capacity-building activities, this project has also been involved in the Vietnam Ireland Bilateral Education Exchange (VIBE) programme. This project has focused on the development of independent modelling capacity within multiple Vietnamese institutions (University of Science & Technology Hanoi (USTH), Institute of Energy Science (IES), National Center for Socio-Economic Information and Forecast (NCIF), Institute of Strategy and Policy on Natural Resources and Environment (ISPONRE) and the Vietnam Petroleum Institute). The exchange programme has involved advanced LEAP training with multiple stakeholders and the collaborative development of a LEAP Vietnam model, which can be utilised to examine Nationally Determined Contribution (NDC) development within Vietnam. Scenario development within this LEAP model is ongoing. Workshops in Hanoi and UCC, including online remote training and use of the ASET tool, formed the basis for this collaboration.

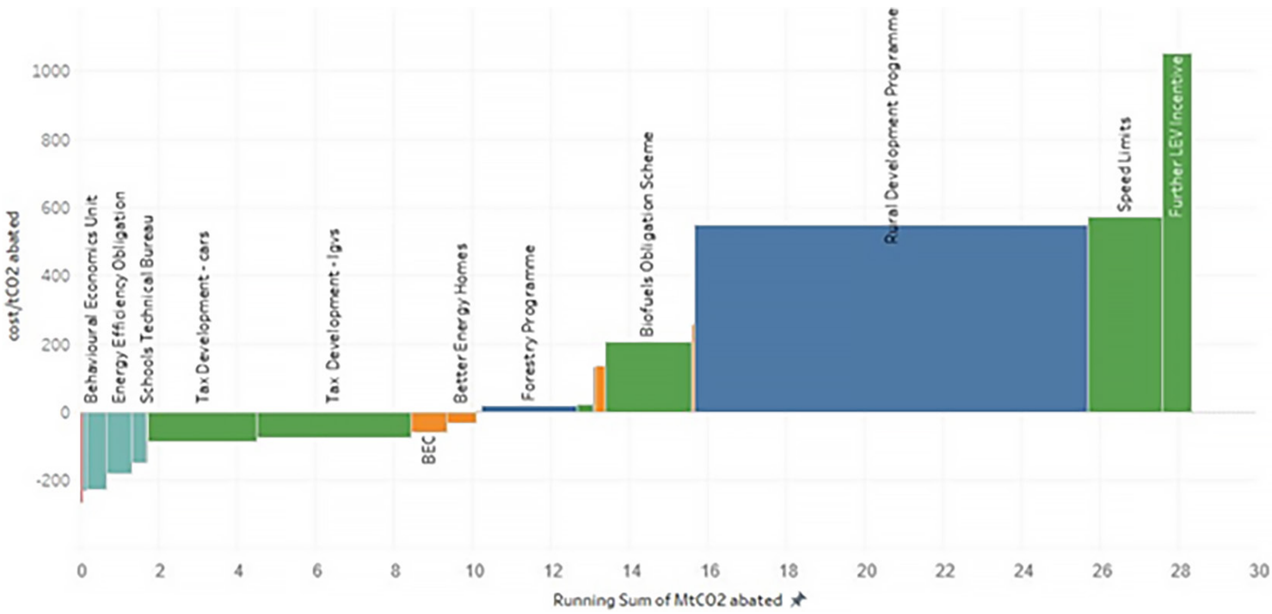


**Figure A1.3. National Mitigation Plan marginal abatement cost curve.**

# Appendix 2 LEAP Base Year Data Sources

**Table A2.1. LEAP base year data sources and reports**

| Sector | Subsector | Technology/fuels | Data type | Data source(s) |
|---|---|---|---|---|
| Residential | Detached<br>Terraced<br>Apartment | Primary/secondary water heating<br>Primary/secondary space heating<br>Lighting, pumps and fans<br>Appliances | Activity | SEAI – BER database<br>CSO – 2016 census |
| | | | Intensity | ArDEM-SQL (Mac Uidhir *et al*., 2019a)<br>SEAI – BER database |
| Services | Public | Oil<br>Natural gas<br>Renewables<br>Electricity | Activity<br>Intensity | CSO – National Income and Expenditure 2017 – Table 22<br>SEAI – National Energy Balance |
| | Commercial: heating and cooling<br>Commercial: heating – natural ventilation<br>Commercial: heating – mechanical ventilation | Hotel<br>Office<br>Restaurant/public house<br>Retail<br>Warehouse | Activity<br>Intensity | SEAI/Element Energy – Extensive survey of the commercial buildings stock in the Republic of Ireland |
| Transport | Car | Private car (driver/ passenger) | Activity | CSO – Transport Omnibus 2017<br>CSO – Vehicle Licensing Statistics Annual Series/TEA17/TEA03<br>Irish private vehicle transport model (Daly and Ó Gallachóir, 2011; Mulholland *et al*., 2017) |
| | | | Intensity | Irish private vehicle transport model (Daly and Ó Gallachóir, 2011; Mulholland *et al*., 2017) |
| | Bus | Bus Éireann – city service<br>Dublin Bus<br>Private bus services<br>Bus Éireann – regional service | Activity | Department of Transport, Tourism and Sport: Transport trends 2019 – An overview of Ireland's transport sector<br>National Transport Authority – Bus & Rail Statistics (June 2018)<br>CSO – Transport Omnibus 2016 – Public Transport |
| | Train | DART<br>LUAS<br>Mainline<br>Suburban<br>International | Intensity | Department of Transport, Tourism and Sport: Transport trends 2019 – An overview of Ireland's transport sector<br>National Transport Authority – Bus & Rail Statistics (June 2018)<br>CSO – Transport Omnibus 2016 – Public Transport<br>Long-range Energy Alternative Planning system (Rogan *et al*., 2014) |
| | Aviation | Domestic<br>International | Activity | SEAI – National Energy Balance |
| | | | Intensity | SEAI – National Energy Balance |
| | Navigation | | Activity | SEAI – National Energy Balance |
| | | | Intensity | SEAI – National Energy Balance |
| | Fuel tourism | | Activity | SEAI – National Energy Balance |
| | | | Intensity | SEAI – National Energy Balance<br>International exchange rate (£/€) (XE, 2019) |

**Table A2.1. Continued**

| Sector | Subsector | Technology/fuels | Data type | Data source(s) |
|---|---|---|---|---|
| Agriculture | Livestock<br>Pasture<br>Tillage | Enteric fermentation<br>Manure management<br>Slurry and solids<br>Soils<br>Pasture<br>Fertilisers<br>Deposition and leaching<br>N_Fix<br>Residue<br>Indirect deposition | Activity<br>Intensity | Agri-TIMES (Chiodi *et al.*, 2016) |
| Industry | NACE 5_9 Non Energy Mining<br>NACE 10_11 Food<br>NACE 13_14 Textiles<br>NACE 16_17_18 Wood Printing<br>NACE 20_21 Chemical<br>NACE 22_23 Rubber & Non-metallic minerals<br>NACE 24_25 Basic Metals<br>NACE 26_27 Electrical Optical<br>NACE 28 Machinery Equipment<br>NACE 29_30 Transport Equipment<br>NACE 12_15_31_33 Other<br>NACE 63 Data Centre | HTP<br>LTP<br>Drying and separation<br>Motors<br>Compressed air<br>Lighting<br>Refrigeration<br>Space heating<br>Other | Activity<br><br><br><br><br><br><br><br>Intensity | DECC, UK – secondary analysis of data from the Office for National Statistics and Building Research Establishment – Table 4.07<br>CSO – National Income and Expenditure 2017 – Table 22<br>EirGrid – All-Island Generation Capacity Statement (2019–2028)<br>SEAI – National Energy Balance |
| Electricity generation | Condensing_Steam_Cycle_Moneypoint<br>Steam_Turbine_Lignite_LR_WO_ED<br>CCGT_DB_GI_Aghada<br>CCGT_Poolbeg<br>NaturalGas_HN_SK_TY_WG<br>OpenCycle_ED_TP_RH<br>Wind_Onshore<br>Wind_Offshore<br>Hydro<br>Solar | Natural gas<br>Oil<br>Coal<br>Wind<br>Solar<br>Peat | Maximum availability (%)<br>Heat rate (GJ/MWh)<br>Historical production (GWh) | PLEXOS Ireland model (Deane *et al.*, 2012) |

**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
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- 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.

EPA Research Report 349

# Develop a LEAP GHG Ireland Analytical Tool for 2050

Authors: Tomás Mac Uidhir, Fionn Rogan and Brian Ó Gallachóir

## Identifying Pressures

This project identifies a gap in the current suite of energy and climate policy analytical tools available to policymakers in Ireland. There is a need for accessible and robust tools that can bridge the gap between analysts and decision-makers. This report highlights the need for the industry and services sectors to receive more detailed policy analysis and for the transport and residential sectors to receive a broader policy analysis, i.e. beyond private car transport and residential retrofitting. There is a need to address the challenges presented by climate change using a systemic approach that incorporates all sectors of the Irish economy, their interactions and their interdependence.

## Informing Policy

Analysis of building grant support schemes in Ireland found that an output-based policy support scheme could improve energy efficiency savings in residential dwellings. During 2010–2015, residential retrofitting could have achieved an additional 86% energy savings under a different set of retrofit combinations. This report also evaluates future policy targets within the government's climate action plan, e.g. 840,000 electric vehicles within private passenger transport by 2030. Scenario analysis highlights the challenge of sufficiently fast diffusion to achieve the electric vehicle target. If the target is met, the difference between early action and late action could be 1.2 MtCO2eq. While ambition for climate policy targets is welcome, it needs to be founded on robust, replicable analysis of feasible pathways that fully understand the challenges and present solutions.

## Developing Solutions

This report presents a range of new accessible computer models and techniques that can (1) calculate greenhouse gas emissions across all economic sectors, (2) quantify greenhouse gas reduction potential and (3) identify the possible growth in energy demand and emissions in the medium to long term. A new method for developing simulation models (the Application Script Editing Tool – ASET) aided in the development of a new accessible and robust simulation energy model – LEAP Ireland 2050 – that covers all sectors of the economy. Each sector is modelled based on the best available data. The level of data granularity enables a range of diverse policy questions about the impact of different climate and energy policy measures to be considered. The user interface within the LEAP Ireland 2050 model serves as an accessible tool for policymakers for future decision-making and planning robust climate policy.

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