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Enhanced energy policy simulation modelling to understand past and inform future climate action in Ireland

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

Date: May 2021

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Declaration

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

Signature: ……………………………………………………………………………….

Date: 17/05/2021

Executive Summary

Addressing the global threat of accelerated climate change requires the rapid decarbonisation of all energy/ non-energy systems worldwide. Societal frustration due to historic climate policy inaction underpins a political will, in many jurisdictions, to address the threat of global warming. Hence, it is important that this momentum is leveraged to ensure meaningful climate action is achieved.

The practicalities of tackling global warming require a diverse range of tools which can appropriately support the formation of climate policy in all economic sectors. This thesis aims to enhance the capacity of energy policy simulation modelling and generate new insights which can inform future climate action in Ireland. A suite of models was used to conduct an ex-post and ex-ante evaluation of climate policies in Ireland. Bespoke sectoral models were developed across different software platforms and merged with the Low Emissions Analysis Platform (LEAP), providing a coherent multi-sectoral GHG model for Ireland.

This new modelling capacity was utilised to conduct an ex-post evaluation of a retrofit policy, quantifying an additional 86% energy savings which could have been achieved during the period 2010 - 2015. This result identified policy recommendations designed to deliver improved outcomes in future retrofit policies, highlighting the advantages associated with an output-based grant scheme versus a measure based one. Proposed 2030 policy targets were examined by analysing different diffusion pathways for electric vehicles and residential retrofits. This quantified an additional 2.15 $MtCO2_{eq}$ savings which could be delivered through early versus delayed action, highlighting the uncertainty surrounding key climate policies and their potential contribution towards Ireland's projected gap-to-target (52 - 101 $MtCO2_{eq}$). Delivering 840,000 electric vehicles and 500,000 residential retrofits could achieve approximately 14.7 – 32.6% of this remaining gap-to-target. This result demonstrates the need for policy implementation pathways, in place of end-of-period headline targets.

There is a need for robust simulation modelling tools which strike a balance between capability and accessibility. Policymakers need these tools to support the planning, implementation, and review phases of policy formation, enhancing the evidence-base and reducing the risks associated with the most severe and unanticipated consequences of climate policy. The newly developed LEAP Ireland GHG simulation model serves this purpose, functioning as an accessible communication tool which can provide an adequate representation of a complex energy system and useful policy insights. The new Application Script Editing Tool (ASET) adds value to this LEAP model by leveraging advanced scripting functionality within LEAP and providing a new means of constructing the model and conducting sensitivity analysis. While this analysis focused on Ireland, the approach and methods could be replicated in other regions.

Table of abbreviations

AC/H	Air-Changes per Hour
AEA's	Annual Emission Allocation's
API	Application Programming Interface
ArDEM-SQL	Archetype Dwelling Energy Model - SQL
ASET	Application Script Editing Tool
BEH	Better Energy Homes
BER	Building Energy Rating
BEV	Battery Electric Vehicle
CAMG	Climate Action Modelling Group
CAP	Climate Action Plan
CCAC	Climate Change Advisory Council
CDKN	Climate and Development Knowledge Network
CO2	Carbon Dioxide
COP	Conference of the Parties
CSO	Central Statistics Office
DAFM	Department of Agriculture, Food and Marine
DCCAE	Department of Communication, Climate Action and Environment
DCENR	Department of Communication, Energy and Natural Resources
DEAP	Dwelling Energy Assessment Protocol
DECC	Department of Energy and Climate Change
EC	European Commission
ECEEE	European Council for an Energy Efficient Economy
EE	Energy Efficiency
EED	Energy Efficiency Directive
EPA	Environmental Protection Agency
EPC	Energy Performance Coefficients
ESD	Effort Sharing Directive
ESRI	Economic and Social Research Institute

ETS	Emissions Trading Scheme
EU	European Union
Eurostat	European Statistical Office
EV	Electric Vehicle
EWP	Energy White Paper
FHL	Fabric Heat Loss
GDP	Gross Domestic Product
GEA	Global Energy Assessment
GHG	Greenhouse Gas
GMST	Global Mean Surface Temperature
GST	Global Stocktake
GUI	Graphic User Interface
GVA	Gross Value Added
HLC	Heat Loss Coefficient
IAM	Integrated Assessment Model
ICE	Internal Combustion Engine
IIASA	Institute for Applied Systems Analysis
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
LCR	Low Carbon Roadmap
LEAP	Low Emissions Analysis Platform
LULUCF	Land Use, Land Use Change and Forestry
MaREI	Marine Renewable Energy Institute
MACC	Marginal Abatement Cost Curve
METÉ	Irish Meteorological Service
MS	Microsoft
NACE	Nomenclature statistique des activités économiques dans la Communauté Européenne
NASA	National Aeronautics and Space Administration
NDC	Nationally Determined Contributions

NDP	National Development Plan
NECP	National Energy and Climate Plan
NEEAP	National Energy Efficiency Action Plan
NMP	National Mitigation Plan
NREAP	National Renewable Energy Action Plan
PHEV	Plug-in Hybrid Electric Vehicle
PM 2.5	Fine particulate matter
PPM	parts per million
PWBER	Post-Works Building Energy Rating
PWEFA	Pre-Works Energy Performance Assessment
RE	Rebound Effect
RED	Renewable Energy Directive
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RES-E	RES-Electricity
RES-H	RES-Heat
RES-T	RES-Transport
SEAI	Sustainable Energy Authority of Ireland
SEI	Stockholm Environment Institute
TFA	Total Floor Area
UCC	University College Cork
UI	User Interface
UNEP	United National Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
VBA	Visual Basic for Applications
VBS	Visual Basic Script
VHL	Ventilation Heat Loss
VIBEE	Vietnam-Ireland Bilateral Education Exchange
VRES	Variable Renewable Energy Sources
WRI	World Resources Institute

Table of Units

GJ	Gigajoule
° C	Degrees Celsius
GBP/EUR	Exchange rate, British Sterling to Euro
GJ/MWh	Gigajoule per Megawatt-Hour
Gt	Giga-Tonne
GWh	Gigawatt-Hour
ktoe	Thousand Tonne of Oil Equivalent
kWh	Kilowatt-Hour
Mhead	Million-head
MJ/ Tonne-km	Megajoule per Tonne-Kilometre
MJ/km	Megajoule per kilometre
MJ/Veh-km	Megajoule per Vehicle-Kilometre
Mt	Million-Tonne
MW	Megawatt
MWh	Megawatt-Hour
Passenger-km	Passenger-Kilometre
TJ/€	Terawatt-Euro
Tonne-km	Tonne-Kilometre
TWh	Terawatt-Hour
Vehicle-km	Vehicle-Kilometre
W/K	Watts per Kelvin

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1 Introduction

1.1 Background

Global warming and the enhanced greenhouse effect are extremely likely (95% certainty) due to anthropogenic greenhouse gas (GHG) emissions according to the Intergovernmental Panel on Climate Change (IPCC) special report on the impacts of global warming (IPCC 2018). The effects of global warming and climate change remain among one of the greatest known threats to all life on earth. Climate change consists of a broad range of technical, societal, and economic issues which present unique challenges in isolation and even more complex challenges when considered in conjunction with one another. Despite the extensive research into interrelated topics such as energy security and the environmental sciences, the global response to the threat has been slow (Kuyper, Schroeder, and Linnér 2018).

Observations of global GHG atmospheric concentrations are known to have consistently increased since the 19th century, in line with the industrial revolution. The concentration of atmospheric Carbon Dioxide (CO_2) is currently ~412 parts per million (ppm), relative to pre-industrial level of approximately 280 ppm. While there is a known cyclical rhythm associated with the rise and fall of atmospheric CO_2 concentrations over long periods of time in Earth's history, CO_2 concentrations have not exceeded approximately 300 ppm in the past 400,000 years (NASA 2019). In the past four years the average annual concentration has increased by ~10.4 ppm – highlighting the unstable increase which underpins the fundamental motivation for this thesis.

In 2015, following the 21st annual United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) (UNFCCC 2015a), 187 parties (UNFCCC 2019) ratified an agreement which set a target of limiting global warming to less than 2°C and to make every effort to keep global temperature rise to below 1.5°C.

Since 1901, global mean surface temperature (GMST) has increased by approximately 1°C due to human activity, with a likely range of ± 0.2°C (IPCC 2018)

The link between increased atmospheric GHG emissions and a warming climate allows for the estimation of a carbon budget which is consistent with a 1.5 °C future climate scenario. A carbon budget defines the link between future warming and cumulative emissions over a specified period. While different approaches are employed in the estimation of carbon budgets, it is important to mention common parameters which should be considered such as the probability of an expected warming outcome, budget time-period and range of considered GHG's. Scientific understanding of carbon budgets has evolved over time, continually evaluating and ultimately increasing the remaining carbon budget from the 420 $GtCO_2$ estimate in 2014 (Stocker 2014), to 570 $GtCO_2$ in 2018 (IPCC 2018) – for a 66% probability of keeping the increase in temperature to below 1.5 °C. While there is some uncertainty regarding the remaining carbon budget, there is a high degree of confidence in our current accounting of annual net global emissions, 42 ± 3 $GtCO_2$ per annum (IPCC 2018). At this rate this provides for approximately 13.5 years from 2018 at current emissions rates, before breaching the 1.5 °C allowed carbon budget. This figure ignores increasing emissions trends, further highlighting the urgent requirement for a global response to climate change and GHG emissions.

The on-going evolution of global energy systems play a fundamental role in understanding the primary anthropogenic causes of global warming and climate change. Changes within the energy system are coupled with climate change, each affecting the other and causing a concomitant feedback. Global temperature rise has caused a shift in demand side heating and cooling requirements, while changes in the variability of wind, solar and hydro resources have impacted on the potential for large-scale deployment of renewable energy sources on the supply side (Cronin, Anandarajah, and Dessens 2018). Improving energy access and reducing energy poverty for all provide a framework which describes an equitable and just transition of the future. This also presents a challenge with respect to increased global energy demand given the tendency for carbon lock-in regarding both demand side needs and supply side solutions within modern energy systems (Unruh 2000).

A delayed response to the threats associated with climate change has and will serve to compound the known implications arising from increasing global temperatures. Currently, sea level rise is projected to rise by between 28 – 82cm, in a 1.5 °C GMST consistent scenario, by 2100. This figure represents a 10cm reduction in the projected sea level rise associated with a 2 °C consistent scenario (Rasmussen et al. 2018). This reduction results in 10 million fewer people in coastal areas being affected by the risks associated with sea level rise and coastal erosion. Additional impacts on biodiversity are associated with increasing global temperatures with large scale species loss and extinction expected in direct proportion to increasing temperatures. Increased temperature and weather variability will result in more extreme temperature variations (longer droughts and flooding events). These variations present a threat to food/ water security, economic growth and ultimately human health (IPCC 2018).

1.2 Why conduct energy modelling?

There are numerous reasons underpinning the motivation to conduct energy modelling and energy system analysis. The twenty first century has witnessed a range of issues relating to energy supply and demand, including security of supply, economic development, energy efficiency, and the development of robust climate policy (Pfenninger, et al 2014; Wiese et al. 2018). Energy modelling can provide a coherent framework which incorporates a range of climate and technological input constraints, offering potential solutions or policy interventions to address the modern challenges presented by climate change. Among the most relevant motivations is the ability of energy models to provide a replicable framework upon which decision makers can formulate robust energy and climate policy. Energy models can quantify the energy and emissions savings potential of a specific policy measure, estimate the cost of policy implementation, evaluate the impact of non-action, and provide insight into the range of uncertainty associated with future outcomes based on specific policy measures. Modelling bridges the gap between the gathering of quantitative data, statistics, and energy planning, supporting the decision-making process and providing vital insights into current emissions trajectories – illuminating the future potential pathways of an entire energy system, serving as a transparent communication tool to deliver clarity on climate targets, progress and failures. In recent times, increasing computer power and data sets has resulted in the use of large ensemble scenario sets and the use of *big data*. Big data refers to larger, more complex data sets which contain granular levels of detail beyond the scope of more well defined relational databases (Madden 2012). Big data presents a range of challenges to the current set of modelling tools, mainly their capacity to analyse, adapt and incorporate new structures capable of utilising all the data in question. Knüsel et al. (2019) considered the more general application of big data, beyond small problems in climate research, concluding that a combination approach of “classic” domain specific knowledge and big data analysis could provide insights into socioeconomic climate research, helping to “overcome” data gaps. Huppmann et al. (2018) and Lamontagne et al. (2018) both present the value that large ensemble analyses play in improving our understanding of the complex interaction between energy and emissions, land-use change and agriculture, and the socioeconomic considerations of integrated assessment models (IAMs) and their results. Yue et al. (2020) utilise a new scenario ensemble tool, applied to the Irish TIMES model(Ó Gallachóir et al. 2012), combining an energy system optimisation model with marginal abatement cost (MACC) curves, to gain insight into technology frequency within the ensemble of results. Yue’s analysis shows that the marginal efforts associated with ever increasing ambitious targets is not linear, but instead contains “tipping points” where the total system cost can increase significantly. These examples serve to highlight the motivation to conduct energy modelling. The insights derived from these models have and will serve to inform climate policy going forward.

1.3 Energy modelling classification and evolution

The range of qualitative attributes which can be used to classify and compare models is diverse and difficult to generalise. Van Beeck (1999), built upon the work of (Grubb et al. (1993), and Hourcade et al. (1996), to define nine distinct model classification criteria including model purpose, structure, analytical approach, methodology, mathematical approach, geographical coverage, sectoral coverage, time horizon, and data requirements. Connolly et al. (2010) added to this classification criteria by further differentiating models by their licensing or availability, the time step (distinct from the time horizon), and the capacity to integrate 100% renewable energy. In more recent times, Hall and Buckley (2016) further extended this criteria to include a total of 15 metrics, adding renewable technology inclusion, storage technologies, demand characteristics and cost in their comparison criteria. Subramanian et al. (2018) provide a generalisable classification scheme, adding to some of the previously established criteria and broadly separating energy models by field, i.e. process systems engineering (PSE) or energy economics (EEc), and level of technological aggregation. Table 1-1 includes a summary of these model classification criteria as they were identified as the most generalisable reviews of energy system models, providing a classification framework to compare utility. Utility is defined here as functionality which facilitates the needs of a range of agents including model developers, model users and decision-makers. These definitions do not claim to offer a comprehensive schema but instead offers a means to differentiate between model types.

#	Van Beeck, N.M.J.P. (1999)	Connolly et al(2010)	Hall and Buckley (2016)	Subramanian et al (2018)
1	Purpose of Energy Model (General, Specific)	Purpose of Energy Model (General, Specific)	Purpose of Energy Model (General, Specific)	Purpose of Energy Model (General, Specific)
2	The model structure: Internal, External Assumptions	The model structure: Internal, External Assumptions	The model structure: Internal, External Assumptions	The model structure: Internal, External Assumptions
3	Analytical Approach: Top-Down, Bottom-Up	Analytical Approach: Top-Down, Bottom-Up	Analytical Approach: Top-Down, Bottom-Up	
4	The underlying methodology	The underlying methodology	The underlying methodology	The underlying methodology
5	The mathematical approach	-	The mathematical approach	
6	Geographical Coverage (Global, Regional, National, Local)	Geographical Coverage (Global, Regional, National, Local)	Geographical Coverage (Global, Regional, National, Local)	Geographical Coverage (Global, Regional, National, Local)
7	Sectoral Coverage	Sectoral Coverage	Sectoral Coverage	-
8	The time horizon	The time horizon	The time horizon	The time horizon
9	Data Requirements	-	Data Requirements	
10	-	Licensing, Availability	Licensing, Availability	
11	-	The time step	The Time Step	
12	-	-	Renewable Technology Inclusion	
13	-	-	Storage Technology Inclusion	
14	-	-	Demand Characteristic Inclusion	
15	-	-	Cost Inclusion	
16	-	100% Renewable Energy Consideration	-	
17	-	-	-	Technology aggregation

Table 1-1 Model Characteristic Schema

Jebaraj and Iniyan (2006) provide a general overview of different energy system models available, focusing on the model purpose and its applicability to energy planning in developing countries. Bhattacharyya and Timilsina (2010) reviewed a range of energy demand forecasting methods and models as they relate to the specific features of developing countries, later defining the analytical approach, geographical coverage, sectoral coverage, and time horizon in their more general review of energy system model comparisons (Bhattacharyya and Timilsina 2010a). Collins et al. (2017) conducted a methodological review of the suitability of modern energy system models to incorporate variable renewable energy sources (VRES), focussing on their applicability with respect to complex dispatch models.

The question to be analysed should inherently determine the choice of modelling tools. When considering an appropriate modelling tool, among the most relevant classification categories are a models analytical approach, underlying methodology, and sectoral coverage. *Analytical approach* (Top-Down, Bottom-Up, Hybrid) can significantly influence the type of questions an energy system model can address. Top-down energy models typically utilise high level aggregated statistics e.g. GDP or Gross Value Added (GVA), to determine a linkage between economic activity and energy demand. Projections of economic growth can then be used to project possible future energy demand. These models are well suited to understanding the broad impact of these macroeconomic variables on energy demand and emissions. In contrast, bottom-up energy models utilise highly disaggregated sectoral specific technology information which characterise the energy use of these technologies, depending on the activity that they are used for. Total energy consumption is therefore estimated by aggregating the activity multiplied by energy use per activity for each individual technology within the sector. Hybrid models utilise a combination of both top-down and bottom-up analytical approaches to describe the entire system.

The *underlying methodology* (Optimisation or Simulation) also plays an important role in the classification of an energy system model. Optimisation models use mathematical functions to determine optimal outcomes based on an objective function e.g., cost. These models consist of a collection of decision variables. The optimal solution consists of the collection of decision variables for which the objective function is satisfied, subject to a series of constraints. These models are useful for understanding high level decisions such as the cost-optimal solution to meet future energy needs. If used in conjunction with a maximum level of emissions that the energy system can emit, the solution can point to the least cost evolution of the energy system to meet a particular emissions reduction ambition. Conversely, simulation models simulate the functions of an energy system, using a mathematical description of a set of energy demands. A simulation model should properly represent the energy demand it is supposed to simulate, replicating the observed behaviour witnessed in the real world-structure in question. These models are useful for understanding the impact of policy measures (for example a change in building regulations) on future energy demand and supply. From a policy perspective these models can inform what impact different policy choices might have on energy and related emissions. Both methodologies rely on the use of scenario analysis to determine the impact of different variables on the whole energy system, relative to a reference scenario.

A model's *sectoral coverage* (Transport, Heat, Electricity Generation, All) plays an important role in understanding the classification of energy models. Some energy models provide a flexible framework which can define sectors based on the best available data e.g. TIMES, LEAP. However, some energy models are designed to represent a specific sector e.g. the PLEXOS energy model which represents the electricity supply sector.

Different types of energy system models can provide a range of insights into the complex nature of energy systems. Modelling can guide the formation of robust climate policy and guard against the most severe and unanticipated consequences of climate policies. Bottom-up simulation modelling can provide an understanding of the impact of specific policy measures through scenario analysis, representing a key modelling tool in a decision makers tool kit.

1.4 Regional response to global concern

This global issue requires a global response. All regions must make every effort to decarbonise and alter our current emissions trajectory urgently. There is a need for all regions to decarbonise, however if developing economies in transition[1] wish to avoid the trend of high per capita emissions witnessed in developed economies[2], they require assistance in bridging the gap between evolving energy demand and clean energy access leapfrogging into sustainable energy pathways (Perkins 2003; K. Lee 2005; 2019). The European Union (EU) consists of 27 individual member states, each of which is classified as a developed economy. The EU has responded to the need for climate action as a single agent, setting ambitious energy efficiency (EE), GHG reduction and renewable energy targets for 2020 as part of the 2020 climate and energy package (EC 2008).

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) (EC 2009b) focussed 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)

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[1] World Economic Situation and Prospects (WESP), Table B/C – Economies in transition/ Developing economies (WESP 2013)

[2] World Economic Situation and Prospects (WESP), Table A – developed economy (WESP 2013)

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, due to their relatively high GDP per capita in 2005.

The EU also established a Renewable Energy Directive (RED) (EU 2009), including binding national targets for the improvement of renewable energy sources (RES) across electricity generation (RES-E), transport (RES-T) and heat (RES-H). Ireland's mandatory RES target under the Directive stands at 16% by 2020 with flexibilities in place to reach this target across self-imposed shares of RES-E/T/H. EE targets are also included in the EU strategy with a 20% improvement in EE levels by 2020, with respect to average energy consumption between 2001 – 2005, contained within the Energy Efficiency Directive (EED) (EU 2012).

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 which 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 includes for a revision of the current 2030 GHG target with an aim to increasing it to between 50 – 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 set their own RES targets across heat (RES-H ~ 12%), transport (RES-T ~ 10%) and renewable electricity generation (RES-E ~ 40%) by 2020, the sum of which accounts for the 16% RES target. Ireland's most recent National Renewable Energy Action Plan (NREAP) (DCCAE 2018) indicates Ireland progress to be a RES share of 9.5% by 2016, shared across 27.2% RES-E, 5% RES-T and 6.8% RES-T. More recent publications from the Sustainable Energy Authority of Ireland (SEAI) project a possible range of 12.3 – 14.3% RES share by 2020 (SEAI 2019d). Despite significant progress towards delivering 2020 RES-E targets, Irelands failure to make significant progress within RES-H and RES-T has resulted in Ireland currently being ranked second lowest in RES progress, amongst EU-28 member states (SEAI 2020a). The National Energy Efficiency Action Plan (NEEAP) reported progress of 11.6% towards Ireland's 20% EE target (DCCAE 2017a), reaching a possible range of 13.7 - 14.2% by 2020.

In 2019, the Environmental Protection Agency (EPA) GHG projections report stated that Ireland is likely to achieve between 5%-6% reduction in non-ETS GHG emissions in 2020, relative to 2005 levels (EPA 2019b). While the period 2016/17 witnessed a marginal decrease in total GHG emissions (0.9% reduction), a growing trend can be seen in the period 2011 – 2017 with an increase of 6.6% recorded, reaching national emissions of 60.7 $MtCO2_{eq}$ in 2017 (EPA 2019c). The failure to deliver on 2020 GHG targets implies additional pressure with respect to delivering more ambitious targets for 2030 and 2050. Ireland has continually increased ambition and not reached targets, resulting in greater failure in climate policy.

The contention that relatively smaller nations such as Ireland need not decarbonise given its carbon footprint, relative to the United States and China, is embedded in the concept that the energy transition is going to be too expensive and difficult. This position overlooks the opportunity which an equitable transition presents in the face of reducing Ireland's GHG emissions and improving multiple levels of inequity in Irish society. Envisioning a cleaner energy future for Ireland means warmer homes, access to various clean modes of mobility and improved air quality. A mismatch between long-term climate policy objectives and the political electoral cycle presents difficulties to changing these “locked-in” perspectives on the energy system and shifting to a cleaner energy future.

1.4.1 Past climate policy challenges in Ireland

Ireland presents an interesting case study to consider regarding GHG emission profiles, climate policy and decarbonisation pathways. A relatively low share of total global emissions, approx. 0.1% of global GHG emissions in 2018, are coupled with the third highest per capita emissions amongst EU28 member states. In 2017 Ireland’s annual emissions stood at 13.3 $tCO2_{eq}$/capita, 51% greater than the EU28 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 GHG emissions from agriculture, approx. 33% of total emissions (EPA 2019b), is substantially above the EU average of 9.8% (European Environment Agency 2019).

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 have continued to grow in line with economic recovery. This growth is driven primarily by growth in transport and heat demand (SEAI 2019f). Following the economic recession of 2007/8, emissions were seen to fall in residential heat and transport (private and freight). Improved EE of residential dwellings due to retrofitting and improved engine efficiency (EC 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, Zhou, and Sweeney 2012). Recent years have witnessed a growing trend in the size and type of private vehicles purchased (Ó Gallachóir et al. 2009), resulting in a resurgence in transport emissions as the Irish economy has recovered (CCAC 2018).

Understanding the slow progress towards 2020 targets across EE, RES and GHG reductions requires an awareness of Ireland's climate and energy policy in recent years. The low carbon roadmap (LCR) (P. Deane et al. 2013) presented a collaboration between the Economic and Social Research Institute (ESRI) and University College Cork (UCC), providing "technical advice and guidance" on the evolution of a low carbon future for Ireland. This document highlights the need for increased activity within EE and renewable energy technologies and outlines the incompatibility of fossil fuels in a reduced carbon future. 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 LCR to outline policy objectives for the period 2015 to 2030. The EWP provided an overview of targets set in the NEEAP and NREAP but failed to provide robust future targets for the period 2015 – 2030 across key sectors. Following the ratification of the Paris Agreement (UNFCCC 2015a), Ireland published the National Mitigation Plan (NMP) (DCCAE 2017b). The NMP provides for an "initial step" 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. The key CAP targets include significant retrofitting of 500,000 residential dwellings, the installation of 400,000 heat pumps, ensuring all new cars and vans are electric by 2030, delivering 950,000 electric vehicles by 2030, and increasing the RES-E share from 30 to 70%.

Irelands recent progress towards RES targets is coupled with a clear failure to achieve GHG targets. Among the reasons behind the difficulties are conflicting objectives within national GHG policy. Agricultural policy provides an example of this conflict with a national impetus towards increasing the cattle herd to allow for the expansion of meat and dairy exports (DAFM 2015) while simultaneously decreasing agricultural emissions. Currently these objectives are mutually exclusive. The sum of these climate policy failures represents the existing challenge for Irelands energy transformation.

The underlying root of these failures is not obvious and is composed of a mixture of sources. While measures are being put in place by the Department of Communications, Climate Action and Environment (DCCAE)(DCCAE 2017c) to address an historic lack of energy modelling capacity in government departments, this has led to a lack of analytical tools underpinning climate policy. Energy models are required to address these failures, as they examine a range of issues related to best practice within policy formation; policy interaction effects, implementation issues, GHG reduction potential, disproportionate impacts in society and cost (National Research Council 2011).

A range of energy system modelling tools have continued to develop in Ireland, in response to the need for more integrated planning and evidence based policy support. These tools include macroeconomic models, energy system optimisation models (ESOM), integrated dispatch models, and simulation modelling tools. The Economic and Social Research Institute (ESRI) has developed a range of macroeconomic models over time, including the ***H**armonised **E**conometric **R**esearch for **M**odelling **E**conomic **S**ystem* (HERMES) (Bergin et al. 2013), the ***CO**re **S**tructural*

Mo**del* (COSMO) (Hollandc et al. 2017), and the latest ***I**reland **E**nvironment, **E**nergy and **E**conomy* (I3E) (de Bruin, Monaghan, and Yakut 2020) model. The I3E model is a computable general equilibrium (CGE) model which reproduces the structure of the economy in its entirety, providing outputs related to intersectoral interaction and economic forecasts etc. University College Dublin's Energy Institute (EI) utilise the integrated ***E**missions and Fuel Mix, **M**arkets and Costs, **Pow**er Flows and Networks, and **E**nd Use, and **R**ates of Uptake* (EMPowER) and Backbone models to consider the system cost and carbon emissions associated with building energy, consumer behaviour, electricity networks, climate, and weather effects as part of their Energy Systems Integration Partnership Programme (ESIPP) (Energy Institute 2019). EMPowER provides electricity system modelling services to DCCAE as part of ongoing modelling support packages to the government of Ireland. The Energy Policy and Modelling Group (EPMG) within University College Cork (UCC) have developed a range of national and global models including the Irish TIMES optimisation model (Ó Gallachóir et al. 2012), the LEAP-Ireland and CarSTOCK simulation models (Rogan et al. 2014; H. E. Daly and Ó Gallachóir 2012; Mac Uidhir, Rogan, and Gallachóir 2020), and the PLEXOS-Ireland, and global integrated dispatch models (J. P. Deane, Dalton, and Ó Gallachóir 2012; Brinkerink, Gallachóir, and Deane 2021). The Irish TIMES model was used in the development of the LCR. The models have developed over time and further development and maintenance of the Irish TIMES, LEAP and PLEXOS models currently take place as part of the ***C**limate **A**ction **P**athways and **A**bsorptive Capa**city (CAPACITY) project at UCC (Rogan et al. 2018). Historically this has resulted in sectoral simulation models remaining siloed from one another, impacting upon the relative value of individual model outputs which might otherwise operate using different key assumption and drivers. The National Energy Modelling Framework (NEMF) (SEAI 2017) seeks to link existing modelling tools, updating and integrating existing policy simulation models across national institutions and providing consistency in modelling assumptions.

In addition to providing insights into these best practices - energy models can also function as a useful communication tool between energy modellers and policymakers, facilitating political support and aiding in future policy discussion and formation. To date, there has been a focus on the development of optimisation models and dispatch modelling of power systems in Ireland and internationally (Lopion et al. 2018). Simulation models typically require a higher level of disaggregated detail to effectively represent energy use in a useful format, resulting in difficulties associated with the development of such models.

There is a need for the integration of robust analytical capacity into the policy planning, implementation, and review phases of policy formation. This thesis identifies the need for more policy simulation tools as a fundamental requirement to delivering improved outcomes in future energy and climate policy formulation. The suite of analytical tools developed and utilised here represent the contribution of this thesis to the knowledge gap which exists in current climate policy target failures.

1.4.2 Future climate policy challenges in Ireland

The complex history of climate policy highlights Ireland's need to develop sustainable policy pathways which deliver a decarbonised society in the medium (2030) and long-term (2050). Ireland's record as climate "laggards" 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 (EV) and retrofitting of the existing building stock. The CAP includes increasing shares of renewable sources in electricity generation but fails to go beyond the concept of "electrify everything and decarbonise generation". 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 put in place an equitable and sustainable pathway, underpinned by evidence-based policy support, to thrive in the period 2021-2030 and provide a trajectory towards a net zero 2050. The CAPACITY (Climate Action Pathways & Absorptive Capacity) (Rogan et al. 2018) project is currently working to develop and maintain the LEAP Ireland GHG energy demand and supply model. It is necessary to provide a framework such as CAPACITY to achieve the on-going development of energy system models which support evidence based policy support.

1.5 Thesis Aims and Research questions

This thesis aims to enhance the capacity of energy policy simulation modelling and to generate new knowledge to inform future climate action in Ireland. The thesis introduces a new exploratory demand and GHG emissions model for Ireland to aid in the on-going improvement of the evidence base which supports climate policy. There is a need for energy system models which provide for detail which can adequately simulate policy pathways while simultaneously remaining accessible enough for the purpose of communicating results. These aims are delivered through addressing the following research questions:

1. What analytical tools are suitable to address the diverse range of challenges facing energy system models in the 21st century?
2. What enhancements can be made in energy policy simulation modelling to enhance modelling capability while simultaneously improving transparency?
3. How can the ex-post evaluation of energy efficiency policies be used to understand past performance and deliver increased emission reductions in the future?

4. How can the ex-ante evaluation of specific climate policies be used to gain greater insight into the steps required to deliver ambitious climate goals?

The thesis structure mirrors these research questions with each chapter addressing one or more point of concern. The thesis must be considered as a whole as it represents a nexus of collaboration, technical innovation, and policy evaluation and recommendations.

1.6 Methodology

This thesis uses a combination of methodological approaches to develop the aims and analyse the different research questions. Each method is described in detail in chapter 2. Empirical data, in combination with techno-economic energy modelling is used as part of an ex-post analysis of Ireland’s residential retrofit policy for the period 2010 – 2015. The combined techno-economic and macro-economic LEAP model is utilised to conduct an ex-ante evaluation of the potential mitigation effects of Ireland’s electric vehicle and retrofitting diffusion rates, in the context of a carbon budget for the period 2021 - 2030. This methodology is utilised to aid in shifting the policy narrative away from end-year targets and to consider the whole energy system over a broader time horizon.

The thesis presents a new combination demand and GHG simulation model for Ireland, developed using the Low Emissions Analysis Platform (LEAP) and the newly developed Application Script Editing Tool (ASET). LEAP (C. G. Heaps 2016b) is a widely used hybrid simulation tool with the capacity to cover all sectors of energy demand and supply, including emissions. LEAP has been used by private organisations, academic institutions and 190 individual countries. The strength of LEAP relies in its scenario analysis functionality.

Simulation tools provide policy makers with implementation pathways towards achieving GHG targets. The new modelling tool, ASET, is developed to add value to LEAPs simple user interface and provide robust sensitivity analysis and model topology design functionality. A bespoke simulation modelling tool (ArDEM-SQL) for the residential sector is developed to gain insight into the potential for improved energy and emissions reductions from Ireland's retrofit policy.

1.7 Thesis overview

Including this introductory chapter, this thesis is presented in six chapters: Chapter 2 describes the range of methodologies employed throughout the thesis, including the development of the new Application Script Editing Tool (ASET), the Archetype Dwelling Energy Model-SQL (ArDEM-SQL), and the LEAP Ireland GHG tool. In addition to these new tools, chapter 2 also explores the concepts of Ex-ante and Ex-post analysis as these concepts are leveraged throughout the thesis. Chapter 3 introduces the ASET tool in more detail. The broader landscape of energy system model classification is explored, and a qualitative method for the evaluation of energy system modelling frameworks is presented. A case study of two transportation models is leveraged to illustrate the benefits of developing a complex simulation model using the ASET framework. The evaluation method is then used to compare the added benefits and limitations of the new proposed methodology. Chapter 3 is currently being finalised for review with Energy Strategy Reviews. Chapters 4 presents the new ArDEM-SQL, dwelling energy model, and uses it to conduct an ex-post analysis of a retrofit support scheme in Ireland. The chapter presents policy implications and proposes a new method for delivering improved outcomes due to bespoke retrofit packages tailored to building archetypes. Chapter 4 has been published in Energy and Buildings. Chapter 5 presents a novel use of the Bass diffusion model, in conjunction with the newly developed LEAP Ireland GHG tool, to investigate the impact of implementation pathways and carbon budgets. This new method explores the feasibility of ambitious climate policy targets explores tailored policy recommendations based on distinct innovation adopter categories. Chapter 5 is currently under review with Energy and Climate Change. Chapter 6 provides an overview of the main findings of this thesis. The conclusions are based on the conclusions of the internal chapters and are discussed in the context of the distinct research questions presented in section 1.5.

Figure 1-1 presents the three fundamental pillars on which this thesis stands:

1. The use and evaluation of energy system modelling and scenario analysis.
2. New techniques to conduct ex-post analysis and enhanced energy policy simulation.
3. Informing Climate Action through ex-ante analysis using the LEAP Ireland GHG tool.

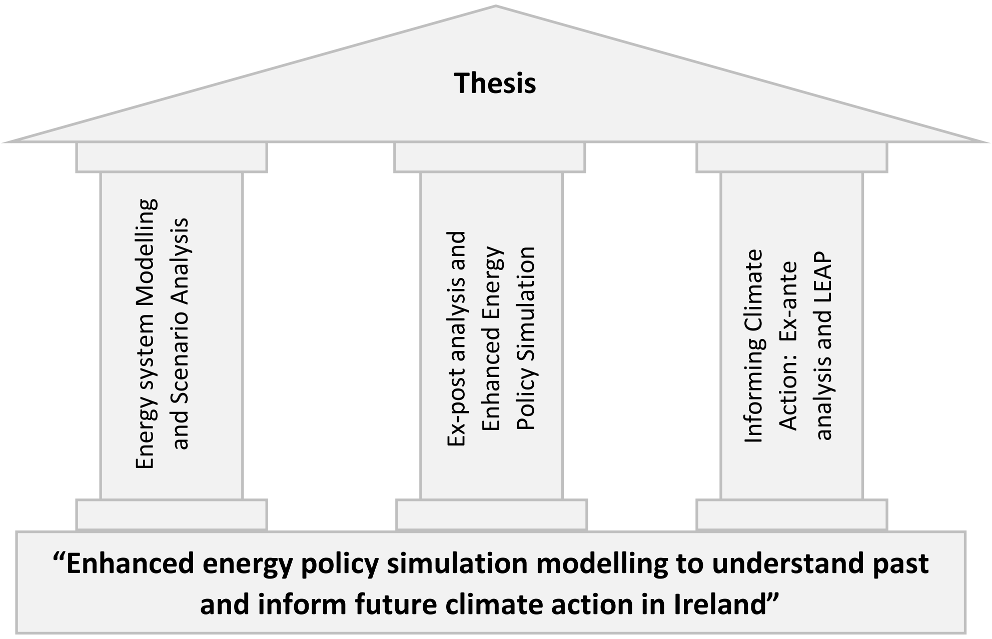

Figure 1-1 Thesis Pillars

This thesis contributes to the literature through the introduction of new methodological approaches which provide new knowledge and insights into the planning, implementation, and assessment of climate policy.

Chapter 2 provides an overview of the modelling tools developed and utilised as part of this thesis. This includes a broad description of the technical framework which underpins the modelling tools driving the ex-post and ex-ante evaluation of climate policy in Ireland. Chapter 3 investigates the limitations of energy system modelling and the concept of matching the appropriate research question to the right energy model. In addition, this chapter identifies and develops key modelling tools which can be used in conjunction with LEAP – presenting the newly developed ASET tool. Chapter 4 utilises the newly developed ArDEM-SQL coding framework to conduct an in-depth ex-post analysis of a residential retrofit scheme in Ireland. This analysis quantifies the energy savings and emissions reductions associated with a range of known retrofit measures completed during the period 2010 – 2015. These known savings are used to calibrate the ArDEM-SQL baseline simulation and then an alternative retrofit scenario quantifies the additional savings which could have been delivered. Policy recommendations are included and insights from the study are used to suggest a newly designed retrofit grant programme based on calculated savings instead of specific measures. Chapter 5 utilises the newly developed LEAP Ireland GHG model to evaluate the potential of Irelands most recent climate policies. The LEAP Ireland GHG model development in this thesis relied on the use of the ASET method described in chapters 2 and 3. The role the ASET tool plays in the pre-existing methodology is presented in Figure 1-2 and Figure 1-3. This model is used to conduct an ex-ante evaluation of two key climate policy measures, namely the large-scale introduction of electric vehicles (EV) and the deep retrofitting of residential dwellings. Varying diffusion rates are used in conjunction with the bottom-up techno-economic LEAP Ireland GHG model to improve the evidence-base which supports the early adoption of retrofit measures in Ireland. Chapter 6 presents thesis conclusions, additional policy insights and future development plans for the LEAP Ireland GHG model.

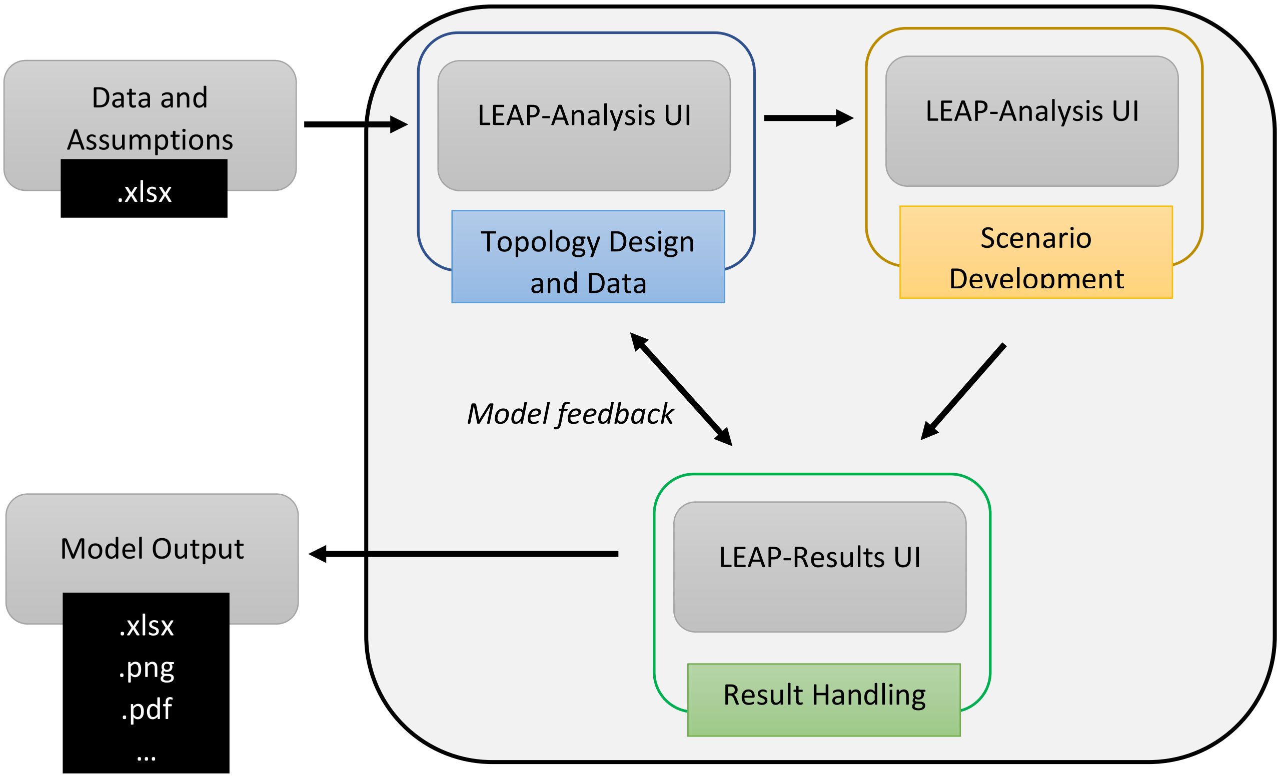

Figure 1-2 Pre-existing LEAP modelling methodology

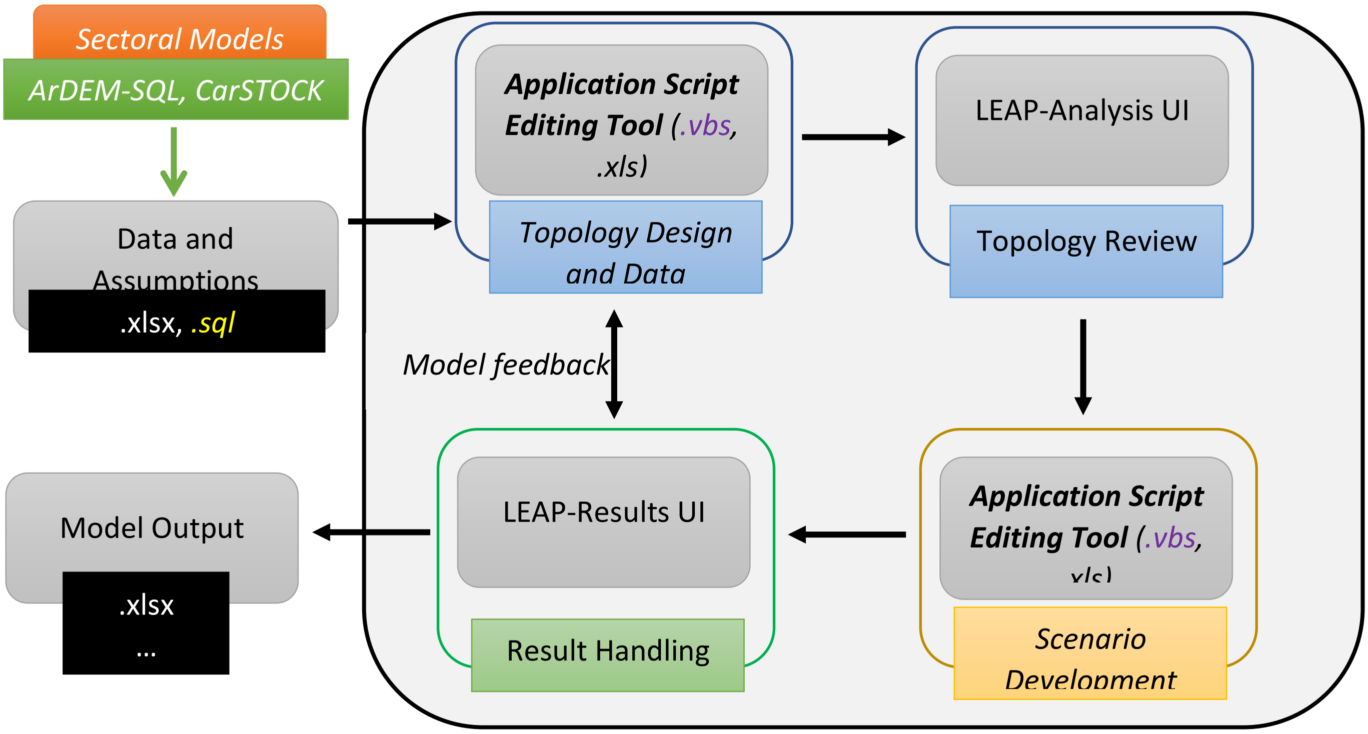

Figure 1-3 Application Script Editing Tool contribution to LEAP modelling methodology

1.8 Role of collaboration

This thesis is based on my own original work and was written by me but involved collaborations and support at many stages. My supervisors Prof. Brian Ó Gallachóir and Dr. Fionn Rogan were involved in and advised on all aspects of this thesis and are co-authors on all journal articles included within this thesis. Their advice has been invaluable to the completion of this work. Chapters 3, 4, and 5 have been submitted for publication with me as lead author. While I have led on each of these articles, there has been collaboration with several other co-authors over the duration of this doctoral thesis. Chapter 2 consists of a more detailed accounting of the various methodologies employed throughout my thesis; section 2.4 is part of a published journal article where I was lead author. Chapter 3 involved collaboration with Dr. Charles Heaps of the Stockholm Environment Institute (SEI), who develop and maintain the LEAP software. Dr. Heaps made fundamental changes to LEAPs built-in Application Interface (API) to allow for the development of the ASET tool described in this chapter. Dr. James Glynn provided advice on modelling limitations and the advantages associated with automation of LEAP broadly. Dr. John Curtis and Matthew Collins of the ESRI supported the ex-post analysis of residential retrofit data from the Sustainable Energy Authority of Ireland (SEAI) in chapter 4 (M. Collins and Curtis 2017b; 2016; M. Collins and Dempsey 2017). Their insights and economic perspective within the grant programme were invaluable in the completion of this analysis and policy recommendations. The data utilised in chapter 4 is detailed further in a separate article which I am lead author, included in appendix A. Chapter 5 is my own work but relies on the inclusion of multiple data sources to complete the LEAP Ireland GHG model i.e. the private passenger transport sector relies on a bespoke transportation model completed by Dr. Hannah Daly (H. Daly and Ó Gallachóir 2011) while the light goods vehicle subsector depends on work completed by Dr. Eamonn Mulholland (Mulholland et al. 2016).

1.9 Thesis outputs

1.9.1 Journal Articles

Tomás Mac Uidhir, Fionn Rogan, Matthew Collins, John Curtis, Brian Ó Gallachóir – "Improving energy savings from a residential retrofit policy: A new model to inform better retrofit decisions" – Energy and Buildings,

(https://doi.org/10.1016/j.enbuild.2019.109656).

Tomás Mac Uidhir, Fionn Rogan, Matthew Collins, John Curtis, Brian Ó Gallachóir - "Residential stock data and dataset on energy efficiency characteristics of residential building fabrics in Ireland" – Data in Brief– see Appendix A – Data in Brief Article (https://doi.org/10.1016/j.dib.2020.105247).

Tomás Mac Uidhir, Fionn Rogan, Paul Deane, James Glynn, Charles Heaps, Brian Ó Gallachóir - "Understanding energy modelling limitations – Unlocking advanced simulation modelling applications using a simple accessible tool" – being finalised for submission with Energy Strategy Reviews.

Tomás Mac Uidhir, Brian Ó Gallachóir, John Curtis, Fionn Rogan - "Exploring EV diffusion and residential retrofitting using a new model to investigate the impact of climate policy on carbon budgets" – Under Review with Energy and Climate Change.

1.9.2 Research reports

Tomás Mac Uidhir, Fionn Rogan, Brian Ó Gallachóir - "Develop a LEAP GHG Ireland Analytical Tool for 2050 (2016-CCRP-MS.34) " – EPA Research Report No. 349 (ISBN: 978-1-84095-951-2).

1.9.3 Conference proceedings and workshops

Tomás Mac Uidhir - *"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)

Tomás Mac Uidhir, Matthew Collins – "Better Energy Homes Scheme with Archetype Dwelling Energy Model (ArDEM)" - ESRI-UCC Workshop (June 2016)

Tomás Mac Uidhir, Fionn Rogan – "VIBE 2017 Advanced LEAP modelling with the Application Script editing Tool (ASET)" – Delivered online via WebEx (2017)

Tomás Mac Uidhir, Fionn Rogan – "VIBE 2017 Project Capacity building on energy and climate modelling - Workshop" – Cork, Ireland (June 2018)

Tomás Mac Uidhir, Fionn Rogan, Jason McGuire – "Project Capacity building on energy and climate modelling – Advanced LEAP training workshop" – Hanoi, Viet Nam (December 2019)

1.9.4 Invited talks and presentations

Tomás Mac Uidhir - *"SEI Summer Internship & the Application Script Editing Tool (ASET)"* - SEI LEAP internship - model development techniques presentation - Boston (2017)

Tomás Mac Uidhir, Fionn Rogan - *"Policy pathways for Ireland – How much energy efficiency is residential retrofitting delivering?"* - ESRI-UCC-MaREI energy research: climate action conference – Dublin (2019)

Tomás Mac Uidhir, Fionn Rogan, Hannah Daly, Brian Ó Gallachóir – "LEAP 2030 GHG Model Development" - EPA-UCC-MaREI energy research – Cork, Ireland (September 2019)

1.9.5 Co-supervision

Aided in the co-supervision of two separate MEngSc thesis which utilised the newly develop Application Script Editing Tool (ASET).

“Energy Consumption and Green-House Gases Emission Model for Vietnam using LEAP-ASET” - Mario P. Castaneda, 2017

“Energy Consumption Model of Jakarta Transportation System: Passenger Road Transport” - Yoga Bagus Wicaksono, 2017

2 Methodology

This chapter outlines the main research methodologies utilised within this thesis. This work required the design of new research methods and models, representing the culmination of these new and existing methodologies. It is necessary to describe these new tools in detail to fully capture the extent of work required in their development, which is not necessarily relevant in the context of the publications which comprise the subsequent chapters. Methodological approaches and modelling tools are explored separately as I describe the concepts of ex-post/ ex-ante analysis, and the design and operation of the new Application Script Editing Tool (ASET), the Archetype Dwelling energy model – SQL (ArDEM-SQL) and the new Low Emissions Analysis Platform GHG tool for Ireland (LEAP Ireland GHG).

2.1 Ex-Ante and Ex-Post analysis

At its core, this thesis utilises energy system models to conduct ex-post and ex-ante analyses of climate policies within Ireland. The tools (ArDEM-SQL, LEAP, ASET), facilitate the assessment of policies which are already in place and provide a robust framework to evaluate the potential for success in future policy planning. Each of these tools is described in further detail in this chapter. In the context of energy system modelling, an ex-post evaluation of climate policy consists of analysing empirical data to assess the past performance of said policy. An ex-post evaluation can facilitate the modification of an existing/ completed policy and guide future decision making, providing insight into the efficacy of the policy and aid in guiding future interventions. Chapter 4 consists of an ex-post evaluation of existing retrofit grant schemes, providing future improved retrofit outcomes through the implementation of bespoke retrofit choices using a new energy system model, ArDEM-SQL.

Ex-ante analysis provides an initial estimate of the potential efficacy of a planned policy. The value of an ex-ante analysis lies within the model which simulates the planned policy. In chapter 5 I utilise a new LEAP Ireland GHG model to evaluate potential mitigation scenarios in line with Irelands most recent and ambitious climate policies. Robust climate policy should contain a combination of ex-ante evaluation to guide initial decision making and on-going ex-post evaluation to assess progress and provide useful feedback to improve and optimise potential policy outcomes. Figure 2-1 illustrates the value of these types of analysis throughout the lifecycle of a policy.

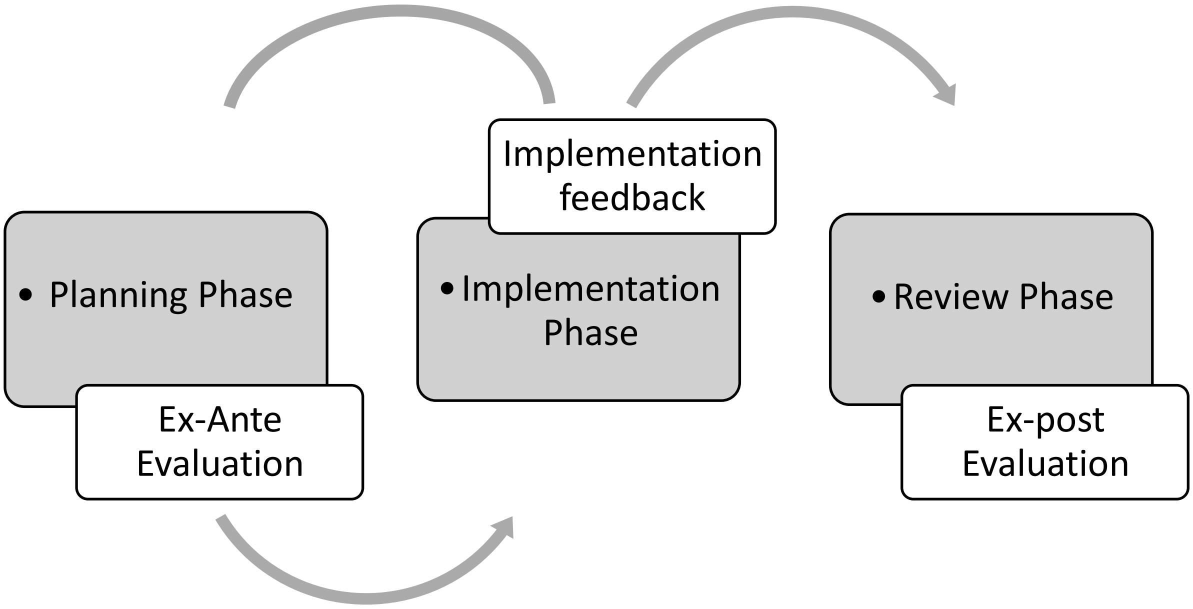

Figure 2-1 Policy evaluation lifecycle steps and type of analysis required to deliver each step

2.2 LEAP

This section describes the LEAP Ireland GHG model completed as part of this thesis. Each sector is described individually, indicating sectoral specific input data sources and specific policy levers which are applicable to each sector. Typical outputs for all sectors include final energy demand (flexible units) and emissions $CO2_{eq}$. The model uses historical base year data for 2016 and includes projections for each subsequent year to 2050. Lopion et al. (2018) highlights the need for future energy system models to improve flexibility and transparency, answering the need for more open-access modelling, "improving " the value in data-transparency and modelling assumptions. The LEAP model developed as part of this thesis has been made fully available online[3], including all data and assumptions.

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[3] https://github.com/MaREI-EPMG/LEAP_Ireland

2.2.1 Demand Model structure

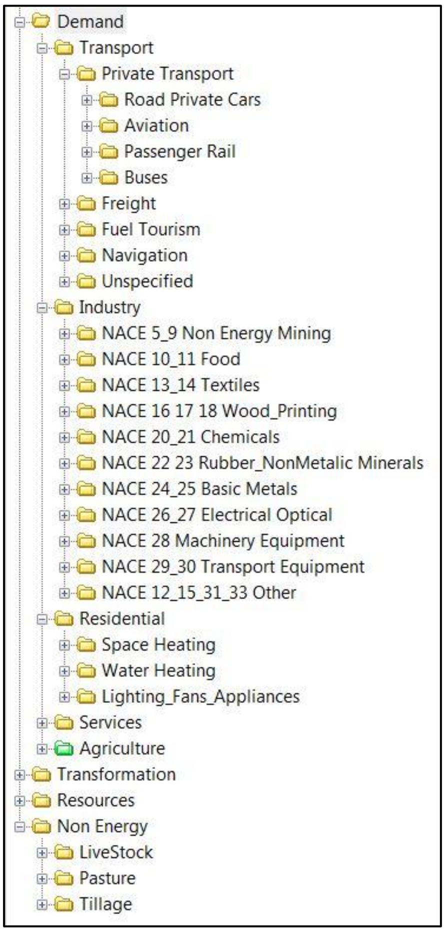


Figure 2-2 LEAP Ireland Demand model topology

LEAP models are designed with a hierarchical tree structure which defines the sectoral definitions for each demand category. The LEAP demand structure for the LEAP Ireland GHG model is shown in Figure 2-2. 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. Energy related demand and emissions are defined by transportation, industrial, residential, services, and agriculture. Non-energy emissions include agricultural livestock, pasture, and tillage. Sections 2.2.2– 2.2.7 provide further subsectoral details and the modelling approach utilised for each subsector within the LEAP Ireland GHG model. This also includes further detailed model topologies, data sources, modelling assumption and data inputs.

2.2.2 Residential

The LEAP residential sector demand is defined by three different end uses: Space Heating, Water Heating and Lighting & 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 included building type, detached, terrace, apartment and energy efficiency classification, divided into three categories (low, medium, 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 electricity (storage heaters and heat pumps), coal, natural gas, solid fuels, and kerosene. While new dwellings are also included in the model, they consist of energy efficiency ratings which preclude the need for retrofitting. This implies a pool of potential dwellings which can be retrofitted over time. There is an applied 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 is supplied from the Central Statistics Office (CSO 2016) and SEAI's BER database (SEAI 2019e). Energy intensity within this sector is represented by an aggregated energy efficiency rating for each archetype and end use. Figure 2-3 shows the final model structure for the residential sector. The total number of archetype dwellings included in the base year is shown in Table 2-1.

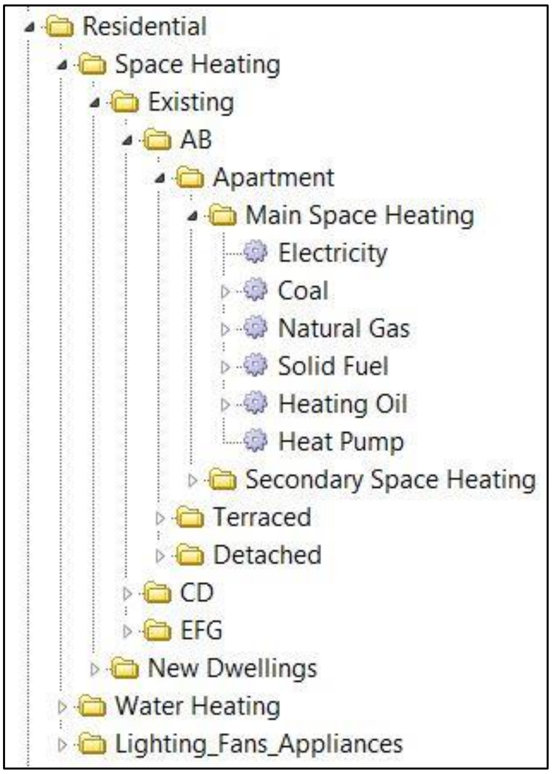


Figure 2-3 LEAP Ireland GHG: Residential model topology

BUILDING ARCHETYPE	NUMBER DWELLINGS
DETACHED AB	88507
TERACED AB	71823
APARTMENT AB	32690
DETACHED CD	433748
TERACED CD	481653
APARTMENT CD	95819
DETACHED EFG	226738
TERACED EFG	218824
APARTMENT EFG	47863

Table 2-1 LEAP Ireland GHG: Dwelling archetype frequency, base year

2.2.3 Services

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 which associates an energy intensity with economic activity within the sector. Total energy demand, measured in ktoe, was provided from historical SEAI energy balances (SEAI 2019c). Figure 2-4 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 €) within NACE (Nomenclature statistique des activités économiques dans la Communauté européenne) classifications O.84, P.85, QA.86, QB.87-88 and R.90-93 (CSO 2019).

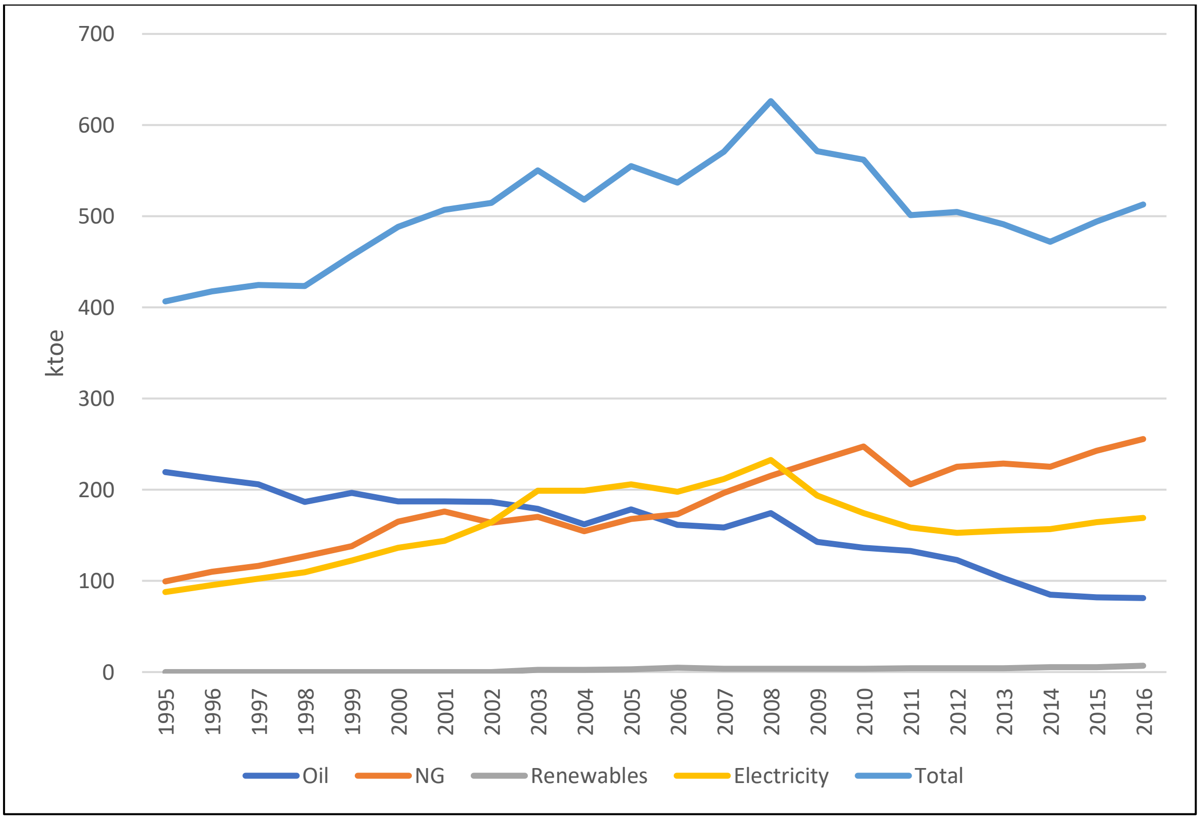
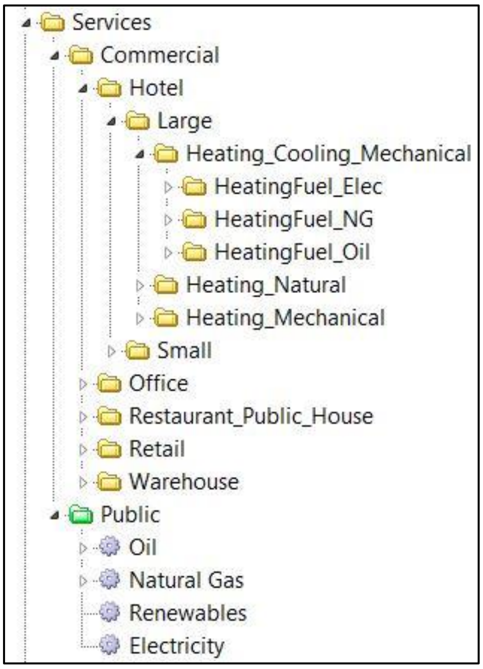


Figure 2-4 Public Services energy demand (ktoe) by fuel type in Ireland, 1995 - 2016

A new dataset provided by SEAI for the commercial services sector disaggregates energy demand into 109 distinct building archetypes (SEAI 2016a). These archetypes include building type (Hotel, Office, Restaurant/Public House, Retail and Warehouse), size (small/ large), heating fuel (natural gas, electricity, oil, solid fuel) and building fabric condition (windows, walls). Figure 2-5 shows the final model structure for the Services sector.



- Services
  - Commercial
    - Hotel
      - Large
        - Heating_Cooling_Mechanical
          - HeatingFuel_Elec
          - HeatingFuel_NG
          - HeatingFuel_Oil
        - Heating_Natural
        - Heating_Mechanical
      - Small
    - Office
    - Restaurant_Public_House
    - Retail
    - Warehouse
  - Public
    - Oil
    - Natural Gas
    - Renewables
    - Electricity

Figure 2-5 LEAP Ireland GHG: Services model topology

2.2.4 Transport

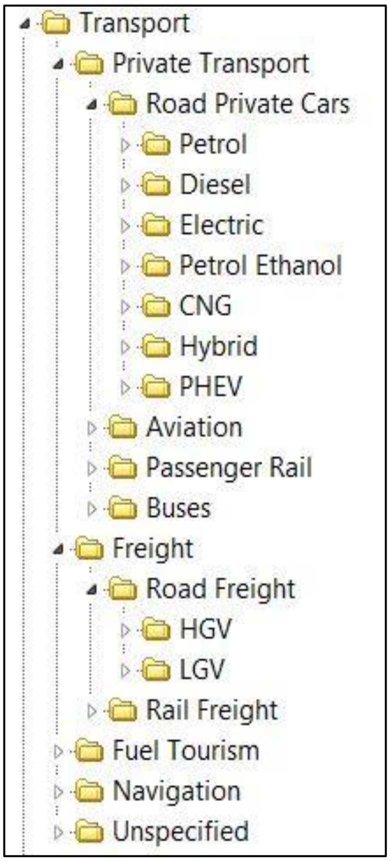
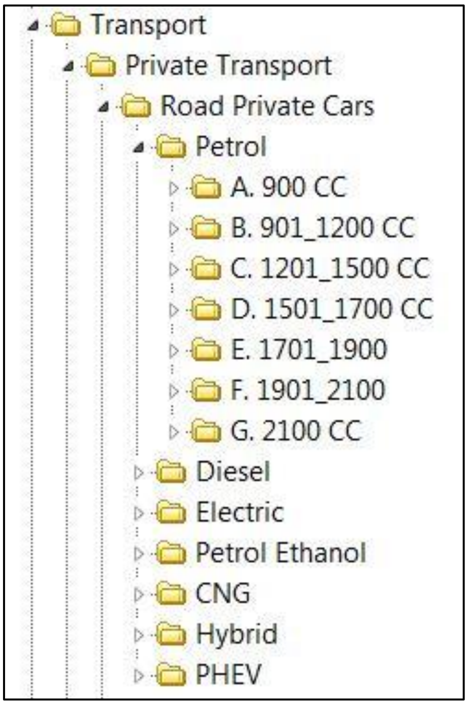


Figure 2-6 LEAP Ireland: Transport model topology

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 2-6 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, 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, > 2100 CC). Data for private passenger transport is supplied from the sectoral specific CarSTOCK model (H. 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 2-7 shows a detailed breakdown of the model topology utilised within LEAP to support this data.



- Transport
  - Private Transport
    - Road Private Cars
      - Petrol
        - A. 900 CC
        - B. 901_1200 CC
        - C. 1201_1500 CC
        - D. 1501_1700 CC
        - E. 1701_1900
        - F. 1901_2100
        - G. 2100 CC
      - Diesel
      - Electric
      - Petrol Ethanol
      - CNG
      - Hybrid
      - PHEV

Figure 2-7 LEAP Ireland: Private passenger transport model topology

Data relating to freight, navigation and fuel-tourism is supplied by the CSO. Fuel-tourism is defined by the ratio of GBP to EUR as this was found to be a strong driver of cross-border fuel consumption and purchasing. Figure 2-8 shows the link between energy demand (ktoe) and exchange ratio (GBP/EUR) (XE 2019). No attempt was made to estimate future differences in the exchange rate and therefore fuel-tourism remains constant at approximately 162 ktoe post 2016, this is compared to SEAI's figure of 184 ktoe in 2018 (SEAI 2019f).

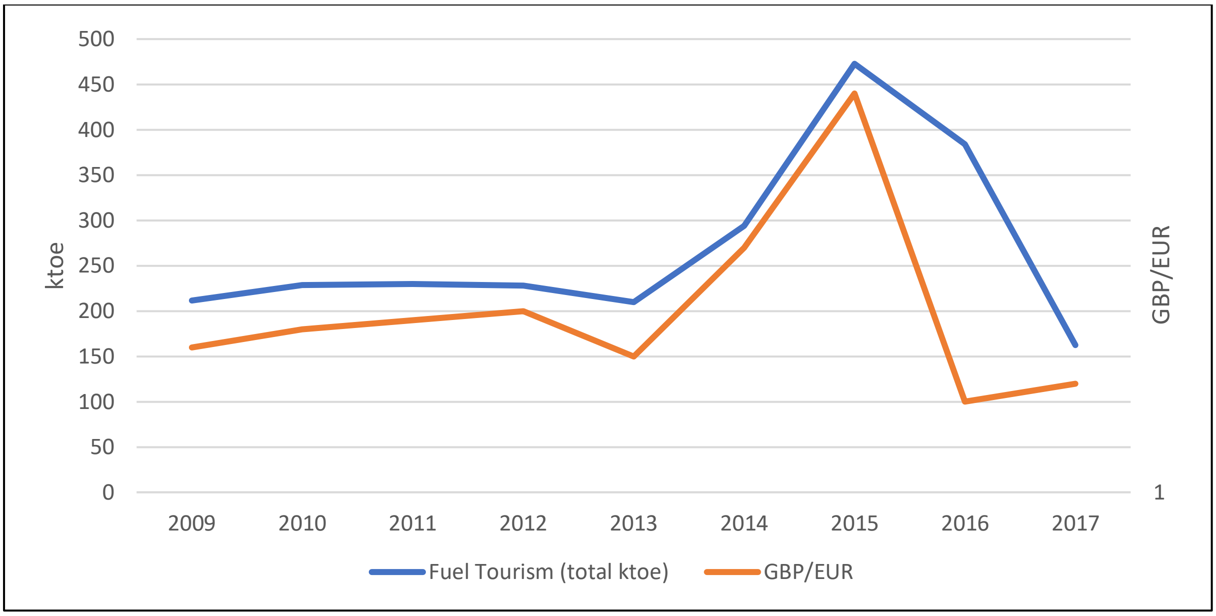


Figure 2-8 Transport fuel-tourism and projected energy demand (ktoe) in Ireland, 2009 -2017

Table 2-2 contains key model input data for each subsector in the transport section of the model. The model is designed to consider energy consumption across public and private transport modes. The transport sector is designed to consider policy levers such as the introduction of EV's, increased penetration of biofuels and modal shift to other forms of public transport.

Subsector	***Activity Driver***	***Intensity Driver***
Road Private Cars	Vehicle-km	MJ/Veh-km
Aviation	NA	ktoe
Passenger Rail	Passenger-km	MJ/Pass-km
Buses	Passenger-km	MJ/Pass-km
Heavy Good Vehicles	Tonne-km	MJ/ Tonne-km
Light Goods Vehicles	Vehicle-km	MJ/Veh-km
Rail Freight	Tonne-km	MJ/ Tonne-km
Fuel Tourism	NA	ktoe
Navigation		ktoe

Table 2-2 LEAP IE GHG 2050: Transport model drivers

2.2.5 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 euro). Data is supplied by the CSO. Non-

Energy related activity is disaggregated into livestock (dairy/ non-dairy cattle, sheep, pigs, and poultry), pasture and tillage (pulses, potatoes, sugar beet, barley, oats, and wheat). The energy intensity and activity figure for livestock/ tillage are provided exogenously from a separate sectoral specific Agri-TIMES model (Chiodi et al. 2016). Figure 2-9 shows the final model structure for the non-energy agriculture sector.

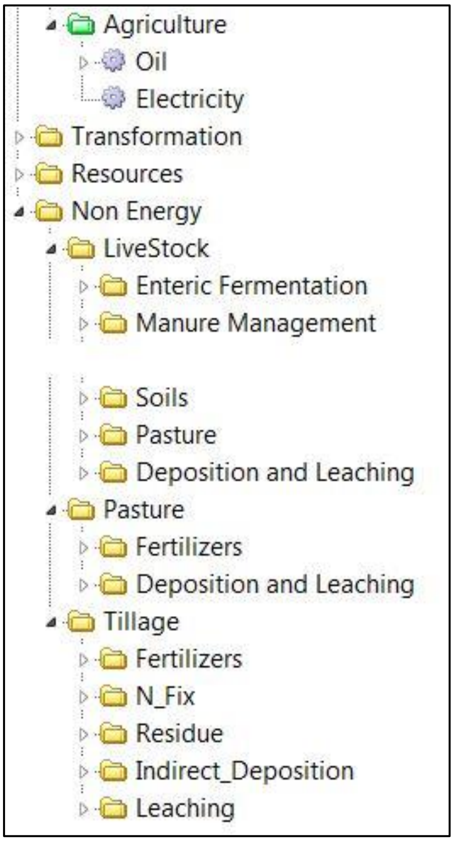


Figure 2-9 LEAP Ireland: Agriculture model topology

Table 2-3 provides base year data for non-energy agricultural activity. This includes livestock figures and tonnage of various crops.

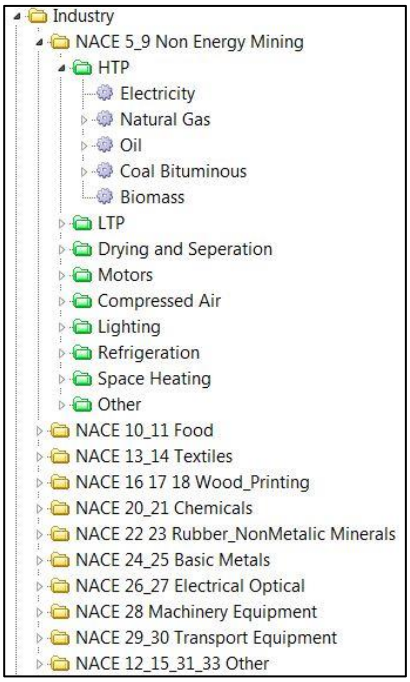
PROCESS	TYPE	UNIT	2016
CATTLE	Dairy	Mhead	1.1
CATTLE	Non-Dairy	Mhead	5.7
SHEEP	-	Mhead	5.5
PIGS	-	Mhead	1.8
POULTRY	-	Mhead	17.1
OTHER	-	Mhead	0.1
TILLAGE	Pulses	Mt	0.0
	Potatoes	Mt	0.4
	Sugarbeet	Mt	0.0
	Barley	Mt	1.4
	Oats	Mt	0.2
	Wheat	Mt	0.9

Table 2-3 LEAP Ireland: Agriculture base year inputs

2.2.6 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 & Printing
- NACE 20-21 Chemical
- NACE 22-23 Rubber & Non-Metalic
- NACE 24-25 Basic Metals
- NACE 26-27 Electrical & Optical
- NACE 28 Machinery & Equipment
- NACE 29-30 Transport Equipment
- NACE 31-33 Other Activity



- Industry
  - NACE 5_9 Non Energy Mining
    - HTP
      - Electricity
      - Natural Gas
      - Oil
      - Coal Bituminous
      - Biomass
    - LTP
    - Drying and Seperation
    - Motors
    - Compressed Air
    - Lighting
    - Refrigeration
    - Space Heating
    - Other
  - NACE 10_11 Food
  - NACE 13_14 Textiles
  - NACE 16 17 18 Wood_Printing
  - NACE 20_21 Chemicals
  - NACE 22 23 Rubber_NonMetalic Minerals
  - NACE 24_25 Basic Metals
  - NACE 26_27 Electrical Optical
  - NACE 28 Machinery Equipment
  - NACE 29_30 Transport Equipment
  - NACE 12_15_31_33 Other

Figure 2-10 LEAP Ireland GHG: Industry model topology

Activity drivers are supplied by the CSO (Subsectoral GVA). Each subsector has a derived energy intensity by dividing sectoral specific energy consumption, taken from the national energy balance, by the activity variable, sectoral GVA (Million €) at constant prices. A best fit curve of energy intensity is then generated using this historical data and used to estimate future energy intensity for each subsector. Figure 2-11 provides an example of this energy intensity calculation for the non-Metalic 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.

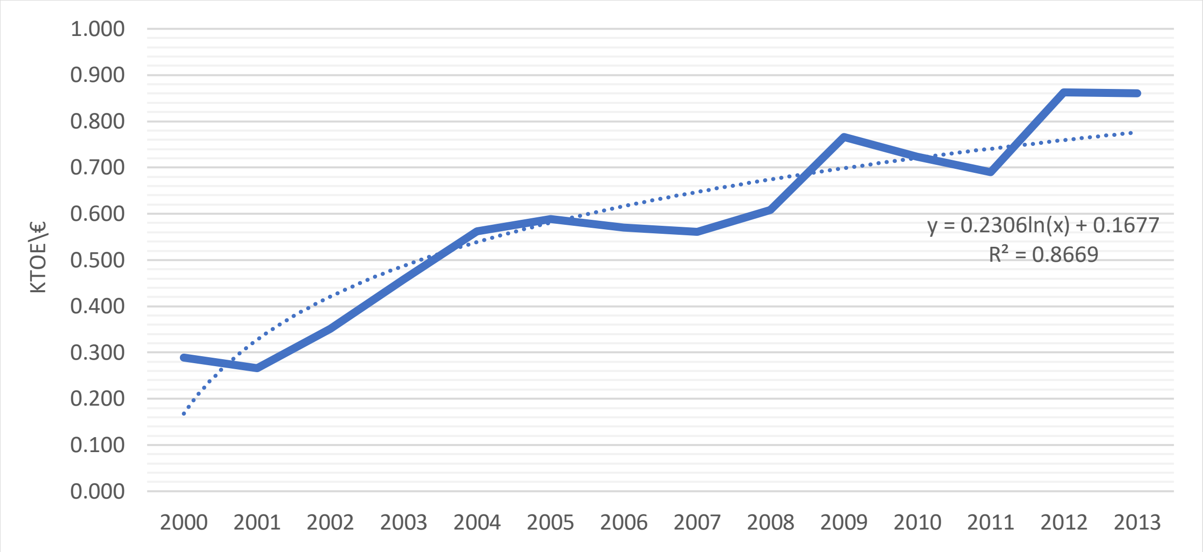
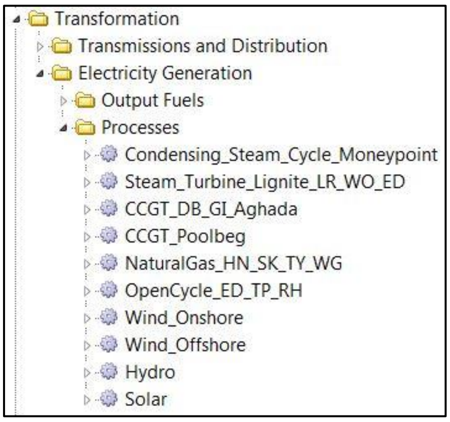


Figure 2-11 Historical energy intensity (ktoe/€) : Industry- other non-metallic mineral products in Ireland, 2000 - 2013

The industry sector leverages UK DECC 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 2-10 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.

2.2.7 Electricity Generation



- Transformation
  - Transmissions and Distribution
  - Electricity Generation
    - Output Fuels
    - Processes
      - Condensing_Steam_Cycle_Moneypoint
      - Steam_Turbine_Lignite_LR_WO_ED
      - CCGT_DB_GI_Aghada
      - CCGT_Poolbeg
      - NaturalGas_HN_SK_TY_WG
      - OpenCycle_ED_TP_RH
      - Wind_Onshore
      - Wind_Offshore
      - Hydro
      - Solar

Figure 2-12 LEAP Ireland GHG: Electricity generation model topology

The electricity generation sector is represented using simplified electricity generation profiles. Baseline data is supplied using the sectoral specific PLEXOS_IE model and generation units are aggregated by generation fuel and plant efficiency (measured by plant heat rate GJ/MWh). Generation types range in efficiency and fuel type (Oil, Natural Gas, Coal, Peat, On/Off-shore wind and solar). Figure 2-12 shows the final model structure for the electricity generation sector. Table 2-4 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 year and weekday/ weekend. Figure 2-13 shows the availability of the wind profile for each time slice used in this LEAP model.

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

Table 2-4 LEAP Ireland: Electricity generation base year data, including exogenous capacity (MW), historical production (GWh), and heat rate (GJ/MWh)

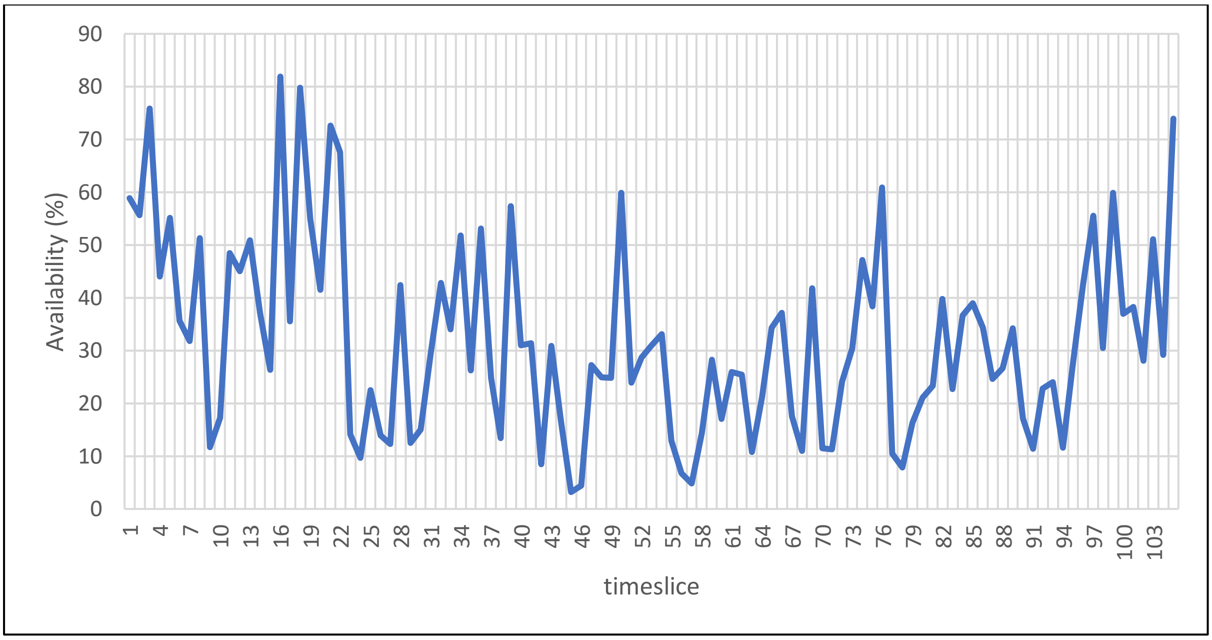


Figure 2-13 LEAP Ireland: Electricity generation sample wind profile and time slices utilised in LEAP Ireland GHG model

2.3 Application Script Editing Tool

The Application Script Editing Tool (ASET) was developed to leverage the existing Application Programming Interface (API) in the LEAP tool. The API allows for programmatic control of LEAP, using scripts to alter data values, calculate results and change model topology (C. G. Heaps, 2016a). While offering powerful functionality, the API requires knowledge of scripting languages e.g. VBScript, to be utilised correctly. The ASET tool is designed to operate between the end user and the API to add value to the existing LEAP program and provide new functionality to assist energy modellers in the development and analysis of energy system models. I have made the ASET tool available freely to other researchers and utilised the tool in the on-going development of a LEAP model for Viet Nam as part of the Viet Nam Ireland Bilateral Exchange (VIBE) program. ASET training has been delivered online and in person in Cork and Hanoi, section 1.8.2 provides more information on these training sessions. It is intended that the tool be made freely available online via an open access license for all research purposes.

LEAP-ASET is an Excel based tool which uses the Microsoft (MS) programming language, Visual Basic for Applications (VBA) to generate the appropriate Visual Basic Script (VB Script) which then automates actions in LEAP through the API. Excel userforms containing VBA scripts offer a user-oriented format for interaction with the API in LEAP. A userform is a custom dialogue box which prompts the user for input using text, drop down boxes and visual information. The API is compatible with multiple scripting languages including VBScript, Jscript, Perl, and Python. VBScript is a subset of VBA[4] which cannot generate userforms and other interactive controls. VBA offers additional control functionality and user interfacing capabilities (i.e. userforms) and effectively generates the appropriate VBScript which is compatible with the API in LEAP. LEAP-ASET therefore leverages the existing API to act as a standard "COM Automation server" (C. G. Heaps, 2016a) meaning that LEAP can be controlled programmatically by other Windows based tools, in this case MS Excel. This program can also be expanded to be utilised using web-forms and survey tools, providing for enhanced collaboration and model building techniques.

ASET can be used to design and modify LEAP model topology and run sensitivity analysis on specific key assumptions. The methodology allows LEAP energy system models to be created more efficiently than before. This improves the LEAP modelling community's capacity to incorporate new data sets and to modify model structures appropriately to adapt to the "ratchet mechanism" associated with NDCs. This has previously been difficult and time consuming in LEAP due to use of the GUI alone. LEAP-ASET leverages a subset of API functions to achieve useful functionality in a simplified userform which requires no knowledge of the programming languages VBA or VBS.

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[4] https://msdn.microsoft.com/en-us/library/ms970436.aspx (accessed 27/11/2017)

2.3.1 Model Topology Creation

LEAP supports a flexible hierarchical tree structure design in which levels of detail are nested within parent branches, typically ending in a technology or end-use. LEAP-ASET can be used to generate user defined model structures. The ability to quickly generate new model topologies allows for the updating/ enhancement of structures to incorporate new data sets, without the need for time consuming techniques using the GUI. This feature can be applied to new models or existing models.

This feature is controlled from ASET through a standard excel spreadsheet. The user is required to enter details of each level of their desired tree structure for the LEAP model. Userforms provide information on the available Scale and Units required that can be used in LEAP and generates the required VBS script which is then executed in the API to generate the model structure. Work to automatically parse the generated VBS script is ongoing but at present this process is manually controlled by the user.

The number of API functions which can currently be controlled from LEAP-ASET is limited to those related to the two objective functions of the ASET tool i.e. model creation and sensitivity analysis. However, the API is a flexible tool that can control the automation of most functions in the LEAP-GUI. Further plans to expand the abilities of LEAP-ASET to include more advanced functionality are also explored in the Next steps section.

2.3.2 Sensitivity analysis of key variables

LEAP currently supports the ability to create multiple scenarios and investigate the impact of varying key model assumptions to determine the overall system sensitivity to a chosen variable. LEAP-ASET adds value to LEAP by allowing a user to execute multiple iterations of a given scenario, by varying a specific key assumption from a chosen minimum and maximum value, in each step size. ASET reads and alters the key assumptions directly from LEAP, removing the need to switch between the LEAP GUI and ASET to identify variable values or execute multiple scenario iterations. This functionality allows a user to quickly (1) quantify the impact of varying key model assumptions on the overall energy system and (2) rank these key model assumptions according to their sensitivity.

The application of this feature has been designed with a focus on simplified user experience. Upon opening the excel Userform, users are presented with all the key assumptions which exist within their selected LEAP model. The value, scale and unit(s) for a selected key assumption are presented clearly and the user is prompted to indicate the desired range for the purpose of sensitivity analysis. Once a userform has been completed, LEAP-ASET controls the execution of multiple scenario iterations directly in LEAP. The chosen key variable is automatically updated in LEAP, using the defined new values and scenario results recalculated and output to a specified file system location in CSV format. The results are automatically sorted into distinct results categories, as specified in the LEAP-GUI “Favorites” folder. ASET will automatically detect any new favourite graph types which are added to Favorites in the LEAP GUI and create a result set for this new graph type as well as a folder to save the results. The process of creating new “Favorite” charts is documented in the LEAP manual (C. G. Heaps, 2016a).

2.4 ArDEM-SQL

I developed the Archetype Dwelling Energy Model (ArDEM-SQL), a new modelling tool which is developed here but based on the ArDEM model by Dineen et al (2015). The original ArDEM model is a simulation model built on the IS EN 13790 - Dwelling Energy Assessment Protocol (DEAP) - (SEAI 2008) which provides calculation methods for annual energy consumption for both space/ water heating, ventilation and lighting for Ireland (Dineen, Rogan, and Ó Gallachóir 2015). This subsection is based on the methodology described in one of my published journal articles[5]Input data is gathered from each individual dwellings 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 complete copy of all supplementary BER database inputs used as part of this analysis are provided in (Mac Uidhir et al. 2019a). A complex 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;

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[5] Mac Uidhir, Tomás, Fionn Rogan, Matthew Collins, John Curtis, and Brian P. Ó. Gallachóir. "Improving energy savings from a residential retrofit policy: a new model to inform better retrofit decisions." Energy and Buildings 209 (2020): 109656 doi.org/10.1016/j.enbuild.2019.109656

- 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 (METÉ 2019). Appendix B – Meteorological data for ArDEM-SQL simulation contains a complete list of all temperatures utilised. The relationship between target internal and external temperatures is important in simulating the heat requirement for residential dwellings. I recognise that the use of monthly mean external temperatures limits the granularity of the study in terms of understanding the complex effects that changes in climatic conditions have on building energy performance. However, this study is focused on understanding the relative difference between two alternative retrofit scenarios and hence it is only important that climatic conditions remain constant within these two scenarios. Data relating to external temperature is provided by the Irish Meteorological Service (METÉ).

The equations governing the relationships between all BER inputs and dwelling energy demand are numerous. Equation 2-1, Equation *2-2* and Equation *2-3* describe the calculation of the building heat loss coefficient (HLC). Ventilation Heat Loss (VHL), measured in Watts/Kelvin (W/K), is calculated as a function of the effective air change rate per hour (ac/h) and building volume. Equation 2-1 shows the ventilation heat loss equation utilised in the model:

Equation 2-1 Ventilation Heat Loss (W/K) $VHL = 0.33 * AC * V$

where, VHL is the Ventilation Heat Loss (W/K), AC is the Effective Air Change Rate (ac/h), V is the Structure Volume (m^3)

Fabric Heat Loss (FHL) is calculated as a function of the area (m^2) and U-Value (W/m^2K) associated with windows, doors, floors, walls, and roof. Equation 2-2 shows the fabric heat loss equation utilised in the model:

Equation 2-2 Fabric Heat Loss (W/K) $FHL = \sum_i (A_i * U_i)$

Where, FHL is the Fabric Heat Loss (W/K), i is the set {Windows, Doors, Floors, Walls, Roof} , A_i is the Component Area (m^2), U_i is the Component U-Value (W/m^2K)

Therefore, the Heat loss coefficient is given by Equation 2-3:

Equation 2-3 Heat Loss Coefficient (W/K) HLC = VHL + FHL

where HLC is the Heat Loss Coefficient (W/K)

The Dwelling Energy Assessment Protocol (SEAI 2008) provides a detailed overview of each equation governing final energy demand, separated into the following calculation categories:

- Ventilation Rate
- Heat Losses
- Domestic Hot Water
- Lighting and Internal Heat Gains
- Solar Heat Gains
- Mean Internal Temperature and Dwelling Thermal Mass
- Space Heat Use
- Space Heating Requirements
- Total Energy Use

The primary limitation of the original ArDEM model is an inability to analyse large datasets, such as the most recent BER database. Previous analyses using the old model used sample BER subsets and are not possible to replicate at scale as the model is comprised of multiple calculations, executing in excel. The new ArDEM-SQL model addresses this limitation by first converting all calculations into the Microsoft SQL language, allowing all BER records to be utilised as part of this study. The

ArDEM-SQL model can aid homeowners and engineers to make better retrofit decisions and is easily replicable. The model is described in the following sections.

The process of converting the calculations to an SQL format was necessary for this study as the BER database had grown to more than 700,000 records and it was not possible to conduct the analysis using Excel. This new model, ArDEM-SQL, bridges the gap between the model's capacity to process expanding datasets, such as the BER database, and is crucial to extend the scope of analyses beyond limited subsets of expanding databases. The scripted nature of ArDEM-SQL means that the model is not limited to a specific range of building archetypes or retrofit measures and can be adapted to serve the purposes of the modeller or decision-maker.

A complete version of the SQL script used in the development of ArDEM-SQL has also been made available as part of this thesis– allowing for the replication of results by third parties. Using the BER database as an input, ArDEM-SQL considers 122 unique building components associated with each record and simulates the energy savings associated with changes to different groupings of retrofit measures (building components). Appendix C – ArDEM-SQL Simulation characteristics includes a list of all components which can be modified and simulated in ArDEM-SQL.

3 Unlocking advanced simulation modelling applications with the Low Emissions Analysis Platform

Abstract

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, Nationally Determined Contributions) – this change has prompted a need for new modelling techniques and features to aid in the development of robust evidence-based policy support. Convergent trends in the challenges faced by energy system models require that the utility of models adapt to their growing complexity, and uncertainty while improving interdisciplinarity and scientific standards. This chapter 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 flexible energy system model topologies 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 in a comparative study of two LEAP models with a focus on private passenger transport.

This chapter provides an overview of energy system modelling categorisations and highlights the added value of ASET using an established qualitative evaluation method. The complete range of current application interface commands which exists within the application interface are also presented, providing suggestions for future research through the development of other modelling tools and techniques.

Keywords

Energy Systems Modelling; LEAP; Capacity Building; Accessibility; Bottom-Up; Top-Down.

3.1 Introduction: Energy Modelling for energy planning

All countries must decarbonise their energy systems if the world is to limit global warming to well below 2 °C, as stipulated in the now ratified Paris Agreement (UNFCCC 2019). Energy systems are complex structures that owing to their size, institutional inertia and complexity tend to get locked into particular configurations making them difficult to change, particularly in short time periods (Unruh 2000). Energy systems tend to change over long periods of time, therefore analysts and policy-makers have used 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, Pye, and Kannan 2009). A range of energy models are available according to different jurisdictions of analysis (i.e. by region, country, or global), questions that analysts sought to answer, interactions between human earth systems, levels of computing power available, and the human capacity of energy modelling available. While many countries have developed considerable modelling capacity, there remain significant modelling needs, particularly among developing countries (Pye and Bataille 2016) (Debnath and Mourshed 2018).

Over time, as computing power has grown (Khaitan and Gupta 2012), energy models have grown in capability, complexity and in extent (Bale, Varga, and Foxon 2015), particularly in the industrialised world. In part, this reflects how the world’s energy system is evolving and becoming more globalised: increased computing power has facilitated more global and more advanced modelling structures which can represent the complicated interplay of the global energy system. User needs have influenced energy modelling developments, this is reflected in the growing emphasis on the need for an integrated approach to energy systems modelling across a range of spatial scales, temporal resolutions, and societal perspectives (Halog and Manik 2011) (Nakata, Silva, and Rodionov 2011). Organisations such as the International Institute for Applied Systems Analysis (IIASA) have coordinated the development of the Global Energy Assessment (GEA 2012) in recognition of the need for this integrated approach, considering industrialised, developing and emerging economies in a coherent framework. This represents a shift in the application of energy modelling as the broader issues associated with equitable access to energy are addressed. However the range of issues affecting industrialised and developing nations, such as moral responsibility of industrialised countries (Ekholm and Lindroos 2015), economic impact, societal acceptance, regional diversity, and environmental effects need to be given appropriate attention (Pandey 2002). These national and associated local issues are often considered in energy models as secondary concerns (if at all) with the results focusing on emissions reductions or cost alone. Modern energy systems modelling has evolved to incorporate many of these previously overlooked aspects of energy use. This has necessitated a trade-off between model functionality and accessibility as the additional layers of complexity can negatively affect the end-user’s capacity to fully understand the model and results. Therefore, there is a growing need to improve the modelling capacity within a regional, national, and local context to further support the development of these alternative modelling concerns.

This chapter presents a new energy system modelling evaluation schema, illustrating a fundamental guide to comparing model utility across a range of competing attributes. This chapter also demonstrates a new method to create an energy system model topology, populate data and conduct sensitivity analysis using the established Low Emissions Analysis Platform (LEAP). This approach, the Application Script Editing Tool (ASET), provides a means of unlocking an underutilised computational resource within LEAP to improve the modelling capacity by facilitating real-time model structure development and other features. A comparative study highlights the advantages associated with creating and populating a complex transport model. This study utilises a previously existing LEAP transport model as a counterfactual with which to measure the added benefits ASET brings to LEAP.

3.1.1 From Kyoto to Paris – The changing political context of energy modelling

Over the course of the 20th century, energy became sufficiently important as an enabler of development for the broader economy and society that the state took an active role in managing the growth and stability of its own energy system. Historically, access to affordable energy (i.e. energy security) was a dominant consideration in state energy policy and energy planning; however, as the environmental and climatic implications of the growing energy system have become clearer, energy policy and energy planning have evolved to consider more than just the four A's of energy security[6] and began to incorporate more challenging activities, which can be summarised as: access to energy (security); cost of energy (equity); and environmental externalities (climate) (Cherp and Jewell 2014; Kruyt et al. 2009). The growing threat and organised response to climate change has seen the international climate negotiations become an increasingly inclusive and collective activity. Much of this international activity has been paralleled with modelling developments. The evolution of this modelling activity is explored in more detail in section 3.1.1. Global analyses of technology pathways that demonstrate the achievability of climate goals such as limiting global warming to 2 degrees (or *well below 2 degrees*) have also been influential in agenda-setting during international climate negotiations (IEA 2016).

The United Nations Framework Convention on Climate Change was agreed in 1992 and represented the first international agreement by which many countries agreed to reduce their GHG emissions. The Kyoto Protocol, agreed in 1997, set an overall target for 2010 of reducing GHG emissions in industrialised countries by 5% against 1990 levels. The participating countries agreed to share and divide up based on various

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[6] Availability, Accessibility, Affordability, Acceptability

formulae, hence the Kyoto Protocol was a 'top-down' style of agreement (Leal-Arcas 2011). However, the Kyoto Protocol only included 37 industrialised countries, known as Annex I countries[7].

The Copenhagen accord of 2009 was established during the 15th United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP 15) meeting in Copenhagen. This agreement pledged to limit average global temperature increase to below 2°C above pre-industrial levels and established a Green Climate Fund to provide financial support to developing nations at risk due to the effects of climate change (Lau, Lee, and Mohamed 2012). These outcomes represent critical milestones in the journey towards a more universal agreement. However, a global agreement on how to achieve the 2° target was not established at this time. The failure to reach an agreement prompted a new strategy towards international climate change negotiations and saw a shift towards a more 'bottom-up' style of negotiations (Victor 2014). In the year preceding the UNFCCC COP21 meeting in Paris, all 197 parties to the original UNFCCC, submitted plans outlining what mitigation they could achieve in their Intended Nationally Determined Contributions (INDCs). The INDCs represented what Governments felt their countries could commit to. The INDC process formed a key input to the Paris Agreement, which when signed in December 2015 included 197 Parties to the convention. On October 5th 2016, a press release from the UNFCCC stated that more than 55 countries representing more than 55% of global emissions had ratified the Paris Agreement (UNFCCC 2016). A total of 184 countries representing 93% of all parties have since ratified the agreement (UNFCCC 2019).

Prior to the COP21 meeting in Paris, a variety of energy modelling was carried out to underpin the Intended Nationally Determined Contribution's (INDC). A total of 155 separate INDC's were submitted before the closure of COP21 on December 12th, representing 182 individual nations. An additional 10 INDCs have been received since the closure of the COP21 meeting.

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[7] https://www.oecd.org/env/cc/listofannexicountries.htm

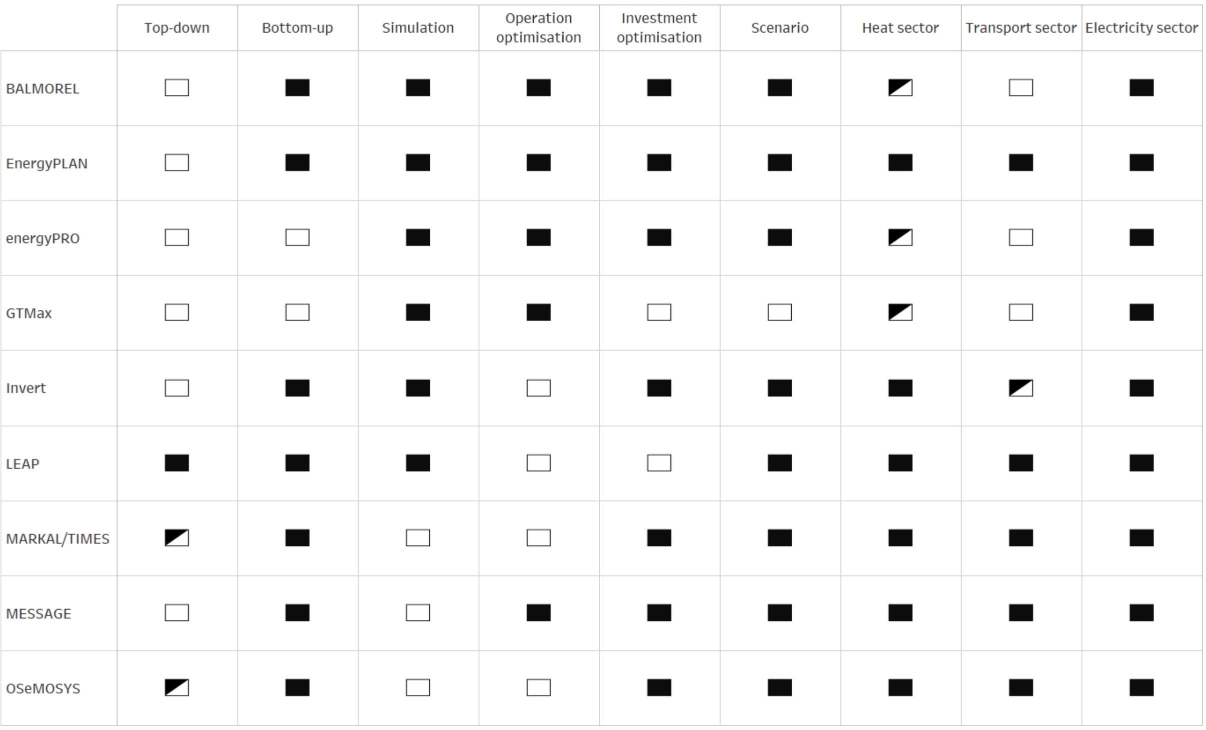
While much of this analysis was done by nations themselves, for countries with limited energy modelling capacity, analysis was supported and facilitated by international organisations such as United National Environment Program (UNEP), the World Resources Institute (WRI) and the Climate & Development Knowledge Network (CDKN). After the COP21 meeting, the INDCs became nationally determined contributions (NDCs). Built into the Paris Agreement is a mechanism for revising plans every 5 years (UNFCCC 2015b). Significant analysis will be required to underpin each of these revised plans that each of the UNFCCC countries will be required to submit in the context of the global stocktake (GST) in 2023 outlined in Article 14 within the Paris Agreement.

The shift to bottom-up NDCs has been a crucial factor in the Paris Agreement being successfully ratified (Falkner 2016). NDC’s presented a solution which facilitated large scale participation amongst parties while recognising the diverse challenges faced by each party (Christoff 2016). However, it will require a significant increase in global energy modelling capacity to ensure its successful implementation.

While global models will and should continue to be used, there is a need for detailed national models which can provide evidence-based policy support to help drive emissions reductions within all signatories to the Paris Agreement.

3.1.2 Energy model classification and challenges

Understanding the range of models which exist, and their classification is key to determining the appropriate model to address a specific research question. Section 1.3 explored a more complete range of classifications as they apply to all energy system models. Here I present a subset of these model characteristics to provide an overview of different model types, including the analytical approach (top-down, bottom-up, hybrid), the underlying methodology (simulation, optimisation), and sectoral coverage (all, transport, heat, electricity generation). More recent publications from (Pfenninger et al 2014; Wiese et al. 2018) examine the distinct modelling challenges which are emerging as energy system models are required to answer questions relating to a diverse range of research areas relating to climate policy. To facilitate ever-increasing requirements such as new research questions and evidence-based policy support, multiple facets of energy system models are changed and updated over time. This process can alter the scope of a specific models ability to consider differing levels of technological, spatial, and temporal detail but also introduce difficulties relating to model transparency and stability (Dodds, Keppo, and Strachan 2015). **Error! Reference source not found.** provides an overview of my chosen distinct modelling characteristics as they apply to well-known energy system models available today. The list of chosen energy models is not exhaustive, models were chosen due to their similarity (underlying methodology, sectoral coverage, and analytical approach). As ASET supplements the LEAP modelling platform, it does not conform to this means of model comparison between platforms. There is limited value in utilising these model classification criteria to rank the utility of different energy system models, as the range of research questions they seek to answer are as diverse and complex as the models seeking to answer them. Section 3.1.3 explores model evaluation methods.



	Top-down	Bottom-up	Simulation	Operation optimisation	Investment optimisation	Scenario	Heat sector	Transport sector	Electricity sector
BALMOREL	□	■	■	■	■	■	◩	□	■
EnergyPLAN	□	■	■	■	■	■	■	■	■
energyPRO	□	□	■	■	■	■	◩	□	■
GTMax	□	□	■	■	□	□	◩	□	■
Invert	□	■	■	□	■	■	■	◩	■
LEAP	■	■	■	□	□	■	■	■	■
MARKAL/TIMES	◩	■	□	□	■	■	■	■	■
MESSAGE	□	■	□	■	■	■	■	■	■
OSeMOSYS	◩	■	□	□	■	■	■	■	■

Figure 3-1 Energy system modelling characteristics

The dynamic evolution of model topology represents a challenge for technologically rich bottom-up energy system models, shown in **Error! Reference source not found.**, as the process of incorporating new data sources into stable model versions can be time consuming and problematic. The ASET tool is designed to demonstrate two specific modelling capabilities within the LEAP framework, these include (1) topology design which leverages a robust scripting framework – presented to users in a simple interface and (2) provide a means to conduct sensitivity analysis of model key assumption using a simple user interface.

LEAP is one of a range of scenario-based simulation modelling tools which possesses many features including the built-in Application Program Interface (API). ASET provides access to the underlying code in the API, leveraging VBA scripts created in Excel to facilitate the two specific features outlined above. In conjunction with LEAPs user friendly interface this facilitates model accessibility while improving functionality. Figure *3-2* illustrates ASET's position within the context of LEAP and other simulation modelling tools which offer integrated scenario analysis, highlighting some of the additional features which were considered for inclusion in the program. ASET leverages multiple API features and commands to produce the topology design and allow sensitivity analysis. While the ASET tool is limited to (1) and (2) from the list of new features, work remains on-going to incorporate more complex model result processing outside of LEAP using Excel and Python. A complete list of all API commands is included in Appendix D – Application Programming Interface command set for ASET.

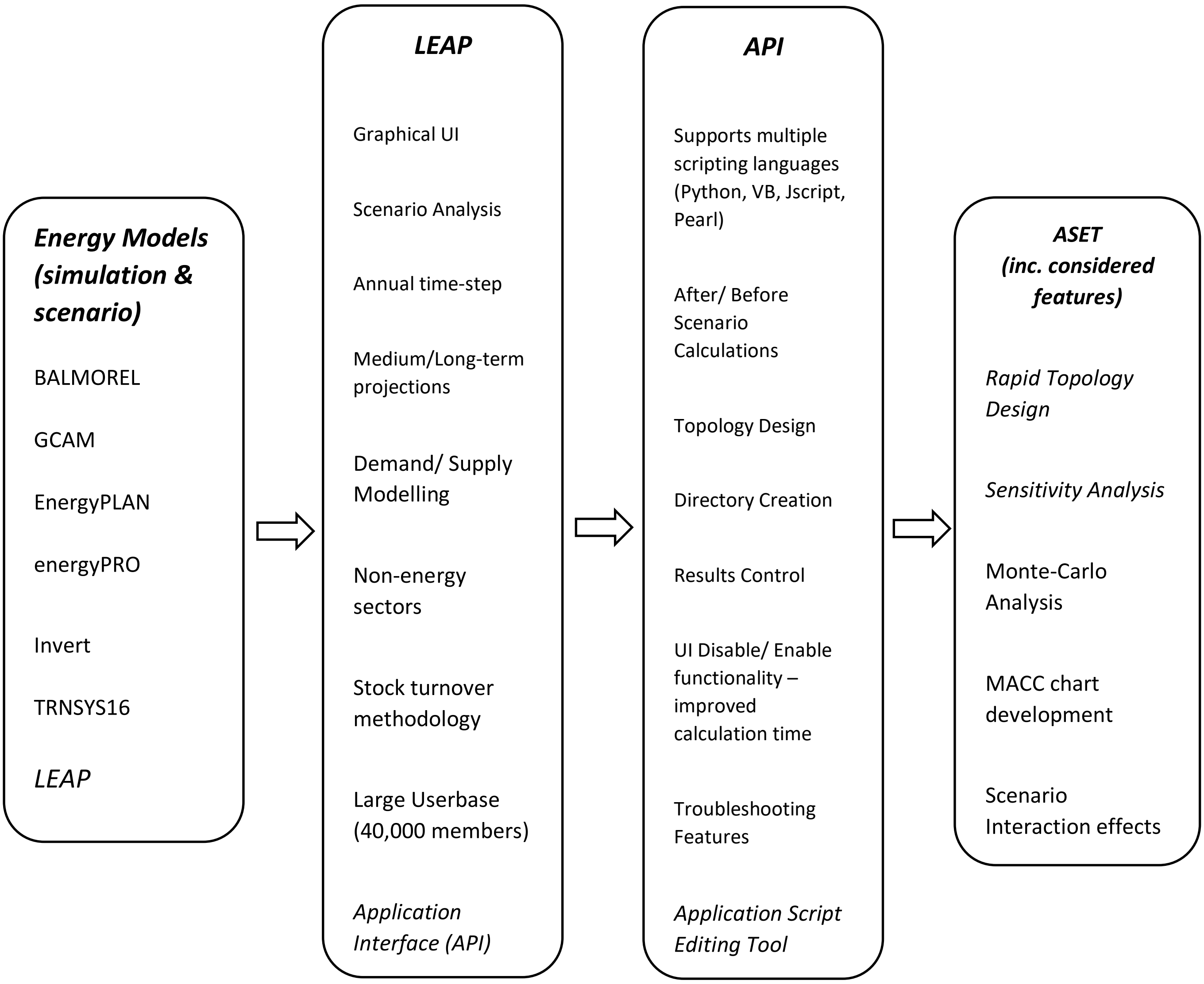


Figure 3-2 Application Script Editing Tool: Application Interface description, relative to other simulation modelling tools.

3.1.3 Modelling framework evaluation method

The complete collection of energy system models available represent a diverse range of tools across an array of platforms, containing multiple levels of detail and functionality. Matching appropriate modelling platforms to the challenges of modern energy system modelling is difficult. The classification of energy system models has evolved in parallel with the growing number of available models. While the increasing power and complexity of energy system models represents an opportunity for more robust and comprehensive evidence-based policy decisions, there is a risk that the technical complexity of constructing, operating and interpreting model results will over-run the modelling capacity of the growing number of users. The importance of detailed country level modelling highlights the need for accessible tools which aid in the development of new models and techniques which improve the range of technical abilities to generate useful results. Lopion et al. (2018) reviewed emerging trends of energy system model characteristics and the challenges faced by models with respect to supporting governments with strategic decision making. They delineate minimum requirements for assessing model utility, choosing models which (1) are calculated on national scale, (2) are applicable to all energy sectors, and (3) are supportive of governmental decision making processes. Lopion' evaluation is applied to 24 distinct energy system modelling platforms (including LEAP), highlighting a recent (since 2010) trend in more open access models written in VBA, GAMS and Python scripting languages. They conclude that there is a need for models to be “more flexible and transparent” to answer the broad range of research questions being asked of modern energy system models. Additionally, future model development will be influenced by providing more open source/ access models with improved data transparency. Wiese et al. (2018) identify (1) complexity, (2) uncertainty, (3) interdisciplinarity, (4) utilization, and (5) scientific standards as the five main challenges facing energy system models, suggesting a three “pronged” framework to deal with these challenges including (*a*) an open-source philosophy, (*b*) collaborative modelling, and (*c*) structural properties. Wiese builds on previous attempts to construct a qualitative "transparency checklist" (Cao et al. 2016), combining previous model classification criteria with broader model generators to derive a qualitative evaluation approach for the assessment of modelling frameworks. Their proposed method to evaluate frameworks (a, b, c) can be further disaggregated into quantifiable metrics. Table *3-1* shows a blank template of the property evaluation method, applicable to any modelling framework or model generator. This is then extended to evaluate the applicability of each property to address the five main challenges (complexity, uncertainty, interdisciplinarity, utilization, and scientific standards)(Wiese et al. 2018), shown in Table 3-2. This evaluation approach provides a comprehensive means of linking model characteristics and properties, to model utility and their capacity to answer the challenges facing modern energy system models. This serves as a useful means of representing the differences between models, or in this case quantifying the additional functionality which ASET provides to the pre-existing LEAP modelling platform.

Open-source philosophy	open-source	
	documentation	
	version control	
	openness of data	
	code review	
Collaborative development	consistency of terminology	
	developer perspective spectrum	
	interdisciplinary	
	testing procedures	
Structural properties	modular	
	object-oriented	
	generic concept	
	data model	

⬜	*no/not available*
🟨	*partly available*
🟩	*available*

Table 3-1 source (Wiese et al. (2018): Energy system model evaluation framework

		Complexity				Uncertainty					Interdisciplinarity			Utilization				Scientific standards				
		Sector coupling	resolution	input data	result processing	epistemic	aleatory	linguistic	decision	planning	human dimension	energy-water-food	common understanding	usability	applicability	re-usability	result communication	transparency	repeatability	reproducibility	scrutiny	scientific progress
Open-source philosophy	open-source																							
	documentation																							
	version control																							
	openness of data																							
	code review																							
Collaborative development	consistency of terminology																							
	developer perspective spectrum																							
	interdisciplinary																							
	testing procedures																							
Structural properties	modular																							
	object-oriented																							
	generic concept																							
	data model																							

☐ *not available*
🟨 *partly available*
🟩 *available*

Table 3-2 source Wiese et al. (2018) : visualisation of evaluation results. Mapping challenges with model properties and characteristics

The rest of this chapter will be described as follows. First, I will provide a short overview of the functionality of the ASET tool in section 3.2, including an overview of the LEAP modelling tool and the application interface which provides the functionality required to use ASET. A comparative study of two separate means of developing a transportation model serves to illustrate the utility of the ASET tool. Section 3.3 describes the *topology creation* and *sensitivity analysis* functionality of ASET in more detail. The results section explores the limitations and advantages associated with the specific case study models developed. Additionally, the qualitative modelling framework evaluation approach described by Wiese et al., is applied to LEAP and ASET, serving to highlight the additional utility criteria which ASET brings to LEAP. The discussion and conclusion sections explore the "impact" of these model classification and evaluation methods and suggest future research to progress the ASET tool in the context of improved scientific standards

3.2 Methodology

The Low Emissions Analysis Platform (LEAP) is an integrated GHG and energy simulation modelling tool developed by the Stockholm Environmental Institute (SEI). LEAP is a tool which is used on different spatial and temporal scales, e.g. national mitigation strategies, global scales and varying time horizons (Connolly et al. 2010) i.e., medium to long term horizons. The tool has many different types of users (e.g. academic researchers, government agencies, non-governmental organisations, energy utilities, consulting companies, etc.) and has been used in more than 190 countries for a diverse range of mitigation strategies including, “A CO2 Neutral Copenhagen by 2025”, “Massachusetts Clean Energy and Climate Protection Plan”, “Bioenergy Technology Roadmap for Colombia 2030”, “Reinventing Fire: China - A Roadmap for China’s Revolution in Energy to 2050”)[8]. The LEAP tool played an integral role in the guiding the NDC’s of 35 nations as part of the Paris agreement (C. G. Heaps 2016b); these countries include Cambodia, Ecuador, Ghana, Haiti, Israel, Lebanon, Mauritania, Mongolia, Mozambique, Niger, Nigeria, the Philippines, Zambia, and Zimbabwe. Appendix E – LEAP utilised in development of INDC and COP 21 includes a complete list of all 35 countries known to have used LEAP as part of their INDC. In addition to mitigation scenario analysis, LEAP has also been used for other applications, such as energy efficiency (Rogan et al. 2014), electricity generation sector (Dagher and Ruble 2011; Bautista 2012; C.-C. Lee and Chiu 2011), household (Kadian, Dahiya, and Garg 2007) and transportation analysis (Bose and Srinivasachary 1997).

LEAP offers a Graphic User Interface (GUI) to facilitate the construction of energy system model topologies, data input and scenario creation. The tool does not require any advanced scripting or coding knowledge and therefore acts as an appropriate tool for developing energy modelling capacity. The GUI allows for the representation of complex energy systems using varied model structures and transparent modelling

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[8] https://www.energycommunity.org/default.asp?action=applications (accessed 21/11/17)

techniques. LEAP offers the functionality to create multiple distinct scenarios and investigate the impact of these scenarios separately, relative to a reference scenario. Multiple functions are available to extrapolate, interpolate and define specific growth projections to forecast future energy demand. This flexibility is useful in the context of constructing energy systems models across different sectors where data availability may differ, allowing for top-down structures to be incorporated into technology rich bottom-up model topologies.

The ability to readily view and analyse results is another benefit of LEAP. The tool offers multiple graph types and allows results to be viewed on an aggregate or granular level, depending on the underlying data available. It also allows for the creation of system energy balances and results via Sankey diagrams. Sankey diagrams are flow diagrams which can represent the relationship between sources and sinks e.g. materials, energy, emissions, and cost. These diagrams utilise arrows, proportional to the quantity being represented. They are often used to represent energy flow diagrams which define the relationship between primary energy input and final energy use, capturing energy losses in the process. As a result, Sankey diagrams can be used to communicate complex energy modelling results in a visual medium (Schmidt 2008).

While LEAP offers the ability to create flexible model topologies which are suited to the available data, the process can be time consuming. Creating a new model can take a lengthy period depending on the complexity of the desired model structure. Similarly, populating the model with data can also occupy a significant share of model calibration time. ASET has been designed in response to this challenge, reducing the time-consuming aspects of technical model construction, data populating, and sensitivity analysis, reducing typical times from weeks/ months to hours/ days.

3.2.1 LEAP – Application Programming Interface

The Application Programming Interface allows LEAP to act as a standard "COM Automation Server", meaning that external programs can be used to interface with LEAP and effectively communicate with other compatible programs such as Excel (C. G. Heaps 2016b). The API consists of a whole range of commands, each with their own properties and methods. Properties are values which can be inspected or changed while methods are functions which call LEAP to complete a task e.g. export results, create/ modify branch structures or even create/ modify data expressions within a model, recalculating results each time a data expression is changed if requested. A selected subset of these commands is shown in Table 3-3, I found these chosen commands to be particularly useful as they facilitated advanced modelling functionality such as sensitivity analysis and topology creation. A complete set of all commands, including their properties and methods is described in Appendix D – Application Programming Interface command set for ASET. While LEAP contains a built-in script editor which allows users to write VBScripts which can automate LEAP, there are little examples of how the API can be used to add the type of advanced functionality described in this chapter.

API Commands	Type	Read/Write	Description
ActiveScript	String	R	filename of active script
AfterCalc	String	R/W	Get/set the filename for script that occurs after all calculations
AfterScenarioCalc	String	R/W	Get/set the filename for script that occurs after each scenario is calculated
BeforeCalc	String	R/W	Get/Set filename for script to run before calculation
BeforeScenarioCalc	String	R/W	Get/Set filename for script to run before scenario calculations
BeforeTransformationCalc	String	R/W	Get/ set filename for script to run before Transformation calculations
BringToFront	Method	NA	Brings LEAP application (UI) window to the front of window stack
Calculate(CalculateWEAP)	Method	R/W	Starts LEAP Calc - returns to Results, TRUE/FALSE for WEAP
CanQuit	Boolean	R	Gets whether LEAP can close down & preps for close down
Clear	Method	NA	Clears PRINT messages in built in Script Editor
CLS	Method	NA	Clears PRINT messages in built in Script Editor
CopyEnergyBalanceChart	Method	NA	Copies the current energy balance to Clipboard
CopyEnergyBalanceTable	Method	NA	Copies the current energy balance TABLE to Clipboard
CopyFile	Method	NA	Copy a system file from one location to another
CopyResultsChart	Method	NA	Copies current results view chart to clipboard
CopyResultsTable	Method	NA	Copies current results view Table chart to clipboard
CreateDirectory	Method	NA	Creates a system directory
DeleteFile	Method	NA	Delete file at specified directory
DisableControls	Method	NA	Disables LEAP Main user interface - allows for intensive data processing
EnableControls	Method	NA	Enable the LEAP Main user interface - used in conjunction with DISABLE

ExportData	Method	NA	Export Data from LEAP TO excel
ExportResultsXLS	Method	NA	Export Current results view chart in Excel Format
Favorites	Object	R	Gets collection of all saved Favorite charts
ForceCalculation	Method	NA	Force LEAP to calculate next time results requested - regardless of data change
IsCalculating	Boolean	R	True If LEAP is calculating
MaxIterations	Integer	R/W	Get/Set max iterations to solve transformation calcs.
Minimize	Method	NA	Minimize LEAP application to windows taskbar
Print(Value)	Method	NA	Prints string, updating APIPrint.txt file
PrintToFile	Method	NA	Print specific string to specified text file location on system
ProgramStarted	Boolean	R	True if LEAP is started
Quote	String	R/W	Returns string wrapped in quotes
Refresh	Method	NA	Refresh screen display
RefreshResources	Method	NA	Refresh resources list
RenameFile	Method	NA	Rename old file on system to new specified name
Restore	Method	NA	Restore LEAP application window if minimised
SaveArea	Method	NA	Save the current area
SaveFavorite	Object	R	Saves favorite to Favorite folder
ShowCalcProgress	Integer	R/W	Get/ Set whether LEAP shows calculation progress - slow calculations
Status	Boolean	R	For development only - not for normal use
Verbose	Integer	R/W	Get/ Set message types during LEAP automation
Visible	Boolean	R/W	Get/ Set whether the LEAP application is visible
WorkingDirectory	String	R	Gets the full path of LEAP working directory

Table 3-3 API Command Subset - command type and description for syntax used in ASET

3.2.2 A New Tool: Application Script Editing Tool

The Application Script Editing Tool (ASET) was developed by me to illustrate the benefits of controlling LEAP programmatically using the built-in API. While leveraging the API offers powerful functionality, it requires knowledge of scripting languages e.g. VBScript, Python, JScript, or Pearl to be used correctly. The ASET tool is designed to operate between the end-user and the API to provide an accessible means of accessing automation in LEAP without encountering a steep learning curve with respect to learning a new scripting language. ASET has been designed to demonstrate the application of two of the identified new features highlighted in **Error! Reference source not found.**. These features include rapid topology creation and the ability to generate an ensemble of scenarios. The ability to generate an ensemble of scenario results provides added functionality to LEAP which was not previously available.

The methodology allows LEAP energy system models to be created/ modified more efficiently than previously possible. This improves the LEAP modelling community's capacity to incorporate new data sets and to modify model structures appropriately, ensuring model structures are designed appropriately for the research questions they are investigating. This has previously been difficult and time consuming in LEAP due to use of the GUI alone.

ASET is designed with a focus on providing the user with a new method of interacting with LEAP models and results. There is a minimal learning curve associated with using ASET and users will be familiar with the Excel-type userforms which unlock the new features. The user interacts with ASET, choosing between sensitivity analysis/ topology design and the appropriate VBS script is generated and passed to the API. The API control functionality then executes the script against a chosen LEAP model and the user can review results in LEAP or separately export results to excel for further analysis. Understanding the method by which ASET connects to LEAP via the API unlocks further potential external functionality as outlined in **Error! Reference source not found.**. Figure 3-3 illustrates this process and outlines the design schema of ASET which can be replicated to produce other external programs which leverage LEAP and the API as the driver.

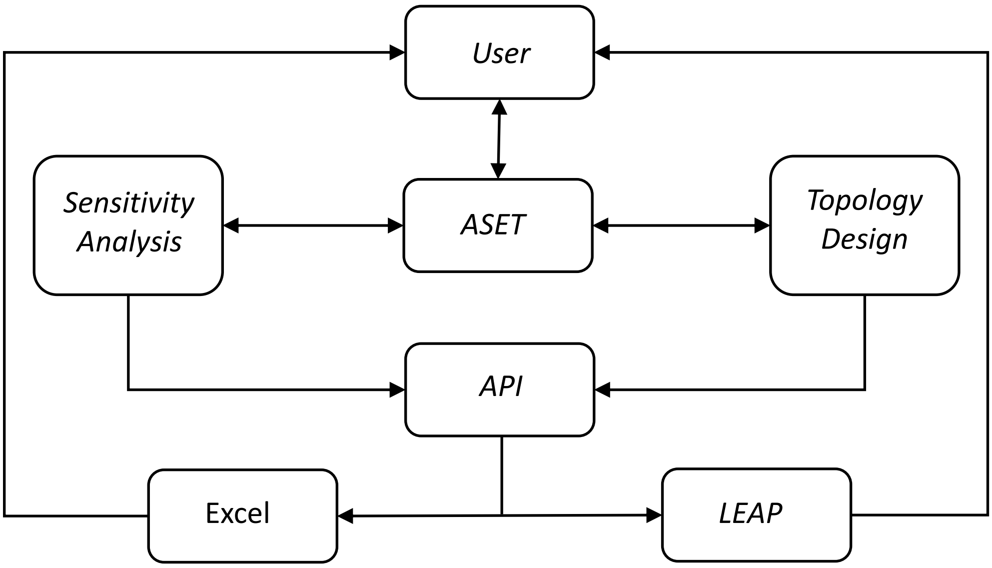

Figure 3-3 ASET methodology schema

3.3 Comparative Study

3.3.1 Overview

This section provides an overview of the advantages associated with creating and populating a complex transport sector in LEAP using the ASET tool. A case study for Ireland is chosen given the access to relevant data and an existing LEAP transport model which serves as a counterfactual with which to measure the added benefits associated with the new model development technique. The noted issues raised serve to highlight the differences between the modelling methodologies and provide results of sensitivity analysis which are possible due to the ASET tool.

A brief overview of the pre-existing LEAP Transport model (*Model A*) is provided, developed using the existing suite of built-in LEAP UI functions. The new LEAP ASET Transport model (*Model B*) is also presented alongside relevant scripts generated within ASET to create/ operate the model. The level of data complexity associated with private passenger transport sector presented a specific challenge with respect to incorporating new, relevant vehicle import data into the LEAP Ireland modelling framework in model B. The main advantages and limitations of both models are also explored.

3.3.2 Model A: a LEAP transport model

Model A consists of a multi-sectoral demand model for Ireland covering all demand sectors of the Irish economy including transport, residential, industry, services, agriculture and electricity generation (Rogan et al. 2014). The passenger vehicle transport module of Model A is developed outside of LEAP in a standalone vehicle stock model (H. Daly and Ó Gallachóir 2011). Data is utilised within LEAP using the built-in *Transport Analysis Stock Turnover* methodology in LEAP (C. G. Heaps 2016a).

Model A disaggregates the private passenger transport stock based on fuel type (petrol, diesel, natural gas, electric), engine size (measured in cylinder size[cc]) and vehicle vintage (25 years of data). Future modelling scenarios are explored in Model A using demand analysis scenario results from the same exogenous car stock model (H. E. Daly and Ó Gallachóir 2012).

Energy demand within Model A is calculated as a product of stock, annual mileage, and vintage specific energy consumption for each vehicle type. Equation 3-1 shows the built-in stock turnover calculations for each vehicle type and vintage. Survival profiles are defined within LEAP. Equation 3-2 utilises stock output calculations in conjunction with annual mileage and fuel economy to produce total energy demand. This methodology allows for energy efficiency scenario analysis relating to private passenger transport. However, the method is limited by the functionality of LEAP's built-in *Lifecycle Profiles* which describe stock vintage behaviour.

$$Stock_{t,y,v} = Sales_{t,v} * Survival_{t,y-v}$$

$$Stock_{t,y} = \sum_{y=0..v} Stock_{t,y,v}$$

Equation 3-1 LEAP endogenous stock turnover equations

$$EnergyConsumption_{t,y,v} = Stock_{t,y,v} * Mileage_{t,y,v} * FuelEconomy_{t,y,v}$$

$$Demand_{t,y} = \sum_{y=0..v} EnergyConsumption_{t,y,v}$$

Equation 3-2 Private passenger transport energy demand equation

Where, *t* is the vehicle type, *v* is the vintage year (0…25), *y* is the year, *Sales* is the number vehicles added in year y, *Survival* is the internally defined lifecycle profile for vehicle type, *Mileage* is the annual mileage for vehicle type t in year y, *Fuel Economy* is the specific energy consumption for vehicle t in year y.

3.3.3 Model B Topology Design: a new LEAP ASET transport model

Model B consists of a multi-sectoral demand and emissions model for Ireland covering all sectors of the Irish economy including transport, residential, industry, services, agriculture (energy & non-energy) and electricity generation. The Application Script Editing Tool provides a fundamentally different method for the development of model topology in LEAP. This method does not need to utilise the built-in *Stock-Turnover* methodology or *Lifecycle Profiles,* the advantages of which will be discussed and presented here.

Model topology is designed in ASET and executed within LEAP's API to create the model structure. This thesis includes an example of the script used to generate the transport model topology utilised within this study (Appendix F – ASET model topology script). This structure is appropriate to accommodate data relating to vehicle fuel type, engine size (cc), vintage and On-Road Factor (ORF). ORF is defined as the the difference between actual and test emissions for road vehicles. Equation 3-3 builds on Equation 3-2 by explicitly including ORF in the energy consumption calculation. ORF is separately included as a key assumption for the purpose of conducting sensitivity analysis on this variable.

$$EnergyConsumption_{t,y,v} = Stock_{t,y,v} * Mileage_{t,y,v} * (FuelEconomy_{t,y,v} * ORF)$$

$$Demand_{t,y} = \sum_{y=0..v} EnergyConsumption_{t,y,v}$$

Equation 3-3 ASET energy consumption calculation

Where, *t* is the vehicle type, *v* is the vintage year (0…25), y is the year, Mileage is the annual mileage for vehicle type t in year y, Fuel Economy is the specific energy consumption for vehicle t in year y. ORF is the difference between actual and test fuel economy (% change in energy intensity).

Stock calculations were managed exogenously using the sectoral specific transport model (H. Daly and Ó Gallachóir 2011). As large volumes of data can be readily inserted into the LEAP model using ASET, there was no need to simplify the model description of lifecycle behaviour in LEAP. Insert statements were generated within ASET and links to the exogenous database (excel) are created to populate all expression values within the LEAP model. It was necessary within Model A to mimic the behaviour of the exogenous private passenger transport model data in such a way that it functioned within LEAP. Model B however utilises this rich data source directly, using model outputs from one model as model inputs into Model A. Controlling the insert/ update functionality externally also allows for the execution of sensitivity analysis of key variables.

3.4 Results: Limitations and Advantages of each method

The chosen example highlights the relative advantage in using ASET to construct/ update the LEAP transport model as it allows the new method to go beyond the limitations associated with the built-in UI features of Model A. LEAP lifecycle profiles do not allow older vintages to contain greater numbers in future years. In practice this is necessary to simulate the import of older vehicle vintages into the transport system in new year's e.g. 2018 import vehicle registered for the first time in 2021 should function with older vintage characteristics. In Ireland, there is a need for the ability to properly account for new imports of vehicles given the close link with the UK private vehicle sector. In 2018 there were 99,456 imported second-hand vehicles into Ireland. It is expected that in 2019 there will be more second hand imports than new vehicle sales (CMM 2019). At present the lifecycle profiles in Model A do not adequately account for vehicle imports and as such overlook an import policy lever which is necessary in national energy demand/ emissions modelling for Ireland. The ASET method allows all[9] data expressions in the LEAP transport sector to be updated in seconds – aiding in the efficient completion of scenario analysis. Appendix G – LEAP UI and ASET model topology comparison contains a side-by-side comparison of the tree structures used within LEAP Model A and Model B.

In addition to the rapid development of model structures and updating data, ASET also facilitates sensitivity analysis of key variables in LEAP through the execution of an ensemble of scenarios. To demonstrate this feature, Figure 3-4 shows the results from varying the reference ORF (16%) within model B between 0% - 40%, in step intervals of 0.5%. Simulation of ORF has a direct impact on the energy/emissions intensity of each vehicle type – these results provide a range of scenario results, providing a *solution space* for energy demand and emissions results. This can be used to identify emission reduction target scenarios and provide insight into the level of effort required

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[9] 2246 data expressions per scenario across environmental loading factors, final energy intensity and activity levels for each vehicle type and vintage.

to reach a specific target. The shaded area around the reference scenario in Figure 3-4 represents calculated scenario results for the range of ORF values. Increasing the ORF to 40% results in a ~20.6% increase in energy demand and GHG emissions for private vehicle transport relative to the reference scenario.

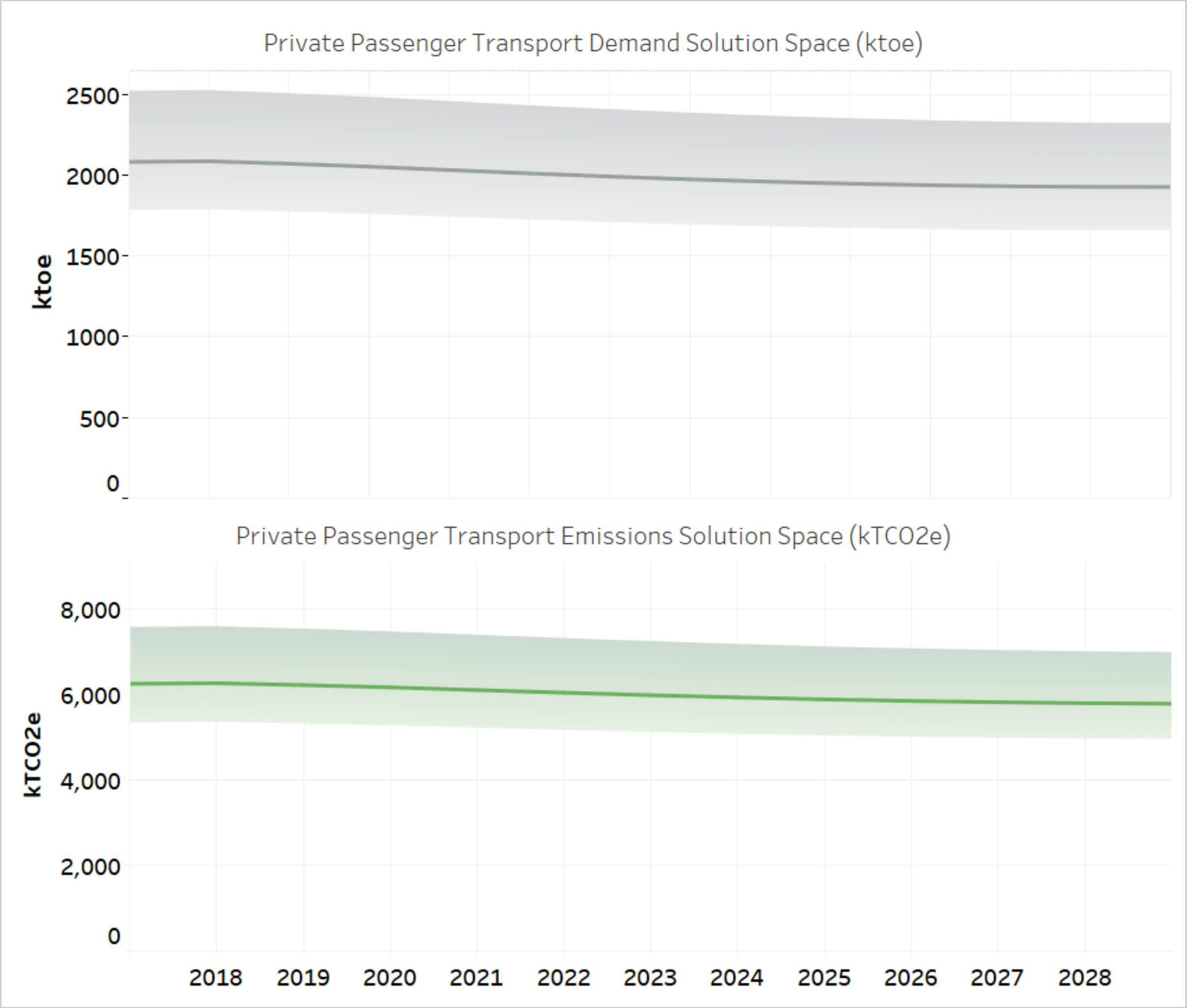


Figure 3-4 Model B: LEAP ASET Results- Private passenger transport multiple scenarios, demand (ktoe), emissions (ktCO2eq)

Figure 3-4 is representative of energy demand (ktoe) and emissions ($kTCO2_{eq}$) for private passenger transport multiple scenario analysis in the LEAP Ireland GHG model The results show a solution space for demand and emissions based on varying On-Road Factor in key assumptions using ASET.

3.4.1 Model framework evaluation and comparison

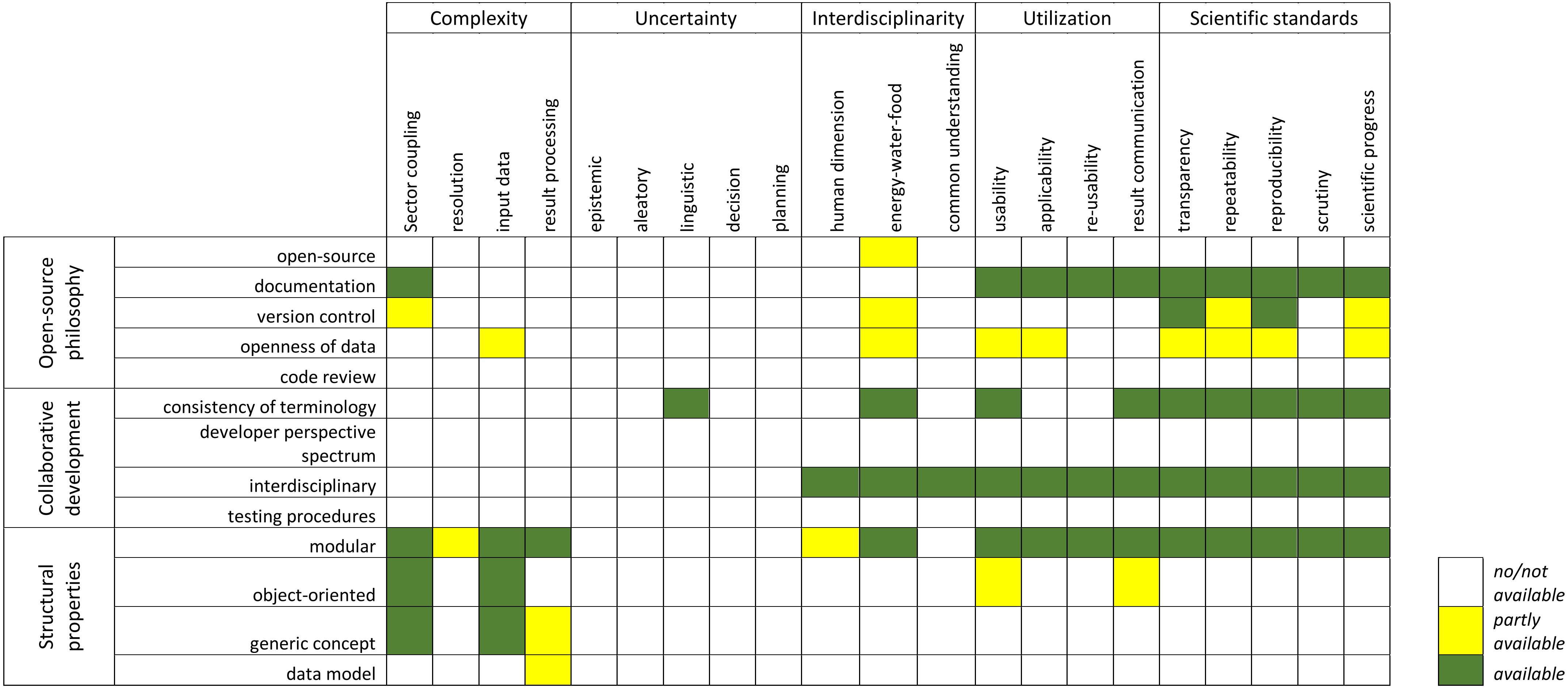
Completing *Table 3-2* for both LEAP and ASET provides insight into the additional functionality added and the added value which ASET provides in the context of addressing the modern challenges presented to energy system modelling frameworks. Table 3-4 completes a detailed breakdown (for LEAP) of the applicability of open-source philosophy, collaborative development, and structural properties as they apply to five key challenges facing energy system models in the 21st century. It is challenging to separate the modelling characteristics of ASET from LEAP as it naturally inherits all functionality from LEAP itself. Table 3-5 completes the same detailed breakdown, applied to ASET, with a focus on making the distinct contribution of ASET clear. Examining each of the framework properties described by Wiese et al., shows the contribution which ASET makes to the LEAP modelling platform and allows for the tool to be considered in the broader context of its contribution towards the challenges facing modern energy system models.

The ASET tool encourages an open-source philosophy as the tool is freely available to the modelling community and the underlying scripts can be scrutinised. While the tool relies on the use of the LEAP modelling software, it facilitates an opportunity for interdisciplinary “add-ins” to the established software. Making the ASET model freely available is a basic precondition for transparency, and it encourages scientific scrutiny and progress.

The ASET tool improves the structural properties of LEAP. Its flexibility to rapidly develop model topologies, significantly enhances the model’s capacity to adapt and incorporate new data sources. In practice, this flexibility can allow the redevelopment of a LEAP models data structure, soft-linking it with other energy system models in a timely fashion. ASETs modular design means that new features can be added to LEAP, independent from each other, facilitating new users to build upon this framework in the development of new bespoke modelling tools and features. At present the ASET tool is written in VBA and requires MS Excel to function correctly. Redevelopment of the functionality within a platform-independent software would increase the usability of the model and encourage more people to work with the code.

The features included in the ASET tool facilitate the inclusion of more complex data structures, reduce the time taken to complete an energy system model, and provide a means to conduct sensitivity analysis of key variables, improving LEAPs capacity to handle model uncertainty. The utility of the existing LEAP model is also improved as these new features present an improvement in model usability, applicability, and re-usability. When considered together, these aspects of the ASET tool improve the scientific standard of the LEAP modelling platform. Table 3-5 also serves to highlight areas within ASET which need to be improved, especially in the documentation of ASET functionality and results handling.

The Wiese evaluation approach also serves to highlight areas in which the ASET tool can be developed further. Firstly, improved documentation on the applicability and reusability of the tool will further enhance the transparency and reproducibility of any modelling results obtained using ASET. Seeking out further collaborative development from a wider range of researchers will improve the interdisciplinary aspects of the modelling tool and guard against relevant features being overlooked in the tool’s future development. This can be achieved through sharing the underlying code online.



		Complexity				Uncertainty					Interdisciplinarity			Utilization				Scientific standards				
		Sector coupling	resolution	input data	result processing	epistemic	aleatory	linguistic	decision	planning	human dimension	energy-water-food	common understanding	usability	applicability	re-usability	result communication	transparency	repeatability	reproducibility	scrutiny	scientific progress
Open-source philosophy	open-source											🟨										
	documentation	🟩												🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	version control	🟨										🟨						🟩	🟨	🟩		🟨
	openness of data			🟨								🟨		🟨	🟨			🟨	🟨	🟨		🟨
	code review																					
Collaborative development	consistency of terminology							🟩				🟩		🟩			🟩	🟩	🟩	🟩	🟩	🟩
	developer perspective spectrum																					
	interdisciplinary										🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	testing procedures																					
Structural properties	modular	🟩	🟨	🟩	🟩						🟨	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	object-oriented	🟩		🟩										🟨			🟨					
	generic concept	🟩		🟩	🟨																	
	data model				🟨																	

☐	*no/not available*
🟨	*partly available*
🟩	*available*

Table 3-4 LEAP: mapping challenges with model properties and characteristic

		Complexity				Uncertainty					Interdisciplinarity			Utilization				Scientific standards				
		Sector coupling	resolution	input data	result processing	epistemic	aleatory	linguistic	decision	planning	human dimension	energy-water-food	common understanding	usability	applicability	re-usability	result communication	transparency	repeatability	reproducibility	scrutiny	scientific progress
Open-source philosophy	open-source			🟩										🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩
	documentation													🟩	🟨			🟨	🟨	🟨		
	version control													🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩
	openness of data																					
	code review													🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩
Collaborative development	consistency of terminology							🟩						🟩				🟩	🟩	🟩	🟩	🟩
	developer perspective spectrum																	🟨			🟨	🟨
	interdisciplinary													🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	testing procedures													🟨	🟨	🟨						
Structural properties	modular	🟩	🟨	🟩		🟨	🟩							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	object-oriented	🟩		🟩										🟨					🟩	🟩	🟩	🟩
	generic concept																					
	data model																					

☐	*no/not available*
🟨	*partly available*
🟩	*available*

Table 3-5 ASET: mapping challenges with model properties and characteristic

3.5 Discussion

Many of the institutions in developing countries who are charged with conducting energy planning face critical shortages of institutional expertise, or lack access to the types of detailed data needed to conduct credible GHG mitigation analyses (Pye and Bataille 2016). In particular, while it is relatively straightforward to develop aggregate modelling based on top-down energy statistics (of the type most countries record in their energy balances), creating a long-range GHG mitigation strategy requires more detailed end-use oriented data and forward-looking scenarios describing possible technology shifts and evidence-based policy advice. LEAP can help overcome some of these barriers because it is freely available, flexible and user-friendly and so is suitable for use by energy and environmental planners rather than by dedicated expert energy modelers, who tend to be rare in many countries. Nevertheless, most countries still face huge capacity building needs to be able to develop and maintain detailed and credible mitigation analyses of the type that are needed if they are to form a credible basis for serious climate action.

The ASET tool has been designed to enable users to access the VBS scripts generated as a direct result of their chosen model structure. To effectively run their scripts, users must access them from within the API, exposing the modeller to the required syntax (VBS) and the API itself. The number of API functions which are currently leveraged by ASET are limited to those related to the two-objective function of the tool i.e. rapid model development and sensitivity analysis. The ability to understand the sensitivity of changes to key assumptions is important to any energy system model. The current LEAP GUI does not natively support the means to conduct sensitivity analysis of key assumptions in the same way ASET does. (Laugs and Moll 2017) highlight the need for a much broader range of energy scenarios which represent more “*extreme representation*” of scenarios to remove the risk of a bias towards the status-quo when utilising energy system models for evidence-based decision making and policy support. The sensitivity analysis added to LEAP via ASET shows the value in displaying a broader range of scenario results. The API is a flexible resource which can control the automation of most functions in the LEAP-GUI. The two functions available within ASET serve as examples of the new functionality which can be developed using the API, when combined with another scripting language such as VB and excel. Further plans to expand the controls within ASET to include more advanced functionality are being explored in line with the final column shown in Figure *3-2*.

It is intended that the transparency of this process will facilitate new useful functionality and provide users with an in depth understanding of the scripting capabilities of LEAP, cultivating learning in each user and contributing to the on-going improvement of the scientific standards within the energy modelling community.

3.5.1 Next Steps

The ASET tool leverages a limited subset of existing API functions to produce the distinct functionality described in the methodology. The API includes many more functions than those utilised in ASET (see Appendix D – Application Programming Interface command set for ASET), hence the ASET tool can be expanded to include much of this functionality to further automate LEAP, as outlined in **Error! Reference source not found.**. Work is ongoing to expand ASET to allow for multiple key assumptions to be varied using controlled distribution functions, effectively allowing for Monte-Carlo analysis in LEAP, through ASET. It is also intended that the feedback from the LEAP user community will assist in identifying key API functionality that can be included in future versions of ASET.

Planned expansion of ASET functionality also includes the ability to enter existing LEAP functions as model inputs, in place of explicit figures e.g. growth, interp functions which are specific to the LEAP model. While ASET already provides modelling outputs in a structured order – a new means of rapidly processing and visualising large result data sets is also being explored. This ability to quickly process results will become more important as the scope of the ASET tool evolves. It is important that the documentation of the ASET tool is also improved to facilitate the inclusion of the broader modelling community in the process of replicating and improving the ASET tool and any subsequent features included in its development.

3.6 Conclusion

ASET adds value to the existing Low Emissions Analysis Platform by providing additional functionality previously unavailable within LEAP. ASET presents a shallow learning curve and users are provided with an introduction to the means of unlocking advanced scripting capabilities within LEAP. Two distinct features provided with this method aid in unlocking the API feature which is already available within the existing LEAP tool, improving the open-source property of the model by improving transparency and replicability of new modelling features in an established modelling framework.

The existing LEAP Application Interface (API) is an underutilised resource within the context of LEAP and the wider energy modelling community. The ASET tool provides a link between the existing LEAP GUI functionality and the inherent advantages associated with programmatically controlling an energy system model. ASET effectively operates as a translator between the end-user and LEAP's API, delivering two new distinct functions without the need for any scripting knowledge of VBScript. This allows users to create and alter model structures and execute sensitivity analysis. The ability to rapidly modify model topology allows users to incorporate new data sources and update data expressions in a timely fashion. In practice, this method reduced the time required to generate a model topology, populate all data, and complete sensitivity analysis, reducing weeks and months to hours and days. This additional functionality of ASET helps to bridge the gap between a range of agents. Model developers benefit from a new, rapid method to build models and conduct sensitivity analysis. Key assumptions are entered explicitly within LEAP and are clearly visible in ASET. While this is a requirement of ASET, it also improves model transparency as all key assumptions are readily visible to the model users, improving their understanding of the model assumptions. Decision-makers benefit from additional evidence-based support on a single modelling platform, LEAP. While this tool provides new functionality, it also functions as a capacity building tool for new users to learn about the API and the complete range of functions which are available within the existing LEAP-API. The generated VBS scripts remain accessible within ASET to provide insight into API functionality and syntax.

The range of energy modelling tools which exist is extensive. Each tool is different in scope, underlying methodology and area of focus i.e. what research questions the model can answer. Section 3.2 reviewed the current literature on model classification and a qualitative method for evaluating modelling frameworks. The added benefits of ASET are explored in section 3.4 and the *evaluation framework* is also utilised to guide areas of future research which will improve the ASET tool and contribute further to the improvement of scientific standards.

Section 3.3 highlights the added value which sensitivity analysis can add to a result set, the range of scenario results presents a complete solution space which can be utilised to explore alternative policy pathways and GHG mitigation targets. The set of scenarios show that a change in ORF (0 – 40%), provides a range of results with respect to final energy demand and GHG emissions. The ensemble of simulations shows a variability of ±20%, relative to the reference scenario, depending on the ORF utilised. LEAP is an exploratory simulation modelling tool which can provide useful insights into the technical potential of GHG mitigation policy pathways. The ASET tool is designed to support the exploratory capacity of the modelling tool through this new functionality. In isolation this new functionality provides additional capabilities to the LEAP modelling tool. However, in the broader context of energy system modelling, ASET presents a means of developing new modelling techniques to aid in advanced scenario development and improve insights into specific research questions.

4 Improving energy savings from a residential retrofit policy – a new model to inform better retrofit decisions

Abstract

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 heating 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 chapter examines and challenges the suitability of popular retrofit combinations as they apply to nine distinct building archetypes in Ireland's housing stock portfolio. A novel archetype simulation model is used (ArDEM-SQL) to evaluate the potential for improved energy efficiency gains within the existing retrofit program. I 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. I firmly 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.[10]

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[10] Chapter published as Mac Uidhir, T., Rogan, F., Collins, M., Curtis, J., Gallachóir, B.P.Ó., 2020. 'Improving energy savings from a residential retrofit policy: a new model to inform better retrofit decisions' Energy and Buildings (doi.org/10.1016/j.enbuild.2019.109656)

Keywords: Energy Modelling, Bottom-Up, Simulation Modelling, Energy Efficiency, Retrofit Policy, Dwelling Archetype, Retrofit Choices

4.1 Introduction

In 2012 the European Union (EU) implemented the Energy Efficiency Directive (EED), which provides for a “common framework to promote energy efficiency” within the EU. This directive set an EU wide target of 20% energy savings, with respect to projections for energy consumption in 2020, as a direct result of energy efficiency measures. The EED identified the existing building stock as the “single biggest potential sector for energy savings” and noted that the rate at which building retrofits are taking place needs to increase (EU Parliament 2012). In 2018, the Directive was amended to include a headline energy efficiency target for 2030 of at least 32.5%.

Each member state set their own energy efficiency target with a requirement to produce a National Energy Efficiency Action Plan (NEEAP), updating this document every 3 years. These NEEAPs outline each member state’s actions to improve energy efficiency and report on progress achieved. Ireland set a national target of improving energy efficiency by 20% by the end of 2020, with respect to average energy consumption between 2001 – 2005, which translates to total energy savings of 31,925GWh by 2020. Ireland’s most recent NEEAP (DCCAE 2017a, 4), released in April 2017, reports achieved energy savings representing 58% of the 2020 target. Energy efficiency improvements from buildings are expected to occupy the largest sectoral share of energy savings in 2020, approximately 29% of estimated total savings. Achieving the 2020 target will require significant additional energy saving (1,904 GWh) from buildings during the period 2017-2020 (DCCAE 2017a). The NEEAP energy efficiency figures highlight the difficulties Ireland faces in achieving its 2020 targets as significant “scaling up” of action across all sectors will be required (SEAI 2016b).

Realising the 2020 targets for energy efficiency will also contribute to likely targets set for the post-2020 period. A proposal for a directive to amend [2012/27/EU] EED sets a 32.5% energy efficiency target for 2030 across EU member states. This ambitious figure highlights the challenge within Ireland's built environment and underpin the motivation behind this analysis to provide insight into improved energy savings from alternative retrofit measures for residential homes while encouraging early action within energy efficiency measures.

Ireland is an interesting case study to investigate residential energy decarbonisation, 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 (SEAI 2018). In 2014, Ireland adopted a national policy position to reduce aggregate CO2 emissions by at least 80% (relative to 1990 levels) by 2050 across electricity generation, built environment and transport sectors (DCCAE 2013). Reflecting this decarbonisation ambition, the National Mitigation Plan (NMP) (DCENR 2017) outlined medium to long term mitigation options within the electricity generation, transport, agriculture and built environment. The NMP highlighted the principle of 'fabric first' for improving the energy efficiency of the existing building stock. This principle requires that there are improvements made to the energy efficiency of a building, such as the installation of insulation and improvements to air tightness, prior to the introduction of less energy intensive renewable sources e.g. electric heat pumps or solar thermal. This is crucial to ensuring that designed levels of comfort and function are maintained within each dwelling while simultaneously lowering the energy demand of the building.

In 2019 Ireland's Climate Action Plan (CAP) increased its decarbonisation ambition to a net-zero emissions target for 2050 (Government of Ireland 2019). Realising this emissions goal will require the rapid decarbonisation of Ireland's built environment, improving the energy efficiency of residential homes and switching to less carbon-intensive fuel sources, while still delivering the same or improved levels of thermal comfort to homes. The CAP highlights the need for increased effort to reduce carbon emissions within Ireland’s built environment and necessitate evidence-based policy support within the sector.

This chapter leverages a detailed archetype energy demand and emissions simulation model of the residential sector to investigate the potential for increased energy savings which can be realised due to different combinations of retrofit measures. I introduce a new methodology that provides insights into sub-optimal retrofit choices by examining the simulated effects of retrofit choice autonomy. A reference scenario includes the combination of retrofit measures which were completed during the period 2010 – 2015, while a second scenario includes the simulated energy savings associated with an alternative set of retrofit combinations for the same period. I have also included an overview of the policy landscape within the existing grant support schemes and used the results from the scenario analysis to offer policy advice and potential improvements to the retrofit scheme. In addition to the methodological innovations, a key contribution from this chapter is the policy insights gained that can have a significant energy efficiency impact.

Ex-post analysis of energy system models which underpin government policy can provide insights into the accuracy of modelling results and aid in guiding future modelling exercises. This type of analysis aids in improving our understanding of the uncertainty associated with model projections in the formulation of new policies. There are examples of differing conclusions in the evaluation of energy efficiency building codes worldwide with (Chan and Yeung 2005) indicating “substantial reduction of energy consumption” associated with the introduction of building energy codes while (Guerra-Santin and Itard 2012) found little/ no correlation between the introduction of a more stringent Energy Performance Coefficients (EPC) and energy consumption, indicating that occupant behaviour may be more important in the context of reducing energy consumption in energy efficient buildings (post retrofit in this context). The diverging conclusions indicate that further investigation into the potential for improved retrofit schemes and future building regulation standards is warranted. While there are examples of ex-post analyses of residential energy efficiency programs in the Irish context (Scheer, Clancy, and Hógáin 2013), (Hull, Ó Gallachóir, and Walker 2009) acknowledge the lack of “consistent ex-ante and ex-post assessment of energy efficiency policies” in Ireland and abroad.

(Swan and Ugursal 2009) provide a review of techniques used in modelling residential energy demand, broadly defining two distinct model classifications, bottom-up and top-down. Bottom-up energy system models can be described as engineering type models which utilise detailed energy performance characteristics of individual dwellings, producing national stock demand through the aggregation of each modelled dwelling. In contrast, top-down energy system models typically utilise macroeconomic drivers such as gross domestic product (GDP) to produce aggregate sectoral energy demand based on the historic link between the macroeconomic variables and demand. The nature of bottom-up energy models means they are typically well suited to investigating the impact of individual energy efficiency policy-measures. In their detailed review of common residential energy demand modelling techniques, (Kavgic et al. 2010) identify the lack of publicly available data relating to inputs and assumptions as a major issue which needs to be addressed. (Dodoo, Yao Ayikoe Tettey, and Gustavsson 2017) define some of the key input parameters and assumptions which significantly effect modelling results for residential buildings, stating the importance of “transparent” and “appropriate” input parameters.

Many alternative methods exist to conduct simulation and optimisation of residential retrofits. (Ma et al. 2012) highlight change in government policy as a key challenge with respect to the retrofitting of existing buildings. An ability to pay for retrofits and successfully incentivise homeowners to improve the energy efficiency of a dwelling is also discussed. Designing sustainable pathways towards delivering substantial retrofitting of existing dwellings remains challenging (Reeves, Taylor, and Fleming 2010) (Y. Xing, Hewitt, and Griffiths 2011). This section combines an ex-post analysis of an existing residential retrofit program with a detailed bottom-up energy system model for Ireland, linking the past performance of a national retrofit program with the detailed energy performance of specific building fabrics. Previous detailed studies have focused on specific building elements e.g. wall type. This study builds on the work of (Dineen, Rogan, and Ó Gallachóir 2015) by extending the range of simulated retrofits to include other options available within the existing retrofit program. This chapter presents a novel ex-post evaluation of the effectiveness of the retrofit program operated by SEAI, highlighting some of the main shortcomings within the existing policy framework, and providing a new means to improve the system going forward based on the proposed methodology. Linking an ex-post analysis with a detailed bottom-up energy system model of the residential sector provides a foundation for the formulation of more robust evidence based retrofit programmes. There is a need for further ex-post analyses of climate policies, proving on-going feedback and evaluation of policy success or failure.

The chapter is structured as follows: Section 4.2 outlines the policy landscape within the existing grant support schemes, highlighting relevant steps within the grant application process which present specific challenges. Section 4.3 presents the methodology and explains the innovation of a new method for analysing larger volumes of data to contribute insights into potential improved energy savings. This includes a detailed description of the disaggregation of the entire building stock into nine distinct archetypes. Section 4.4 provides a breakdown of the data sources utilised as part of the scenario analysis. Section 4.5 presents the results from the scenario analysis while section 4.6 provides a discussion and conclusions including policy insights.

4.2 Policy Landscape: Retrofit Programs

A number of retrofit grant schemes are operated by the Sustainable Energy Authority of Ireland (SEAI). These grants vary in grant allowance and target different household types, Table 4-1 summarises these schemes and indicates the target group and support lifetime for each. This section provides a detailed description of the Better Energy Homes (BEH) scheme, the focus of this analysis.

Scheme Name	**Scheme Lifetime**	**Description**
Better Energy Warmer Homes	2010 - 2019	Delivers free energy efficiency upgrades to homeowners who receive certain welfare pay in dwellings built and occupied prior to 2006.
Warmth and Wellbeing	2016 - 2019	Works on a referral basis, aims to provide extensive free energy efficiency upgrades to homes. Measures include attic/ wall insulation, boiler replacement and window/door replacement where inefficient.
Better Energy Homes	2009 - 2019	Offers a range of retrofit measures with different grant values based on the nature of the retrofit. Scheme supports homeowners to retrofit dwelling – providing approx. 1/3 of total retrofit works as subsidy.
Pilot Deep Retrofit	2016 -2019	Pilot programme targeting less energy efficient dwellings, investigating the challenges and opportunities of deep retrofit.

Table 4-1 SEAI Retrofit grant support schemes, description and support lifetime

The BEH scheme is open to all homeowners and landlords and is not means tested. Broadly the grant is intended to represent one-third of the total cost of retrofit works, although the value of each grant has changed over time as shown in Table 4-2. In December 2011, the fourth evolution of the scheme began to issue different grant values based on the type of home i.e. terraced, detached or apartment. The grants available have continued to be modified under the latest evolution of the scheme, as of April 2018 grants for high-efficiency boiler upgrades have been removed and replaced with a grant for a range of heat pumps.

Measure	**Category**	**Sub-Category**	**Mar-09 €**	**Jun-10 €**	**May-11 €**	**Dec-11 €**	**Mar-15 €**	**Apr-18 €**
Roof	Attic Insulation		250	250	200	200	300	400
Wall	Cavity Insulation		400	400	320	250	300	400
	Internal Insulation		2500	2500	2000	-	-	-
		Apartment	-	-	-	900	1200	1600
		Terraced	-	-	-	1350	1800	2200
		Detached House	-	-	-	1800	2400	2400
	External Insulation		4000	4000	4000	-	-	-
		Apartment	-	-	-	1800	2250	2750
		Terraced	-	-	-	2700	3400	4500
		Detached House	-	-	-	3600	4500	6000
Boiler	High efficiency boiler (oil or gas) upgrade with heating control		700	700	560	560	700	-
	Heating Controls Upgrade Only		500	500	400	400	600	700
Heat Pumps	Air-Water		-	-	-	-	-	3500
	Ground-Water		-	-	-	-	-	3500
	Exhaust Air-Water		-	-	-	-	-	3500
	Water-Water		-	-	-	-	-	3500
	Air-Air		-	-	-	-	-	600
Solar	Solar Water Heating		-	-	800	800	1200	1200
BER	Building Energy Rating		100	100	80	50	50	50
Bonus	3rd Measure		-	-	-	-	300	300
	4th Measure		-	-	-	-	100	100

Table 4-2 SEAI grant value and archetype disaggregation of Better Energy Home Scheme, (2009-2018)

Since June 2010, the BEH scheme has included a mandatory assessment of the building energy performance to be completed after the completion of the grant works. This assessment is known as the Building Energy Rating (BER) and is also subsidised within the grant structure. The BER database gathers detailed energy performance data relating to all types of residential dwellings across a 15-point energy efficiency scale, rated alphabetically from A1 to G. A more detailed description of the relevant BER data utilised as part of this study is provided in section 4.4.

Homeowners decide the specific measures to adopt in private grant applications made through the BEH scheme. Applicants are required to complete a BER assessment after works have been completed as part of the grant scheme, to ensure minimum building standards are achieved. It is not necessary to complete pre-works building energy performance testing before choosing a specific retrofit measure, with the exception of the new heat pump grant.

Therefore, the grant scheme is designed to focus on specific inputs, i.e. retrofit measures, and not outputs, i.e. energy savings. This presents a significant challenge to the grant receiver with respect to understanding the best-suited grant for their specific retrofit needs. The grant application procedure is summarised in Figure 4-1. It is worth noting that step 2, choosing a technical advisor, prior to step 3 engaging a registered contractor, is only required for the heat pump grant at present. The BER assessment and estimation of energy efficiency savings is made after the retrofit work has been completed and before the grant is paid.

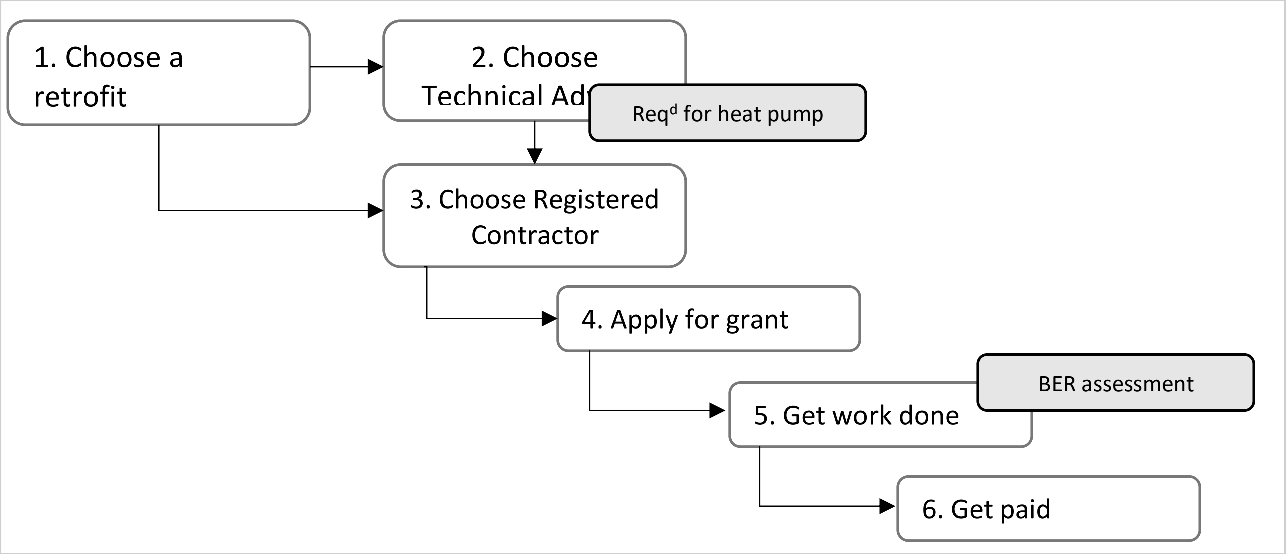

Figure 4-1 SEAI, Better Energy Home scheme, grant application process

The scheme has seen variations in levels of participation and depth of retrofit grants completed due to a number of factors including geographic location, dwelling age, and seasonal trends (M. Collins and Curtis 2016). The BEH scheme has also witnessed fluctuating rates of grant application abandonment (approx. 15% of all first-time applications) as a result of factors such as retrofit complexity, certain combinations of retrofits, and dwelling age (M. Collins and Curtis 2017b).

This retrofit grant scheme represents a complex, ambitious energy saving endeavor which is multifaceted and difficult to analyse. This thesis chapter builds upon previous work to analyse the energy savings potential of Irelands existing building stock (Dineen, Rogan, and Ó Gallachóir 2015), extending the boundary of analysis from wall retrofits to a range of simulated retrofit combinations as outlined in the grant scheme shown in Table 4-2. This contribution allows the broader retrofit program to be simulated and provides additional insights into energy efficiency savings which can be potentially realised.

At present the BEH scheme does not incentivise homeowners to choose retrofit measures which offer the greatest energy savings. This highlights the issue of homeowners not necessarily choosing the best suited retrofit for their dwelling type. There is room to improve building energy efficiency standards in Ireland through the implementation of a bespoke building retrofit grant scheme which more effectively considers the pre-existing condition of a household as part of the initial application process. The process of customising retrofits to homes (by archetype) is intended to address the issue of homeowners choosing suboptimal retrofit measures and hence improve the cost/saving benefits of the overall scheme. This section introduces a new simulation tool and leverages a new data set to demonstrate how improved energy savings can be achieved by matching the appropriate retrofit measure combination to each specified dwelling archetype.

4.3 Methodology

4.3.1 A New Energy Model: simulating energy efficiency savings from retrofits

The newly developed ArDEM-SQL model was utilised to simulate the energy savings associated with a range of retrofit measures. The ArDEM-SQL model is described in detail in section 2.3 of chapter 2. That section describes in detail the modelling inputs, assumptions, and typical outputs.

4.3.2 Building Archetypes and National Stock

The national building stock was disaggregated into nine distinct dwelling archetypes based on the building energy performance certificate or building energy rating (BER). For the purposes of this analysis, each dwelling was divided into three categories (low, medium, high) based on the BER alphabetic labelling system AB, CD and EFG. Each energy performance label is further subdivided by dwelling type i.e. terraced, detached and apartment. Energy demand for each archetype was calculated using the ArDEM-SQL model.

Data on the housing stock is taken from two sources. Detailed data on housing characteristics is taken from the BER database. Central Statistics Office (CSO) Census data (CSO 2016) was used to weight the BER data to ensure the analysis is representative of the national housing stock. The year of construction was used to weight the total number of each dwelling archetype as they appeared in the BER database. A detailed description of the data utilised from the CSO and BER databases is provided in section 4.4.

Building archetype stock and demand are combined to estimate total primary and final energy consumption (kWh/annum). Figure 4-2 shows a flowchart of the steps used to calculate total demand for a chosen energy efficiency measure using this methodology. The flowchart shows the process for calculating the stock and energy demand for each archetype.

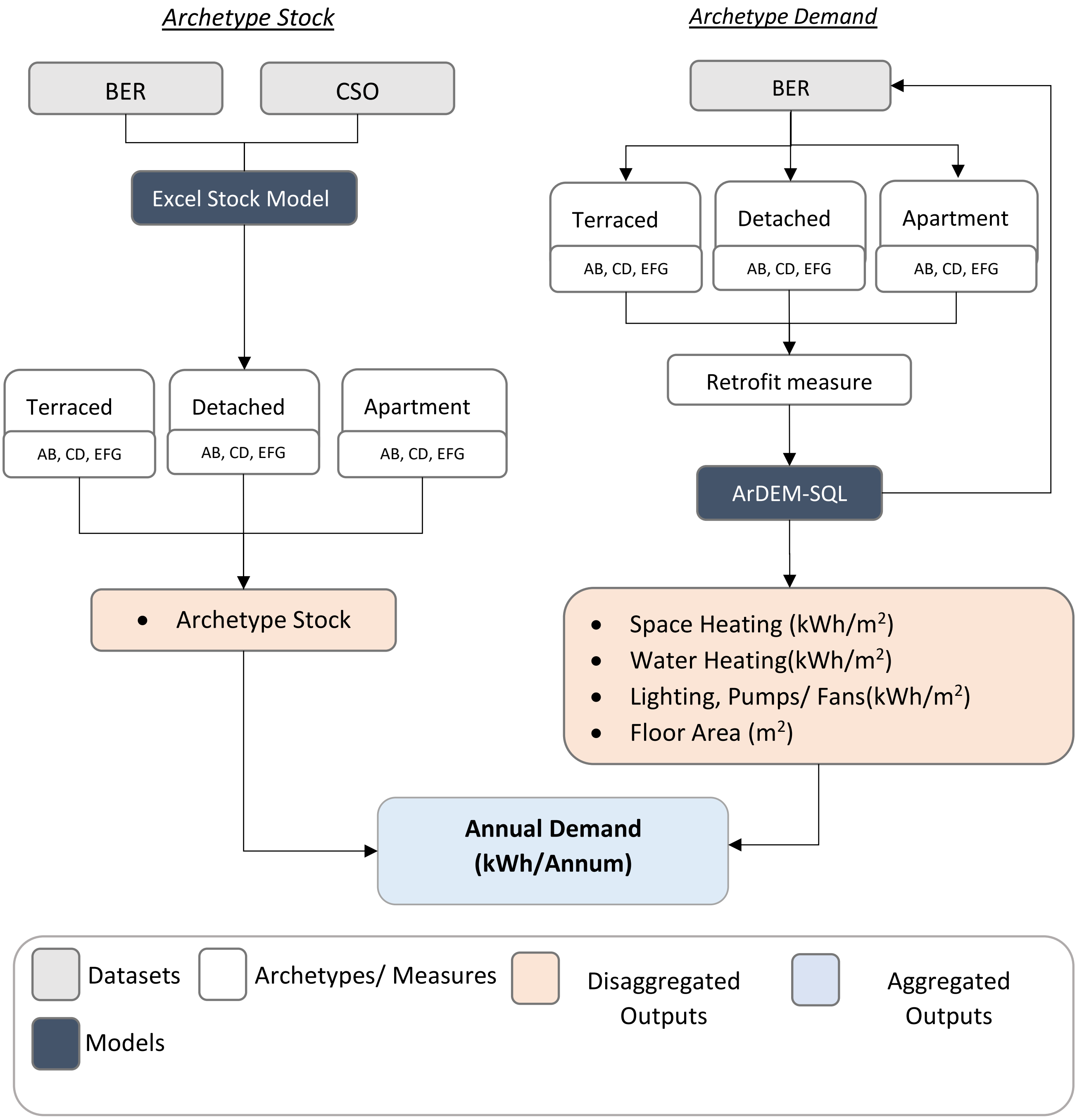

Figure 4-2 New methodological workflow to calculate annual energy demand and emissions of residential sector using ArDEM-SQL, Ireland

4.3.3 Retrofit Measures

The range of retrofit measures chosen to establish the current baseline scenario of the retrofit program are in line with the available grants at the time of the analysis, while alternative retrofits are consistent with the five most common retrofit combinations undertaken during the period 2010-2015. Simulating the potential energy savings from the retrofit scheme was dependent on modelling the total building stock and final energy demand for each building archetype.

The alternative retrofit scenario (alt scenario) is comprised of the retrofit measure which yielded the greatest energy savings for each building archetype {chosen from the five most common retrofit combinations}, while the baseline scenario consists of the actual retrofit measures that were applied during the period 2010-2015. The difference in total energy savings between these two scenarios is then compared to determine the additional energy savings potential which can be realised through the implementation of bespoke retrofits based on building archetype.

Calculating final energy demand (Equation 4-1) and energy savings by retrofit combination (Equation 4-2) is completed by multiplying the total number of each archetype home by the energy demand of that archetype.

$$D_T = \sum_{k=1}^{n} (A_k I_k)$$

Equation 4-1 Total Energy Demand, residential housing stock

where, D_T is the Total Energy Demand, n is the total number of archetypes, A_k is the Frequency of each archetype, I_k is the Energy Intensity of each archetype

$$D_M = \sum_{k=1}^{n} (A_k I_{ki} - A_k I_{kT})$$

Equation 4-2 Total retrofit energy savings, total retrofitted stock where, D_M is the Energy Savings by retrofit measure (M), n is the total number of archetypes,

A_k is the Frequency of each archetype dwellings eligible for retrofit measure, I_{ki} is the Pre-retrofit archetype energy intensity, I_{kr} is the post-retrofit archetype energy intensity

4.3.4 Retrofit measures and rebound effect

This methodology assumes some standardised energy consumption level and occupancy using the ArDEM-SQL modelling calculations. The ArDEM-SQL model includes default information relating to lighting energy consumption (9.3 kWh/m^2 year). Occupancy is defined as a function of total floor area (TFA), measured in square metres (m^2). Equation 4-3 shows the relationship between TFA and dwelling occupancy.

$$\text{if TFA} <= 333 \text{ then; } R = 0.033*\text{TFA} - (0.000036*(\text{TFA}))^2$$
$$\text{if TFA} > 333 \text{ then; } R = 7$$

Equation 4-3 Occupancy Calculation - ArDEM-SQL

where, *R* is the Occupancy, *TFA* is the Total Floor Area (m^2)

While the simulation can be modified to adjust target internal temperature; hence calculating the impact on savings potential due to increased thermal comfort, it is important to note that these additional calculations are not considered as part of this study. The precise definition of rebound effect is not always clear, especially in the context of thermal retrofits. Galvin (2014) explores the terminology inaccuracies associated with the rebound effect in academic policy literature. Galvin identifies three main definitions of rebound, including classic, the energy savings deficit, and the energy performance gap, noting that the mathematical formulation of each can lead to a range of a 29.9% to 66% across different retrofit examples. There is no way to “convert” different mathematical representations between one another and hence it is important that any comparison of rebound, within the context of thermal retrofit measures, is conducted using the same mathematical formulation. Sorrell et al. (2009) conducted a review of empirical estimates of the "direct rebound effect", defined as the increased energy consumption (post-retrofit) which offsets the energy savings which may otherwise have been achieved. Sorrel et al. conclude that while the rebound effect is likely less than 30% (for household service demands within the OECD), sufficiently accurate data on energy consumption, and energy efficiency are a pre-requisite to the accurate determination of the rebound effect, resulting in *inconsistent* estimates for the rebound effect. All references to rebound effect (RE) within this study define RE as the "shortfall" in energy reduction, relative to expected energy savings resulting from a specific retrofit measure, as defined by Haas et al. (2000), represented by Equation 4-4.

$$RE = \frac{F}{\Delta D}$$

Equation 4-4 Rebound Effect - Reduction in expected energy efficiency savings potential

where F is the shortfall in energy savings, ΔD is the expected energy savings

This study acknowledges that while the methodology is used to consider behaviour with respect to retrofit choice, it does not consider the rebound effect as it applies to shortfall in energy savings due to behaviour. The rebound effect has no impact on these results, as it is assumed that the dwellings will take back some of the energy savings regardless of the retrofit choice and it is the relative difference between the two scenarios which quantifies the potential savings possible due to alternate retrofits. There was insufficient data to make any reasonable connection between the scale of rebound effect as it applies to different combinations of retrofits, hence it is not considered as part of this study. Future monitoring of pre/ post-works energy consumption would aid in filling this knowledge gap and understand the impact of rebound effect within the retrofit policy.

4.4 Data

Dwelling energy performance data was taken from the Building Energy Rating (BER) database. The BER database represents all types of residential dwellings across a 15-point energy efficiency scale, rated alphabetically from A1 to G. Energy performance within each building is rated in units of $kWh.m^{-1}.year^{-1}$. All homes which are being sold or rented are subject to a BER assessment and are subsequently recorded in the database, which is constantly growing and updating. The BER database contains 11 distinct building type descriptions including {End/Mid-terrace house, Semi-detached house, Top/Middle/Ground Floor apartment, Apartment, Detached house, Basement Dwelling, House, Maisonette}. The public database includes 139 details associated which each of the 735,906 records [11].

Since June 2010, the Better Energy Home (BEH) scheme has mandated an ex-ante BER assessment. While assessing this post-works BER (PWBER), an independent assessor will also estimate a pre-works BER. This is based on re-entering values for any parameters affected by the retrofit works according to information provided by the contracted worker who installed the works or, if not provided, estimates based on standard values for the building's year of construction. The BER database is administered by SEAI. It is publicly available for download for research purposes. While the PWBER database is effectively a subset of the BER database, it is not publicly available outside of the BEH register.

Data for the period 2010-2015 from the PWBER database has been utilised as part of this study to define retrofit combination frequency in the baseline scenario. Table 4-3 shows the percentage share of retrofit combinations which were completed within the PWBER data. In total there are approx. 112,000 PWBER records across all received retrofit combinations. The 5 most frequent combinations are considered as part of this analysis; these include, Attic and Cavity insulation, Boiler with heating

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[11] BER records accessed 1/8/2018

controls (w/ HC), External Wall insulation, Solar thermal, Attic and Cavity insulation and Boiler w/ HC. These 5 combinations account for 84% of all analysed retrofit combinations within the PWBER data.

Retrofit Combination, All Archetypes	Total Records	% Share	Retrofit Combination, All Archetypes	Total Records	% Share
Attic + Cavity	57542	51.37%	Attic + Cavity + Boiler + Solar	177	0.16%
Boiler w/ HC	20649	18.44%	Attic + Internal + Boiler + Solar	172	0.15%
External Wall	7385	6.59%	Attic + External + HC only	120	0.11%
Solar	5859	5.23%	Attic + Cavity + Solar	99	0.09%
Attic + Cavity + Boiler	2652	2.37%	Internal + HC only	84	0.07%
Attic + Internal	2321	2.07%	Attic + External + Boiler + Solar	72	0.06%
HC Only	2297	2.05%	External + HC only	71	0.06%
Attic + External	2033	1.82%	Attic + Cavity + HC only + Solar	70	0.06%
Attic + Boiler	1667	1.49%	External + Boiler + Solar	65	0.06%
Attic + Cavity + HC only	1297	1.16%	Attic + Solar	46	0.04%
Internal	1155	1.03%	Cavity + Boiler + Solar	38	0.03%
Attic + Internal + Boiler	1063	0.95%	Internal + HC only + Solar	37	0.03%
Attic	983	0.88%	Cavity + Solar	31	0.03%
Cavity	933	0.83%	External + Solar	30	0.03%
Boiler + Solar	674	0.60%	Attic + Internal + HC only + Solar	27	0.02%
Cavity + Boiler	430	0.38%	Attic + Internal + Solar	16	0.01%
Attic + HC only	409	0.37%	Cavity + HC only + Solar	14	0.01%
Attic + External + Boiler	381	0.34%	Attic + External + HC only + Solar	12	0.01%
Internal + Boiler w/ HC	318	0.28%	External + HC only + Solar	11	0.01%
Attic + Internal + HC only	285	0.25%	Attic + External + Solar	9	0.01%
External + Boiler	281	0.25%	Internal + Solar	7	0.01%
Cavity + HC only	185	0.17%	Internal + Boiler + Solar	0	0.00%

Table 4-3 SEAI Better Energy Homes, Retrofit combination frequency – post-works BER data

In each case the grant provider, SEAI, requires that a minimum set standard is achieved for each retrofit (SEAI 2019a). These minimum standards and specification are used in the simulation, Table 4-4 shows this minimum standard.

Retrofit Measure	***Standard Target***	***Unit***
Attic Insulation	0.16	W/m^{2}K
Cavity Wall Insulation	0.27	W/m^{2}K
External Wall Insulation	0.27	W/m^{2}K
Internal Dry Lining	0.27	W/m^{2}K
Boiler and Heating Controls	90	%
Heating Controls	-	NA
Solar Heating	10	kWh/m^2.yr

Table 4-4 SEAI, Target U-Value and efficiency improvement minimum standards in simulation

These figures are used in ArDEM-SQL to simulate the improvement of building fabrics for each archetype. Boiler and Heating control upgrades are modelled differently in ArDEM-SQL by altering a combination of control variables in the SQL script. The ArDEM-SQL model uses a variable for heating system efficiency, hence simulating an upgrade requires that this figure be replaced with the 90% efficiency standard rating. To simulate the upgraded heating controls, there is a 20% reduction implemented to the variable which represents the number of unheated hours per annum in the ArDEM-SQL model. This figure can be changed in alternate simulations but is consistent throughout all simulations identified here.

4.4.1 Central Statistics Office

Statistics on the total number of each dwelling type are provided by the Central Statistics Office' (CSO) national census of population. The database contains 5 distinct building type descriptions including {Terraced, Semi-detached, apartment in purpose built-block, apartment in converted house/commercial building, detached house}. The census data is publicly available online (CSO 2016).

4.4.2 Model Calibration: Archetype Stock

The building type descriptions as they appear within the BER database were matched with the definitions in the 2016 CSO data (CSO 2016) using the mappings described in Table 4-5. For the purposes of this analysis “Basement Dwelling”, “House”, “Maisonette” descriptions are not considered, as the ambiguous naming convention means they cannot be readily categorised in line with data available from the CSO. At the time of writing, these three excluded housing types account for 46,661 records, approximately 6% of the total 735,906 records contained within the BER database.

BER House Type	CSO House Type	ArDEM Output
End of terrace house Mid-terrace house Semi-detached house	Terraced House Semi-detached house	Terrace
Top-floor apartment Mid-floor apartment Apartment Ground-floor apartment	Flat or apartment in a purpose- built block Flat or apartment in a converted house or commercial building	Apartment
Detached house	Detached House	Detached
Basement Dwelling House Maisonette	N/A	

Table 4-5 House type definition and aggregation by data source

Each housing type is then further disaggregated by BER grouping (AB, CD, EFG). These BER categorisations broadly represent low, medium, and high energy performance buildings and simplify the results to gain a clearer understanding of the effectiveness of the retrofit program.

Both the BER and CSO databases contain data regarding the year of construction for each archetype which can be used to estimate the total number of chosen dwelling archetypes at a national level. This is achieved by first dividing the chosen archetype set (Detached, Terrace, Apartment) within the BER database into the same year of construction bands that exist within the CSO database. Figure 4-3 shows the frequency distribution of house types (Apartment, Terraced, Detached) as they appear in both the BER and CSO databases, while Figure 4-4 shows the distribution by year of construction.

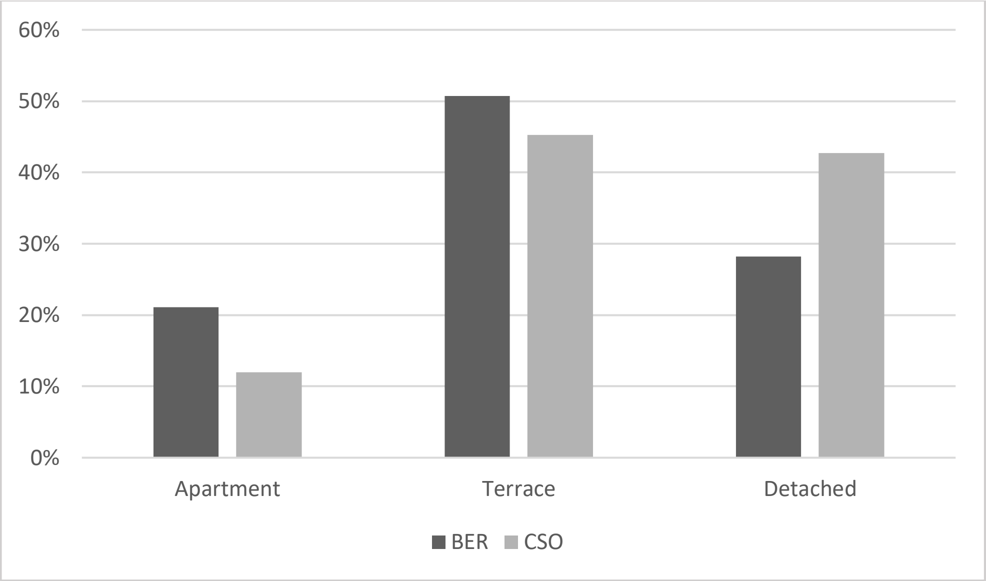

Figure 4-3 Frequency distribution by house type, BER versus CSO

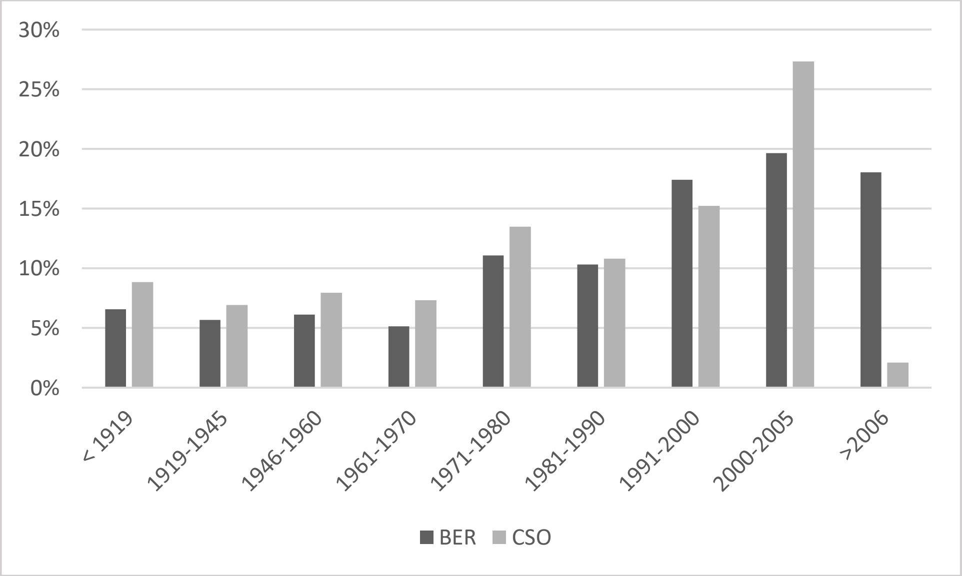

Figure 4-4: Frequency distribution by year of construction, BER versus CSO

The number of dwellings by year of construction within the BER database (B_y) is then scaled to align with the total number of dwellings as they appear in the CSO dataset (C_y) – for each archetype. Equation 4-5 describes the scaling factor (S_y), used for each year of construction bracket.

$$S_y = \frac{C_y}{B_y}$$

Equation 4-5 National Scaling Factor, BER to CSO

Within each year of construction band, and building type (from the BER database), the total number of AB, CD and EFG dwellings are then scaled by this factor Sy. This obtains the total number of dwellings which exist within each building archetype. Equation 4-6 calculates the total number of archetype dwellings (A_k) within each year of construction bracket.

$$A_k = S_y * B_{yarc}$$

Equation 4-6 Number of archetypes dwellings by year of construction

, where A_k= Frequency of each archetype, S_y = Scaling Factor, B_{yarc} = Number Dwellings by BER category

A_k= Frequency of each archetype

Figure 4-5 shows the aggregated BER grades by archetype building once the process of calibrating the national stock figures is complete. These numbers represent the A_k variable in Equation 4-1, Equation 4-2.

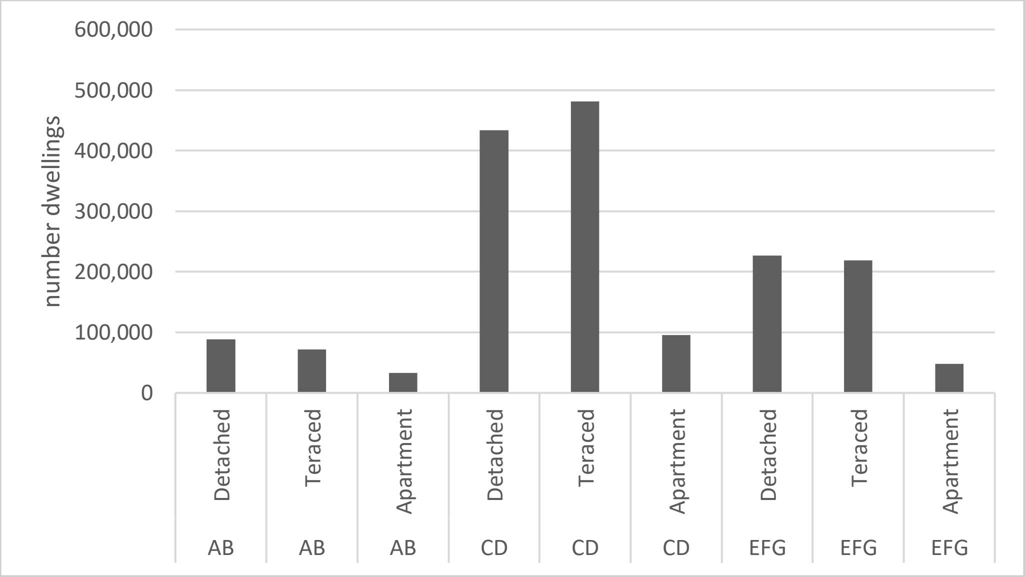

Figure 4-5 Aggregated number of dwellings by archetype

4.4.3 Model Calibration: Archetype demand

The ArDEM-SQL model was calibrated to data recorded as part of the PWBER requirement for each retrofit completed within the BEH scheme. A relative comparison of each BER grade was simulated in ArDEM-SQL and compared to the PWBER energy savings data. ArDEM-SQL was adjusted accordingly to more accurately simulate the energy savings associated with each energy saving measure. This process is illustrated in Figure 4-6 where the energy savings of each BER group have been compared for a range of retrofit combinations. The model calibration was completed for each archetype specified.

There are no records in the PWBER database related to the archetype AB-Apartments, for external wall, Attic & Cavity & Boiler w. Heating controls or Solar water heating retrofit combinations. Hence the energy savings shown in Figure 4-6 are estimates based on the ArDEM-SQL model for this archetype. Differences within EFG categories are likely due to the unbounded nature of G-rated dwellings. While all other BER energy consumption ranges are bounded, G-rated classifications are defined as dwellings with annual energy consumption greater than 450 kWh/m^2.annum. The BER database contains 52,592 records of G-rated dwellings, representing 29% share of total EFG records. The average value for a G rated dwelling is 650 kWh/m^2.annum. It is worth noting that the large difference in estimated energy savings for EFG_Apartments which received a solar water heating retrofit is likely due to the small sample set within the PWBER data as only 2 records exist for EFG_Aptartment solar water heating.

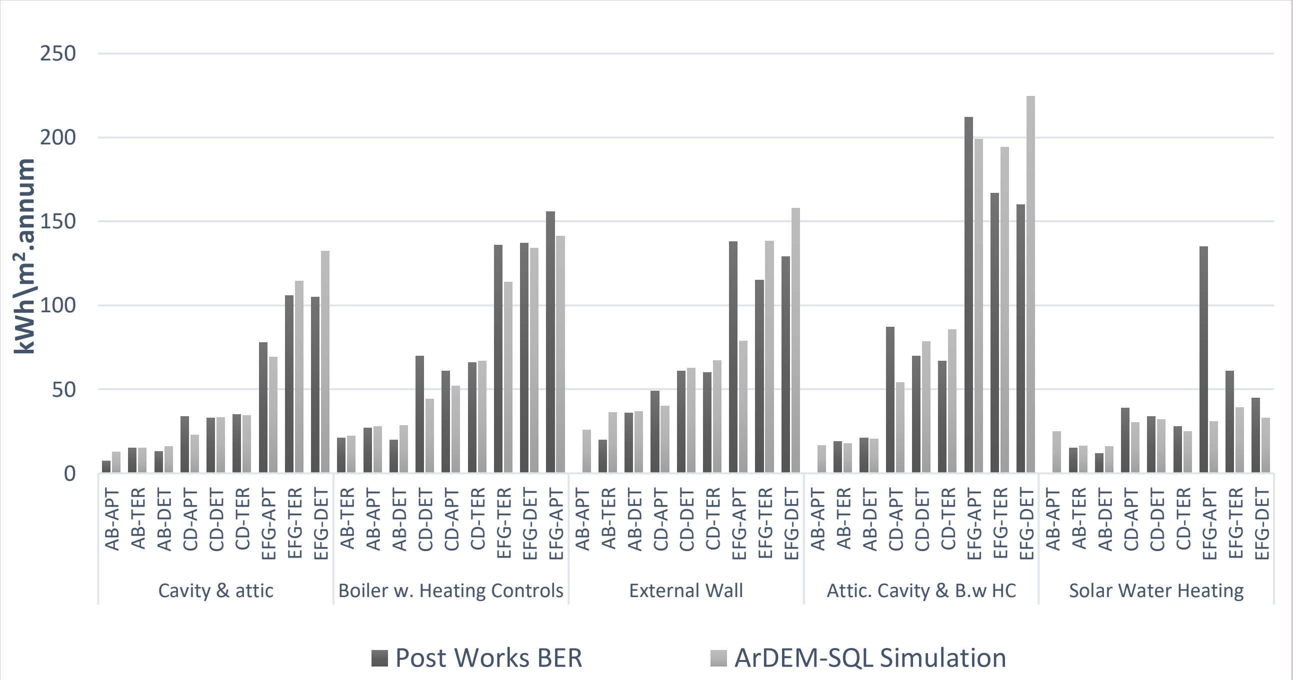

Figure 4-6 Archetype energy consumption: Post-works BER data versus simulated ArDEM-SQL

The data associated with each retrofit is then utilised to obtain the energy intensity of each archetype home. In conjunction with the total number of homes, previously calculated, this allows us to utilise Equation 4-1 and simulate the total energy savings associated with a range of retrofit combinations and estimate the total potential for improved energy savings that exists within different sets of simulated retrofit combinations.

4.5 Results

This section outlines the results of the baseline scenario and alternative retrofit scenario. The results are presented as the energy savings associated with the five most common retrofit measures, as they apply to each of the nine dwelling archetypes and total additional energy savings associated with the alternative retrofit scenario, relative to the baseline scenario.

4.5.1 Simulated archetype baseline energy consumption

Energy consumption by end use, in units of kWh/year, for each archetype has been simulated within ArDEM-SQL to determine baseline consumption prior to simulating the results of the 5 most common retrofit measures. Table 4-6 shows the baseline energy consumption for each archetype dwelling, subdivided into three distinct end uses – Lighting, Pumps & Fans; Space Heating; and Water Heating. The ArDEM-SQL model tracks the fuel used for each end use and these results are the weighted averages of energy consumption within each archetype, across all fuel types. Equation 4-7 shows the formula for calculating the weighted average of energy consumption across n fuel types, delivering the same service demand.

$$K = \sum_{i=1}^{n} \frac{w_{i^*} x_i}{w_i}$$

Equation 4-7 Weighted Average Calculation for Energy Consumption (kWh/m2 year)

, where K = Weighted average of energy consumption for each fuel type, x_i = energy consumption for fuel (i), w_i = number dwellings using fuel (i), n = each fuel delivering service demand

It was necessary to use the weighted average while calculating overall final energy demand by end-use within each archetype. In practice, ArDEM-SQL considers 15 separate fuel types delivering each end-use demand. It was found that there was a variance in the total energy intensity within certain fuel types associated with different dwelling archetypes. The weighted average is intended to account for this variability by also accounting for the differences in percentage share of different fuels delivering the same end-use demand. The analysis considers five common retrofit combinations applied to nine distinct archetypes – resulting in 45 individual retrofit results – further disaggregating each archetype by fuel would result in 675 individual retrofit results. Therefore, the scope of the analysis was limited to include the weighted average of energy consumption across all fuel types within each dwelling archetype.

Dwelling Demand by archetype (kWh/annum)			
Detached	**AB**	**CD**	**EFG**
Lighting	1416	1336	891
Space Heating	11741	15868	27831
Water Heating	4302	4945	4794
Terraced			
Lighting	696	726	670
Space Heating	4947	9337	17685
Water Heating	3351	4149	4422
Apartment			
Lighting	580	720	423
Space Heating	3061	10305	6420
Water Heating	2683	3858	2331

Table 4-6 Baseline Dwelling Annual End use energy consumption (kWh/annum) - ArDEM-SQL

Using the baseline archetype energy consumption (Table 4-6) and the modified dwelling stock data (Figure 4-5), utilising Equation 4-2 to calculate the baseline energy consumption for 2016 and compare this to the recorded data from SEAI’ energy balance to determine model validity. Table 4-7 shows the results of total final consumption by end-use, for each chosen archetype in 2016. The total baseline simulated energy consumption is 33.3 TWh/Annum (approx. 2.86 Mtoe). SEAI publish the aggregate residential energy consumption, which does not include a breakdown of consumption by archetype. The SEAI figure for 2016 is 2.7 Mtoe, making the simulated archetype energy consumption 94% accurate when compared to the aggregate energy consumption. This provides a useful sense check to the overall analysis as it was not possible to check the simulated figure against published SEAI archetype figures.

	End-Use	AB	CD	EFG
Detached	Lighting, Pumps & Fans	125,320,525	579,345,516	202,074,861
	Space Heating	1,039,197,518	6,882,618,974	6,310,314,543
	Water Heating	380,739,385	2,145,005,881	1,086,972,226
Terraced	Lighting, Pumps & Fans	49,984,843	349,572,198	146,700,721
	Space Heating	355,300,123	4,497,381,765	3,869,923,248
	Water Heating	240,695,369	1,998,365,662	967,531,301
Apartment	Lighting, Pumps & Fans	18,959,945	69,004,438	20,264,362
	Space Heating	100,064,924	987,460,542	307,300,494
	Water Heating	87,702,691	369,681,897	111,546,570
	Total:	2,397,965,323	17,878,436,871	13,022,628,326

Table 4-7 Baseline Total final energy consumption by end use and archetype (kWh/annum) – (ArDEM SQL)

4.5.2 Alternative archetype retrofit measures

Table *4-8* shows the weighted average (for all fuel types) of energy savings (kWh/m^2.annum) for each archetype dwelling, based on the five most common retrofit measures identified in the post-works BER data. It is worth noting that while 51% of all recorded retrofit measures used the combination "Attic and Cavity insulation", this retrofit combination does not appear as the most effective measure in any of the scenarios or for any of the archetype homes.

	Apartment			Terraced			Detached		
Retrofit Combination	AB	CD	EFG	AB	CD	EFG	AB	CD	EFG
Cavity & Attic	7	34	78	15	35	106	13	33	105
Boiler w. Heating controls	**27**	61	156	**21**	**70**	136	20	66	137
External Wall Insulation	-	49	138	20	61	115	**36**	60	129
Solar Thermal	25	39	135	15	34	61	12	28	45
Attic, Cavity & Boiler w. Heating Controls	**27**	**87**	**212**	19	**70**	167	21	**67**	**160**

Table 4-8 Energy Savings by archetype (kWh/m2.annum) for each retrofit combination

The retrofit measure combination, Attic & Cavity including Boiler with Heating controls yielded the largest savings for the majority of archetype dwellings. This is unsurpising as it is the only combination including three measures in one retrofit. Although apartments with a rating of AB yielded the same energy savings (27 kWh/m^2/annum) through implementation of Boiler with Heating controls upgrade only as those which upgraded Boiler w. Heating controls and Cavity & Attic insulation. The same retrofit combination substitution was also evident for Terrace CD dwellings with identical savings of 70kWh/m2.annum for Boiler with Heating controls only. This highlights the advantage of analysing and simulating retrofit combinations to identify alternative retrofit combinations for different types of archetype dwellings. Table 4-9 provides a summary of each alternative retrofit which yielded the most energy savings potential, for each archetype dwelling.

	Apartment	Terraced	Detached
AB	Boiler w. Heating Controls	Boiler w. Heating Controls	External Insulation
CD	Attic, Cavity & Boiler w. Heating Controls	Boiler w. Heating Controls	Attic, Cavity & Boiler w. Heating Controls
EFG	Attic, Cavity & Boiler w. Heating Controls	Attic, Cavity & Boiler w. Heating Controls	Attic, Cavity & Boiler w. Heating Controls

Table 4-9 Alternative retrofit measures from ArDEM-SQL by BER grade and house type

4.5.2.1 Alternative retrofit combinations and standards

Using the recorded baseline data for number of retrofits by archetype, estimated energy consumption savings per square metre for each archetype and the average archetype floor area (from ArDEM-SQL) I estimate final energy savings of 746 GWh when considering all completed retrofits for the five most frequent retrofit combinations. Substituting the recorded retrofit for each archetype with those of the alternative retrofit (Table 4-9), while maintaining the total number of retrofits completed, I estimate an energy savings potential of 1,389 GWh, realising an additional 643 GWh or an 86% additional energy savings potential relative to those in the baseline data, see *Figure 4-7*.

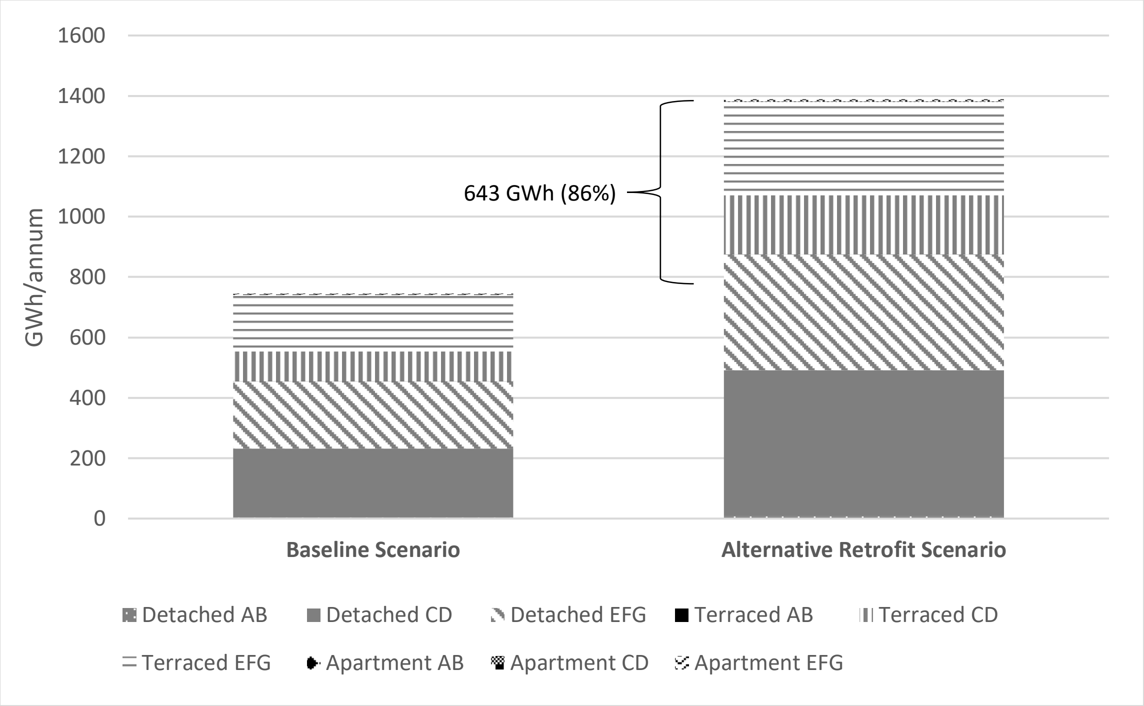

Figure 4-7 ArDEM-SQL, Estimated energy savings across all dwelling archetypes (baseline versus alternative retrofit scenario)

Further, the additional energy savings are not evenly distributed across all building archetypes, detached CD/EFG and terraced CD/EFG account for 98% of the potential additional energy savings when using the alternative retrofits identified. This is best illustrated using a specific example from the data as it relates to Terraced CD archetypes. In the post-works BER data 61% of Terraced CD rated homes availed of the Attic & Cavity insulation retrofit combination, achieving an average energy saving of 34.5 kWh/m^2/annum savings. The ArDEM-SQL model identifies the alternative retrofit combination for this archetype as Attic & Cavity & Boiler with Heating controls (of which only 2.1% selected in the PWBER data), estimating an average annual energy saving of 78.6 kWh/m^2/annum, an increase of 44.1kWh/m^2/annum relative to the figure recorded within the PWBER data. The simulation shows that this choice change leads to additional total energy savings of 95 GWh/ annum from this archetype dwelling, see Figure 4-8.

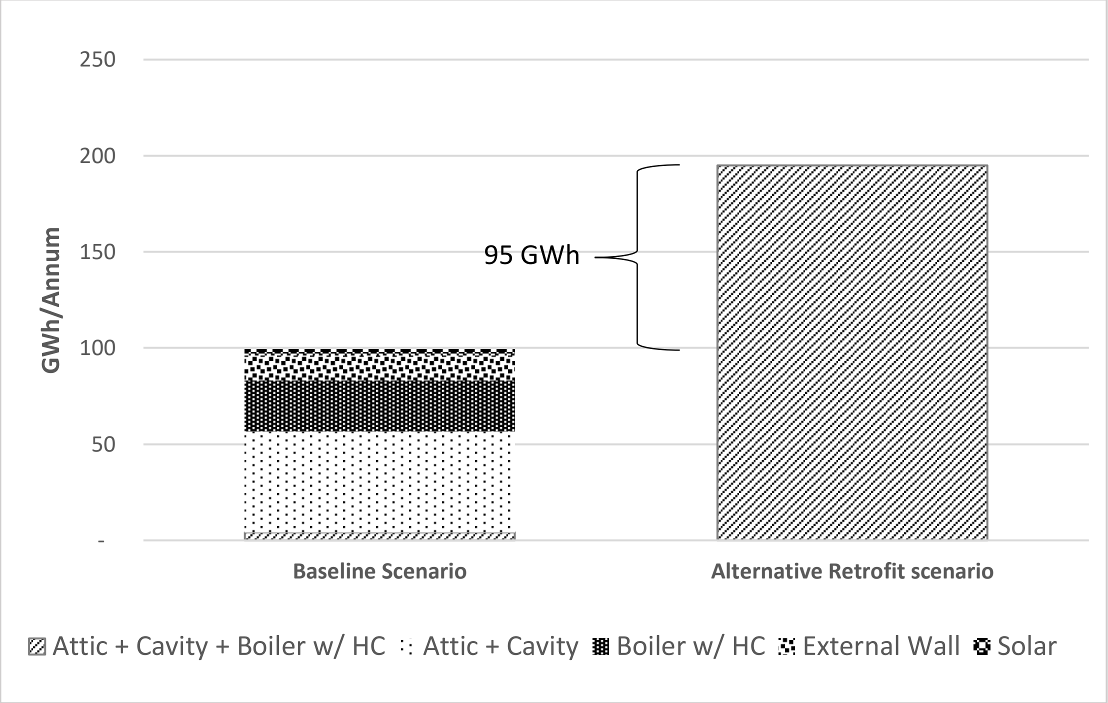

Figure 4-8 ArDEM-SQL, Terraced-CD archetype. Additional energy savings, baseline versus alternative retrofit scenario

4.5.2.2 Alternative retrofit scenario cost

Estimating the total cost to the homeowner is difficult within the current grant scheme as the pre-works condition of a dwelling is not considered in the grant value issued. Hence it is not possible to estimate the total cost (to the grant receiver) of achieving the minimum BER standards shown in Table 4-4, by archetype. Similarly, the PWBER data used does not include the date of the specific retrofit combination completion. Therefore, as the grant value for each measure has varied over time it is not possible to accurately estimate the cost within the scheme. Assuming the grant value issued is kept consistent with one scheme year (April 2015 – Table 4-2), the total cost of the grant scheme increases from €130 Million euro to €169 Million Euro in the alternative retrofit scenario, i.e. a 30% increase. This additional cost is not evenly distributed amongst all building types with detached dwellings and apartments witnessing an 83% and 41% increase respectively and terraced homes reducing in cost by 18.6%.

4.5.3 Contribution to 2020 target

To date approximately 18,654 GWh of total savings have been made through the implementation of NEEAP 3, achieving Irelands target goal of 31,925 GWh energy savings for 2020 will require an additional 13,271 GWh of total savings of which 1,904 GWh will be required from buildings during the period 2017-2020 (DCCAE 2017a, 4). This highlights the importance of early adoption within the grant scheme as all else being equal, the additional 643 GWh annual energy savings potential identified would account for approxamitely 2,572 GWh total savings during the four-year period 2017-2020, exceeding the identified gap to target of 1,904 GWh for buildings. (This additional 2,572 GWh is representative of approx. 19.4% of the remaining gap (13, 271 GWh) to national target as of April 2017).

4.6 Conclusions and policy implications

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 an energy performance rating (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 which achieve minimum energy savings at a scale not previously undertaken in Ireland.

This chapter seeks to (1) develop a new tool that could be used to analyse the growing volume of detailed building energy data available in Ireland, (2) evaluate what could have been done differently for Irish retrofit policy and (3) offer some policy recommendations based on this analysis.

This chapter provides a method of simulating the energy savings potential of alternative retrofits, as they apply to nine distinct dwelling archetypes in Ireland's building stock. The simulation tool is used to explore the potential of improving the total energy savings which could be realised from retrofitting activity. In the context of increased retrofitting ambition planned in Ireland, this represents an important tool which can provide additional information to homeowners and policymakers in making better retrofit decisions.

The methodology applied is flexible and can be adapted to explore the potential for other types of retrofits not currently offered by the current grant schemes. It can also be adjusted to consider a different set of archetype homes if required. The simulation modelling tool is sufficiently flexible that it can be easily adapted for use in other countries, given sufficiently detailed dwelling energy performance data.

The simulation of alternative archetype retrofit measures yielded additional energy savings of 86% when compared with the observed energy savings as they appear in the baseline scenario. The additional energy savings are not evenly distributed across all building archetypes with detached CD/EFG and terraced CD/EFG account for 98% of the potential additional energy savings when using the alternative retrofits identified, suggesting that greater energy savings are possible when retrofit measures are applied to less energy efficient dwellings. It is clear the current grant scheme is delivering sub-optimal savings and that the existing incentives should be reviewed. The potential for an improved retrofit program and the development of a standardised pre-works energy performance assessment (PWEFA) completed by an independent third party would aid in achieving the goal of bespoke retrofits which are customised to each home based on the pre-works condition. This PWEFA would also serve to improve our understanding of the rebound effect associated with various retrofit combinations, as they apply to human behaviour and its interaction with a range of retrofit technologies.

This raises the question of retrofit choice autonomy, should scheme participants choose measures which are deemed unnecessary or inappropriate following the analysis conducted as part of a mandatory pre-works BER assessment. This chapter provides a methodological foundation to assess the effectiveness of potential retrofit combinations to aid in designing alternative archetype retrofit schemes which are output based, i.e. grants which are paid for achieving verified savings per unit grant. I found in the analysis that there is a large variation in the potential realised energy efficiency savings based on the pre-works condition of the dwelling, including the dwelling type. Therefore, it may be worthwhile further disaggregating the grant value based on the pre-works energy efficiency rating of a dwelling, prioritising less energy efficient homes.

The tool improves the modelling capacity within the residential housing sector to improve efficiency and provide insights into the steps necessary to achieve deeper retrofit targets, at scale, through new iterations of the SEAI grant scheme. The study finds that homeowners are making sub-optimal retrofit decisions as part of the retrofit grant scheme. While I acknowledge that it is difficult from a policy perspective to advocate a policy which mandates the specific retrofit measures a homeowner can apply to their dwelling. However, if the grant was output based (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, etc) – the focus of homeowners could pivot towards energy savings and away from specific retrofit measures. The tool developed here would be useful to homeowners seeking to maximise energy savings and to policymakers in setting grant values for achieving specified levels of energy savings.

5 Exploring EV diffusion and residential retrofitting using a new model to investigate the impact of climate policy on carbon budgets

Abstract

This chapter presents a novel use of the Bass diffusion model together with a new greenhouse gas (GHG) emissions model for Ireland. The approach provides a robust framework to understand technology diffusion pathways, enables international comparison and feasibility assessment of policy targets, and delivers policy insights tailored to innovation adopter categories. The GHG model is developed using the Low Emissions Analysis Platform, applying a detailed bottom-up design methodology. The scenarios explore the impacts of two key policy goals: (1) the introduction of 840,000 electric vehicles (EV) and (2) the retrofitting of 500,000 residential dwellings (representing ~40% of current car stock and ~30% of residential dwellings respectively). This chapter quantifies differences in cumulative CO2 emissions by comparing early and delayed action compliance scenarios. Early versus delayed action can deliver an additional 19.5% (1.22 MtCO2eq) reduction within private passenger transport and an additional 6.3% (0.76 MtCO2eq) within the residential sector, between 2021-2030. The chapter also develops precedent scenarios using known diffusion rates that provide a benchmark evaluation of these climate policy targets and highlight their unprecedented scale. These precedent scenarios reach just 24% of the EV target and 47% of the residential retrofit target, which highlights the risk of focusing on end-of-period headline targets, the importance of diffusion rates and implementation pathways for policy formation. The chapter addresses the need for a robust framework which can progress the policy narrative to include implementation pathways and carbon budgets, not just final year headline targets. Finally, some tailored policy recommendations are provided based on distinct innovation adopter categories.[12].

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[12] “How feasible is unprecedented? Modelling diffusion pathways for ambitious climate policy targets” -” Submitted to Energy and Climate Change.

Keywords

LEAP, energy efficiency, policy support, policy simulation, simulation modelling, carbon budgets, diffusion of innovation

5.1 Introduction

The European Union (EU) distinguishes greenhouse gas (GHG) emissions from different sectors for policy purposes. GHG emissions from energy intensive industry, power/ heat generation and commercial aviation are included within the EU Emissions Trading Scheme (ETS). The ETS Directive 2003/87 (EU 2003) sets out an overall emissions ‘cap’ at EU level (that reduces over time) and provides for a ‘trading’ mechanism. Companies are allocated a certain quantity of emissions allowances. An ETS company can reduce its emissions to stay within the allowable amount, or purchase emissions allowances from another company who has reduced its emissions more than was necessary to stay within its allowable amount. While the ETS sector has struggled to deliver the expected increasing price signal for allowances and faced structural challenges in its implementation, it has evolved to function more effectively over time (Narassimhan et al. 2018). GHG emissions outside of the ETS, i.e. from transport, built-environment, agriculture, and waste are collectively known as non-ETS emissions. The EU policy for reducing non-ETS emissions is articulated in an Effort Sharing Decision (ESD), Decision No 406/2009/EU (EC 2009b), in which each member state has a non-ETS target which is legally binding. These classifications are essential to understanding the evolution of the EU strategy to tackle climate change across a range of varying sub-sectoral challenges (Lacasta et al. 2010) as non-ETS emissions associated with agriculture, transport and heat prove more challenging to address.

The 2009 ESD established 2020 GHG emission reduction targets at member state level within the EU for the non-ETS sectors. The ESD includes annual GHG reduction targets for the period 2013 – 2020, measured in tonnes of CO2 equivalent and expressed as Annual Emission Allocation's (AEA's), effectively establishing a non-ETS carbon budget for each Member State. Member state targets vary based on relative wealth, measured by gross domestic product (GDP) per capita. Under the ESD, Ireland's mandatory target is to achieve at least a 20% non-ETS GHG reduction in 2020, relative to 2005 levels. Cumulative AEAs establish an effective non-ETS carbon budget of 338 $MtCO_{2eq}$ for the period 2013-2020. The responsibility for national GHG emission inventories and projections in Ireland falls to the Environmental Protection Agency (EPA). In 2019, the EPA's GHG projections report stated that Ireland is likely to achieve between 2%-4% reduction in non-ETS GHG emissions in 2020, relative to 2005 levels (EPA 2020a). This projected carbon budget in the period 2013-2020 will be 349 $MtCO_{2eq}$, indicating a shortfall of 11 $MtCO_{2eq}$ (EPA 2019a). Ireland has purchased some non-ETS emissions allowances and will need to purchase additional allowances to ensure compliance with the 2020 target. According to these latest GHG projections, only two member states, Ireland and Malta, are projected to fail to meet their 2020 GHG targets (European Environment Agency 2018). This makes Ireland an interesting case study in the evaluation of the impact of carbon budgets on climate related policy.

For 2030, non-ETS GHG emission targets are specified under the Effort Sharing Regulation (ESR) (EC 2016). Ireland's current 2030 target is to reduce GHG emissions by 30%, relative to 2005 levels. Based on annual targets from 2021 the non-ETS carbon budget for the period 2021-2030 is 378 MtCO2eq. Given the shortfall in achieving 2020 emission reductions, there is a knock-on effect to 2030 targets that will require additional policy measures. The EPA is required to produce a range of emission projection scenarios as part of the EU Monitoring Mechanism Regulation (MMR) (EU 2013). The MMR requires each member state to report emissions projections in two scenarios, a 'with existing measures' (WEM) and 'with additional measures' (WAM). The most recent EPA projections estimate a carbon budget deficit of 51 MtCO2eq for the period 2021 – 2030, and a surplus of 8.9 MtCO2eq in the

WEM and WAM scenarios, respectively. The 2030 targets are due to be increased, in line with the EU's increased ambition for 2030 (to achieve a 55% rather than 40% reduction in total GHG emissions by 2030 relative to 1990 levels).This chapter utilises the new modelling tool, LEAP Ireland GHG, to enable GHG scenario analysis for Ireland. The model is used to undertake scenario analysis on two key policy ambitions in Ireland's Climate Action Plan: rapid diffusion of electric vehicles and significant deep retrofitting of residential buildings. The chapter quantifies the cumulative emissions savings associated with early versus delayed action implementation of these key climate policies. The modelling is underpinned by analysis of two adopter categories (early market actor and mainstream market actor), which given the distinct behaviours of these two groups, enables insights into tailored policy formation. The market actors are simulated using the Bass diffusion model which describes the diffusion process of new products as the interaction between users and potential users (Bass 1963). A more complete review of the Bass model formula and methodology is provided in section 5.2 and 5.3.

Ireland is an interesting case study as many of the policy challenges faced are applicable to other member states, including challenges with reducing non-ETS emissions with heat, transport, and agriculture. This study addresses the need for a robust framework which can progress the policy narrative to include implementation pathways and carbon budgets, not just final year headline targets.

Section 5.2 provides the policy context for this analysis. Section 5.3 discusses the methodology, presenting the LEAP Ireland GHG model and the Bass diffusion formula. Section 5.3 also constructs the scenarios to explore the impact on GHG emissions of early or delayed target compliance for the period 2021 – 2030. There is a focus on the diffusion of electric vehicles within private passenger transportation and the retrofitting of existing dwellings in the residential sector. Section 5.4 presents the results and section 5.5 draws conclusions and highlights some of the policy implications based on adopter specific recommendations.

5.2 Background

5.2.1 Policy Context

Ireland has produced multiple policy documents during the period 2013-2020. Notably the National Development Plan (NDP) (DPER 2018) and the more recent Climate Action Plan (CAP) (Government of Ireland 2019). These policy documents outline measures across all sectors of the economy, i.e. transport, residential, services, industry, power generation and agriculture. Table 5-1 outlines some of the headline policy targets, relevant to this study, outlined within the NDP and CAP indicating the year of implementation and sub-sectoral area. This analysis explores two key areas of policy priority in Ireland, addressing the introduction of electric vehicles (EV) within private passenger transport and residential retrofitting.

Policy	***Sector***	***Sub-sector***	***Target***	***Description***
NDP	Transport	Private Passenger Transport	500,000 EV’s	Deliver 500,000 electric vehicles by 2030, inc. additional charging infrastructure
			Non-zero Emissions Vehicle ban	No new non-zero emission vehicles sold post 2030
	Residential	Existing Dwellings	45,000 Dwellings p.a.	Retrofit 45,000 dwellings per annum to minimum ‘B’ standard (<= 125kWh/m^2.annum)
			840,000 EV’s	Deliver 840,000 electric vehicles by 2030, inc. additional

CAP	Transport	Private Passenger Transport		charging infrastructure
			Non-zero emission ban	No new non-zero emission vehicles sold post 2030
	Residential	Existing Dwellings	500,000 Dwellings (inc. 400,000 Heat Pumps)	Deliver 500,000 residential retrofits to minimum B2 standard (<= 100 kWh/m^2.annum) and install at least 400,000 electric heat pumps

Table 5-1 National Development Plan and Climate Action Plan residential retrofitting and private passenger transport targets

Ireland’s more recent CAP committed to a significant increase in the number of EV’s by 2030, specifically a shift from 500,000 to 840,000 EV’s by 2030. Nomenclature is important in the context of EV policy discussion as the percentage share of these overall targets being delivered by Plugin-Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV) has also changed over time. The CAP target consists of 25% PHEV (210,000) and 75% BEV (630,000) by 2030.

5.2.1.1 Progress to date

Assessing progress to date with respect to EV penetration and retrofitting activity requires an understanding of the evolving nature of the targets over time. With respect to EV diffusion, Ireland has witnessed a significant gap between policy targets and delivered results. In 2008, a 2020 EV target of 10% of all vehicles was established, translating into approximately 230,000 EV’s by 2020 (DCENR 2009, 1). In 2014, this was revised downward to a total of 50,000 EV’s by 2020 (DCENR 2014, 3). In 2019 there are approximately 9,481 BEV/ PHEV’s on Irish roads (SIMI 2019). Figure

5-1 shows the historic number of registered BEV and PHEV vehicles on Irish roads, highlighting the 2020 target of 50,000 EV's by 2020 and the need for 41,519 EV sales in 2020 to reach the target.

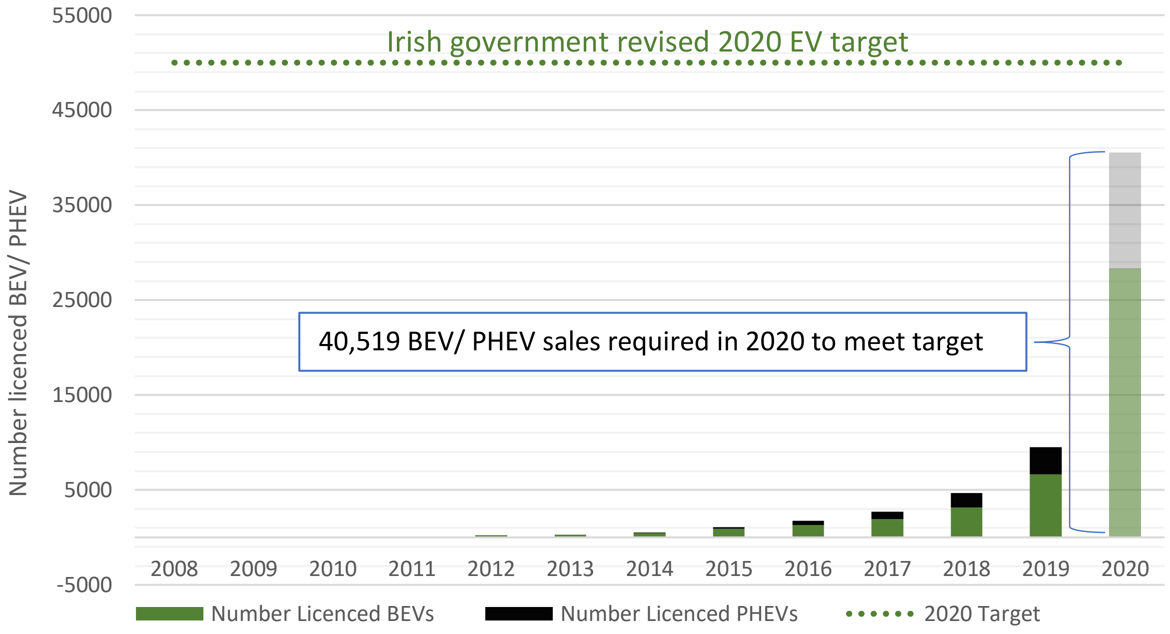


Figure 5-1 Historic number of BEV/ PHEV vehicles, in Ireland (2008 – 2020)

Retrofitting uptake activity and depth has also been slower than expected. Retrofit depth can be broadly categorised as shallow/ deep retrofit. A shallow retrofit typically consists of discrete building fabric upgrades which focus on a limited number of retrofit measures, achieving limited energy efficiency improvements. Conversely a deep retrofit focuses on achieving much deeper levels of energy efficiency improvements by applying an integrated retrofit strategy which considers the effect of a combination of retrofit measures. Proposed 2030 targets have shifted over time, NDP policy specifies approximately 405,000 dwelling retrofits during the period 2018 – 2027 (to a minimum standard of at least 125kWh/m^2.annum). CAP policy increases this target, aiming to deliver 500,000 residential retrofits by 2030 (to a minimum standard of at least 100 kWh/m^2.annum), including 400,000 heat pumps delivered to existing dwellings. At present, Ireland is completing approximately

23,000 residential retrofits per annum (Government of Ireland 2019), the majority of which are shallow retrofits. Retrofit grant schemes in Ireland have the potential to deliver significantly greater energy efficiency improvements than previously witnessed (Mac Uidhir et al. 2019b). Between 2017-2019, 325 residential dwellings received grant support to achieve deep retrofits, achieving an energy efficiency rating of at least 75 kWh/m^2/annum (SEAI 2019b). Figure 5-2 shows the current rate of shallow/ deep retrofits, with current trends projected to 2030, relative to the 2030 CAP retrofit target. Shallow retrofit activity does not typically reach the stated levels of energy efficiency improvement required in the target and accounting for shallow retrofit activity, the target is missed by 178,000 retrofits by 2030. Deep retrofits account for approximately 875 of all retrofits by 2030 at this current rate, representing just 0.3% of all projected future retrofit activity.

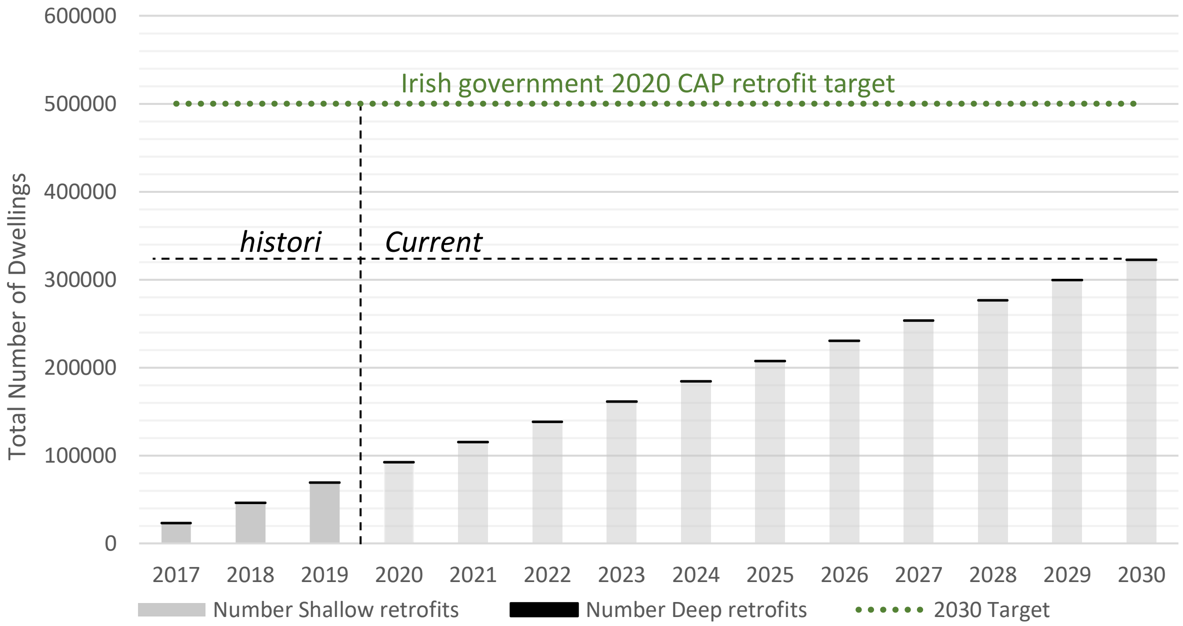


Figure 5-2 Historical and projected number shallow/ deep dwelling retrofit grants in Ireland (2017 – 2030)

5.2.1.2 Potential difficulties with delivering targets

The progress to date figures highlights the scale of the task with respect to achieving more ambitious 2030 targets. CAP policies recognise the need to improve the supply chain in delivering deeper retrofits at scale, however as technology adopters, does not consider the potential supply constraint difficulties associated with delivering the unprecedented number of EV's required by 2030 (Olivetti et al. 2017), (McKinsey 2018). Additionally, current policy does not provide clarity on what type of vehicles will be displaced and what homes will be retrofitted. (O'Neill et al. 2019) highlight additional difficulties associated with the large scale importing of diesel vehicles from the UK and the lack of clear policy for the future of diesel vehicles post 2030. A key policy difficulty with respect to large scale deployment of EV's lies within the interdependence of the required national charging infrastructure and personal user incentive to switch to an EV. There is a need to provide an evidence-base on which to formulate robust policy which adequately considers the wide range of mitigation outcomes associated with delivering climate policies. By considering the implications of the carbon budget approach between 2021 and 2030, this study explores these questions and examines the difference between varying policy implementation pathways which deliver the same fixed end-year national targets. The results highlight the number and type of vehicles and dwellings which will be displaced/ retrofitted in each year. An essential component in delivering all the benefits associated with these ambitious 2030 targets requires that the policies also adequately consider the delivery pathways.

5.2.2 Diffusion of Innovations

The theory of diffusion of innovation explores the rate at which innovations are adopted across a range of adopter categories and innovation characteristics. Rogers categorises five adopter types (innovators, early adopters, early majority, late majority, and laggards) and a range of innovation characteristic (relative advantage, compatibility, complexity, trialability and observability). A five-stage "innovation-decision" process is described as: 1) knowledge, 2) persuasion, 3) decision, 4) implementation and 5) confirmation (Rogers 2003)with each stage representing a step in the decision-making process from initial awareness of an innovation to final adoption and implementation.

The theory has been supported and modified by multiple empirical studies. Analysis by Franceschinis et al. (2017)of household preference for ambient heating technologies finds evidence to support the diffusion of innovation theory, while aggregating the five adopter categories into three categories: early, late-majority and late adoption characteristics. Simpson and Clifton (2017) confirm the presence of early-majority diffusion characteristics with respect to financial incentives and the adoption of residential solar heating in Australia, highlighting the difficulties associated with crossing the “chasm” between early-adopters, who typically prioritise environmental and technological concerns, and the early-majority, who typically prioritise financial concerns, in the context of diffusion(Moore and McKenna 2014). Noel et al. (2019) explore the concept of “conspicuous diffusion”, in which the theory of conspicuous consumption (Veblen and Galbraith 1973) is combined with Roger’s diffusion theory to gain insight into the impact which status and perception play on diffusion of electric vehicles in broader society. Noel et al. show that the diffusion of electric vehicles in the Nordic region follows the theory of conspicuous diffusion particularly well, concluding that the successful conspicuousness of EVs (Tesla, Nissan) has stimulated the adoption of the technology amongst innovators, maximised the technological distinction within society, and stimulated peer-to-peer status “emulation” as the adoption creates a new social norm and enters the early-adopter market. Additionally, this process encouraged other manufactures (VW, BMW) to begin conspicuous diffusion and promote further technology choice.

Many aspects of the theory of diffusion have received widespread recognition, e.g. technological diffusion tends to follow an S-shape curve, the total number of potential adopters’ changes over time and changes within the internal evolution of the innovation affects overall diffusion. These diffusion characteristics highlight the need to view diffusion as an on-going and evolving process with respect to the diffusion of any specific innovation (Kemp and Volpi 2008). As already noted, the different adopter categories are sometimes aggregated depending on the level of data available. These different adopter categories can be used to provide tailored policy recommendations, since what works as a policy measure for one group (e.g. early adopters) might not work for a different group (e.g. late majority). Based on the literature, an overview of some of these differences is given in Table 5-2.

	Early market actors	**Mainstream market actors**
Socio-Economic Status	More likely to be wealthier	Less likely to be wealthier
Motivation	Environmental concerns; future opportunities; driven by initiative	Cost of product being economical; reaction to a need for compliance
Information	High level of knowledge; active searcher for information; relies on diverse sources of information	Knowledge restricted to standard products; passive recipient of information
Peer influence	Not strongly influenced by peers; confident in own judgement	Actively influenced by peers; external authority carries weight
Risk	Risk-taking; sees risks as manageable	Risk averse; avoids risks & uncertainty where possible
Solution preferences	Unique, bespoke, different	Standard solutions preferred
Benefits	Perceive benefits strongly	Good enough is sufficient
Behaviour	Leads; contrarian	Follows; conformist

Table 5-2 (source, adapted from, Wilson et al, 2017 and Egmond et al, 2006)

5.2.2.1 Policy Instruments and diffusion

In an analysis of housing associations in the Netherlands (Egmond, Jonkers, and Kok 2006) use two aggregated adopter categories of early market (innovators and early adopters) and mainstream market (early and late majority) to develop a set of tailored policy instruments for improving building energy efficiency at a quicker rate than previously. They define four main categories of policy instruments: (1) judicial, (2) economic, (3) communicative, and (4) structural.

Judicial instruments create a legal requirement to abide by regulations such as new building regulation standards or the certification of the energy performance of a building. These instruments tend to focus on the introduction of new minimum standards and serve less value in addressing the replacement of less energy efficient technologies which are already in use.

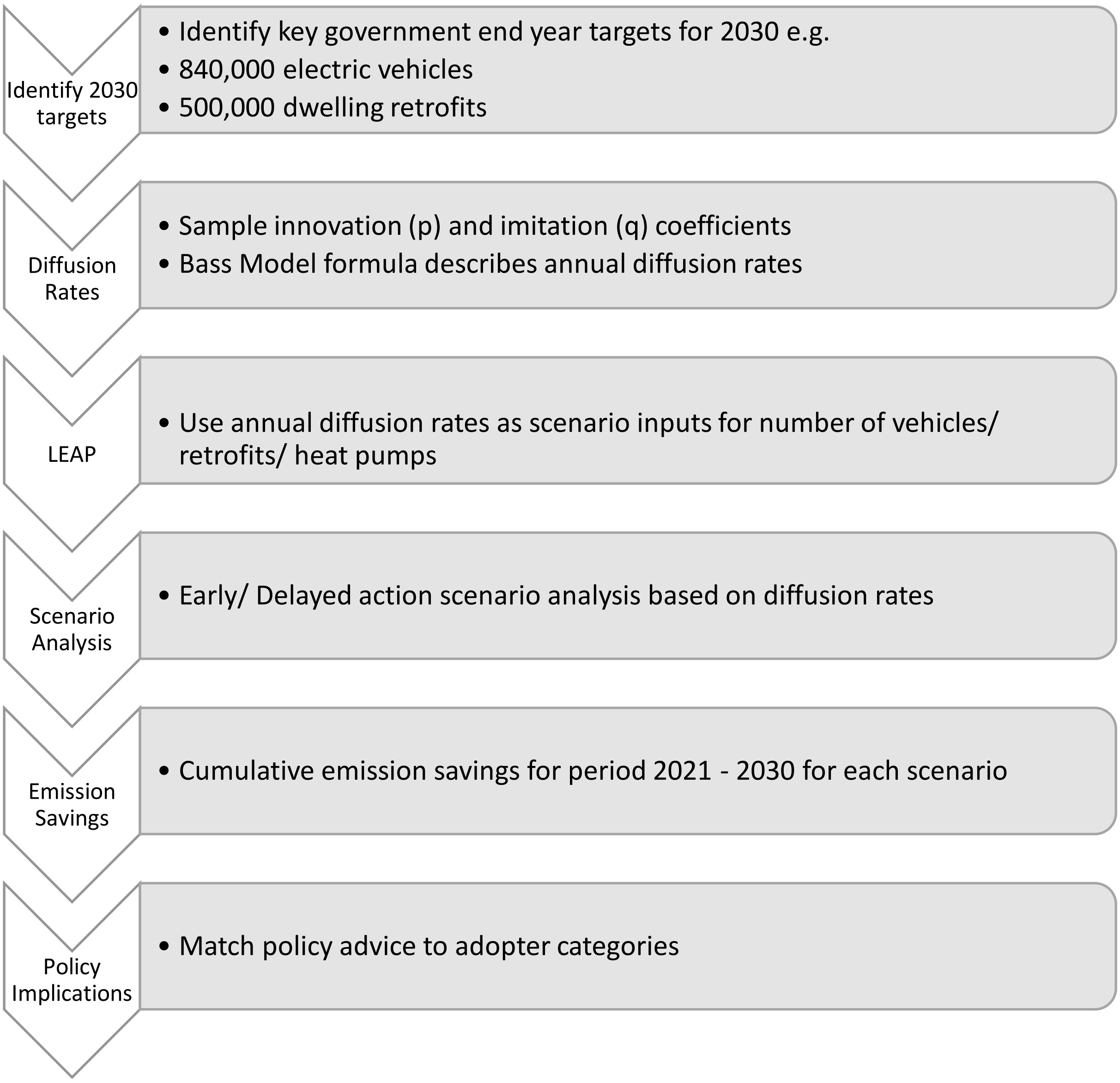
Economic instruments can be either positive or negative. Positive economic instruments such as financial subsidies risk the free-rider effect, whereby early-adopters who would otherwise have adopted an innovation benefit from reduced cost, with less impact on the late adopter categories. Negative economic instruments, such as levies and taxation based on energy efficiency can be effective at influencing late adopter categories, but only if this adopter type is informed.

Communicative instruments can go beyond the simple conveyance of information and serve to reduce cost and uncertainty while simultaneously improving societal awareness and acceptance of a new technology/ measure, bridging the gap between early adopters (who may participate in informational and demonstration schemes) and the late-majority/ mainstream market groups.

Physical provisions such as district heating schemes have the potential to influence late adopter categories as they represent less risk through instilled cooperation and adoption of a technology at scale. To give one example of an insight arising from combining adopter categories and policy instruments: the authors point out that given that early-market actors are often highly motivated, financial incentives are less effective for this group, whereas they are effective for mainstream-market actors.

5.3 Methodology

The methodology has six parts: (1) The identification of key 2030 policy measures, (2) The use of Diffusion Rates which deliver identified targets, (3) LEAP simulation modelling to quantify emissions reductions associated with each diffusion scenario, (4) Scenario analysis and comparison, (5) Quantification of cumulative emissions savings, and (6) Policy implications and impact on adopter categories. Each section is described in detail while Figure 5-3 outlines each step within the methodology.



Identify 2030 targets
- Identify key government end year targets for 2030 e.g.
- 840,000 electric vehicles
- 500,000 dwelling retrofits

Diffusion Rates
- Sample innovation (p) and imitation (q) coefficients
- Bass Model formula describes annual diffusion rates

LEAP
- Use annual diffusion rates as scenario inputs for number of vehicles/ retrofits/ heat pumps

Scenario Analysis
- Early/ Delayed action scenario analysis based on diffusion rates

Emission Savings
- Cumulative emission savings for period 2021 - 2030 for each scenario

Policy Implications
- Match policy advice to adopter categories

Figure 5-3 Policy implementation pathway carbon budgets - Methodological flowchart

5.3.1 Diffusion Rates

In a simplification of Rogers adopter categories, Bass (1963) describes the process of how new products get adopted as an interaction between *users* and *potential users*. The Bass model formula (*Equation 5-1*) describes diffusion of innovation as a function of innovation (p) and imitation (q) variables within the potential market (M) (Bass 1969). The coefficient of innovation (p) is not dependent on the number of prior adoptions and is therefore considered an external influence on market diffusion. However, the coefficient of imitation (q) is proportionally linked to the number of cumulative adoptions over time (A(t)). The Bass model formula utilises these coefficients to amalgamate adopter categories, providing a simplified mathematical description of complex diffusion rates, which facilitates scenario analysis.

$$\frac{f(t)}{1-\frac{A(t)}{M}} = p + \frac{q}{M}.[A(t)]$$

Equation 5-1 Bass Model formula

Where, f(t) is the rate of change of installed base fraction, M is the potential market (ultimate number of adopters), p is the coefficient of innovation, q is the coefficient of imitation, A(t) is the cumulative adopter function

It is inherently difficult to forecast future rates of innovation and imitation within the Bass equation as they are usually specific to the innovation being considered and require at least four historic periods to estimate. In the absence of historic values, it is possible to utilise p, q values for a similar innovation to those being studied. Comparative analyses of similar innovation diffusion trends are required to provide insights into the potential success and implementation pathways for Ireland.

Several studies have examined the market diffusion of electric vehicles in multiple regions (Fojcik and Proff 2014; Gnann et al. 2018; 2015; Jensen et al. 2016), including estimates of imitation and innovation coefficients. However, less is known about the potential for large scale market penetration of residential retrofitting. Schleich (2019) analysis of the adoption of high, medium, and low cost energy efficient technologies for 15,000 households across 8 EU countries concludes that regional comparisons based on a single "harmonized methodology" are lacking. Sandberg et al. (2016) analysis of 11 EU countries highlights that while EU energy efficiency building policy presents increasingly ambitious "renovation rates", it rarely evaluates the "likeliness of reaching these rates". Rosenow and Galvin (2013) evaluate energy efficiency programmes in Germany and the UK, finding that disparities exist in the programme formulation to account for the difference between modelled versus measured energy efficiency savings achievable from a retrofit programme.

This chapter uses a previous study of the market diffusion of EVs within Norway (Jensen et al. 2016; Massiani and Gohs 2015) as a benchmark for Ireland's potential for EV diffusion. Norway was chosen as a case study because its market penetration of EVs has been relatively successful (IEA 2019). For residential retrofitting, no such alternative region was identified which could serve the same benchmarking function. Therefore the work of (Collins and Curtis 2016; 2017a; 2017b) on residential retrofitting in Ireland was used. This analysis on retrofit take-up, depth and abandonment rates was used to develop benchmark diffusion rates. In their investigation of the potential diffusion coefficients for residential energy efficiency renovations, Curtis et al. identify adoption of retrofit measures is likely to be consistent with the classical theories of Two-Step Flow of Communication and Rogers' Diffusion of Innovation theory. The precedent scenario for residential retrofitting focuses on the impact of advertising and investment spill over on diffusion, referred to here as the AdInS scenario.

Mahajan et al. (1995) provide an overview of generalisations for p and q values, indicating an average p value of 0.03 and average q value of 0.38. However Jeuland (1994) notes that the value of p is often quite small, less than 0.01 and q is rarely smaller than 0.3 or greater than 0.5. When p = 0 the Bass model S-curve reduces to a logistic distribution and when q = 0 the model reduces to an exponential curve. The generalised figures are summarised in Table *5-3*.

Study	*p-value*	*q-value*	*S-curve response*
Mahajan et al.	0.03 (average)	0.38 (average)	Regular
Jeuland et al.	p > 0.01 (often)	0.3 < q < 0.5 (often)	Regular
-	0	NA	Logistic
-	NA	0	Exponential

Table 5-3 Bass model innovation (p) and imitation (q) generalised coefficients

The exploratory p and q values for each scenario are shown in Table *5-4* and described in detail in section 5.3.3. Compared to the average p and q values as found in the literature, our policy scenario p and q values are quite low; however, compared to the precedent scenarios I developed, our policy scenario p and q values are quite high. It is also worth noting that the profile of our delayed action scenario p and q values (i.e. p < q) is similar to the literature cited average values.

Scenario	***p***	***q***
Reference values (from literature)	0.01-0.03	0.3-0.5
CAP EV Early_action	0.023	0.21
CAP EV Delayed_action	0.010	0.34
EV Norway	0.002	0.23
CAP Retrofit Early_action	0.021	0.14
CAP Retrofit Delayed_action	0.015	0.20
Retrofit AdInS	0.013	0.06

Table 5-4 Innovation (p) and Imitation (q) coefficients by scenario

This chapter identifies potential p, q values which deliver end-year targets over a period of analysis. It is an accepted practice to utilise similar historic technology diffusion rates to provide an initial estimate of potential p, q values for an analogous technology (Jensen et al. 2016; Lilien, Rangaswamy, and Van den Bulte 2000; Radojičić and Marković 2009). This chapter is not primarily an assessment of implementation pathway feasibility, but instead provides an approach to estimate the difference in carbon reduction potential in differing policy implementation pathways using different p, q coefficients and a simulation model (LEAP).

5.3.2 LEAP Ireland GHG model

The Low Emissions Analysis Platform (LEAP) is an integrated GHG and energy simulation modelling tool developed by the Stockholm Environmental Institution (C. G. Heaps 2016b). LEAP is a tool which is used on different spatial and temporal scales, e.g. national mitigation strategies, global scales, and varying time horizons. One primary strength of LEAP lies in its capacity to conduct scenario analysis and consider the impact of specific climate policies.

This section outlines the LEAP Ireland GHG simulation model structure and scenarios relevant to this chapter, a broader definition of the LEAP Ireland GHG model is provided in chapter 2. The LEAP Ireland GHG model builds on the previous work of (Rogan et al. 2014), adding additional levels of detail in the form of complex datasets for the Industry, Commercial Services, Transport, Residential and Agriculture sectors. These datasets are required to analyse national GHG mitigation strategies and allow for the inclusion of GHG emissions at a detailed subsectoral level. Each subsector is described separately for clarity, including a description of key inputs/outputs used within that sector.

The LEAP energy system modelling tool was identified as providing a representative platform which could incorporate the need for flexible detailed bottom-up modelling structures within transport, residential, industry, commercial services and agriculture while also including a top-down econometric structure within other subsectors, as data required. A more complete description of common energy modelling classifications is provided in (Connolly et al. 2010)

5.3.2.1 LEAP transport

The private passenger transport subsector is described by various vehicles of different fuel types (Petrol, Diesel, CNG, Electric) and engine sizes (< 900cc, 901 – 1200cc, 1201 – 1500cc, 1501 – 1700cc, 1701 – 1900cc, 1901 – 2100cc, > 2100cc), for twenty-five years of vintage information between 2016 and 2030. Activity for each vehicle size is measured in vehicle kilometres and final energy intensity is measured as Megajoule per kilometre (MJ/km). The model assumes EVs replace smaller internal combustion engines (ICE) first, EVs take the place of larger ICE sizes as the need to replace significant numbers of private passenger vehicles increases to 2030.

5.3.2.2 LEAP residential

The residential sector is described by nine unique building archetypes. These included building type, detached, terrace, apartment, and energy efficiency classification, divided into three categories (low, medium, high) based on the Building Energy Rating (BER) alphabetic labelling system AB, CD and EFG. The model focuses on the retrofitting of existing dwellings and hence assumes new dwellings, post-2020, are constructed to a standard not requiring retrofitting. This implies a pool of potential dwellings which can be retrofitted over time. Activity for this sector is therefore measured by the number of each archetype dwelling and energy intensity for each archetype is measured in kWh m^{-2} $year^{-1}$. In LEAP, energy intensity within this sector is represented by an aggregated energy efficiency rating for each archetype.

5.3.3 Scenario Analysis

This section outlines the key assumptions and reasoning behind chosen metrics utilised within the scenario analysis. Two key areas of policy discussion in Ireland revolve around the introduction of EV's within private passenger transport and the retrofitting of residential dwellings. This section has identified key policies within these sectors and generated appropriate modelling scenarios within the LEAP Ireland GHG model to simulate the GHG reductions which are technically possible due to their implementation. These scenarios use the diffusion rate figures to explore the impact of turnover rate within EV's and retrofitting. An account and justification of what is being replaced is provided within each scenario description.

5.3.3.1 EV Scenario assumptions

The rapid introduction of EVs raises multiple questions with respect to the development of vehicle types/choices and the required infrastructure within private passenger transport. In the case of the introduction of EVs, I have assumed that smaller internal combustion engines (ICE) will initially be replaced by electric engines, this assumes smaller, efficient ICE vehicles are being replaced by EVs (J. Xing, Leard, and Li 2019), in the short-term. As the total stock of smaller ICE vehicles is replaced, larger ICE engines need to be replaced with EVs in both scenarios. Table 5-5 provides an overview and description of each EV scenario described scenario.

Scenario	***Sector***	***Metric***	***2016***	***2030***	***Description***
Reference	Transport	BEVs	1600	37400	Low Growth EV uptake
		PHEVs	400	23400	
CAP EV Early Action	Transport	BEVs	1600	634768	Rapid Early growth in EV uptake achieving 2030 target
		PHEVs	400	212194	
CAP EV Delayed Action	Transport	BEVs	1600	632349	Delayed Growth (2023 start) in EV uptake, achieving 2030 target
		PHEVs	400	212269	
EV Norway	Transport	BEVs	1600	147748	EV uptake proportional to Norway diffusion potential
		PHEVs	400	49853	

Table 5-5 LEAP Ireland GHG base year/ final year EV uptake scenario assumptions

Figure 5-4 represents the p, q values for the early/ delayed action EV scenarios and the annual sales of new EV's for each year in the analysis period.

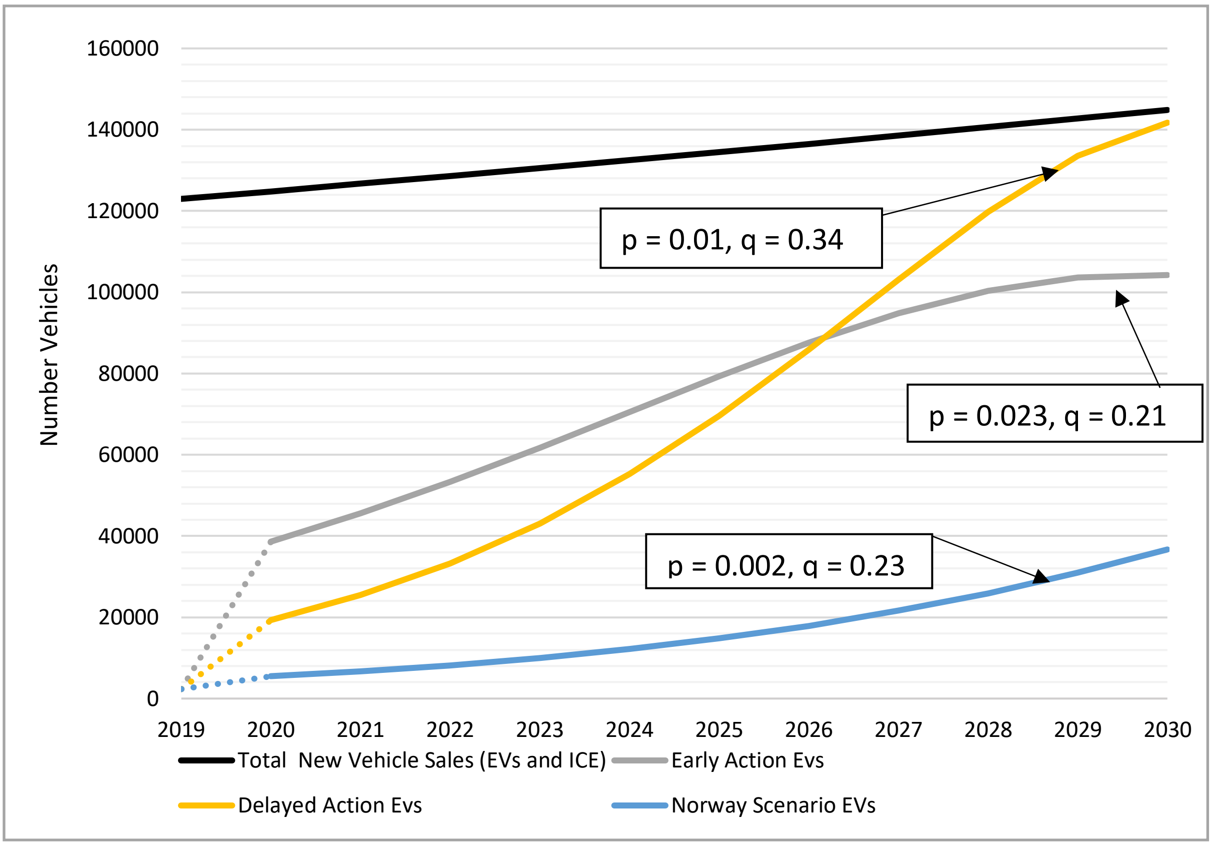


Figure 5-4 Electric Vehicle Scenarios - New Sales of Electric Vehicles per annum, in Ireland (2019 – 2030), including scenario p, q values

5.3.3.1.1 ICE vehicle replacement assumptions

This scenario group simulates the impact of initially replacing smaller ICE vehicles (<900cc, 901cc – 1200cc, 1201cc – 1500cc) with electric vehicles. In both early/ delayed action scenarios there is a progressive increase in the vehicle engine size, reaching engine sizes of 1701 -1900cc by 2030 in the early action scenario and engine sizes in excess of 2100cc in the delayed action scenario. Figure 5-5 and Figure 5-6 show the number of vehicles, by fuel type and engine size, replaced in each year between 2021 and 2030 for the early/ delayed action scenarios respectively. Figure

5-7 shows the annual ICE replacement by engine size in the EV Norway scenario, not exceeding small 900 – 1200 CC petrol engines in any year as the total number of EV's introduced is reduced relative to the target compliant scenarios.

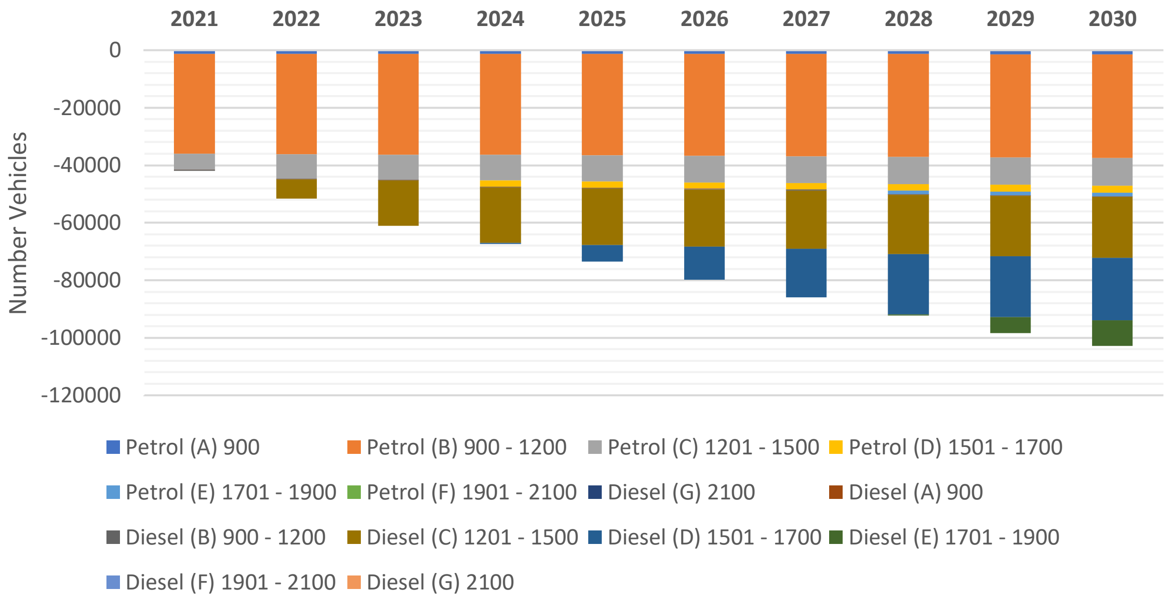


Figure 5-5 ICE Vehicle displacement: Early action target compliant scenario in Ireland, (2021 – 2030)

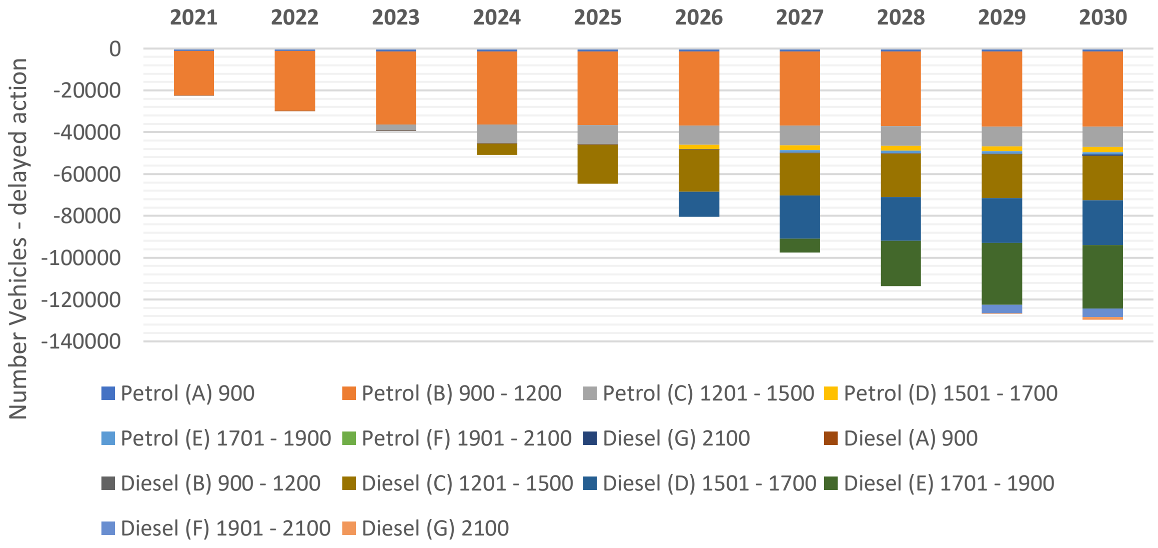


Figure 5-6 ICE Vehicle displacement: Delayed action target compliant scenario in Ireland (2021 – 2030)

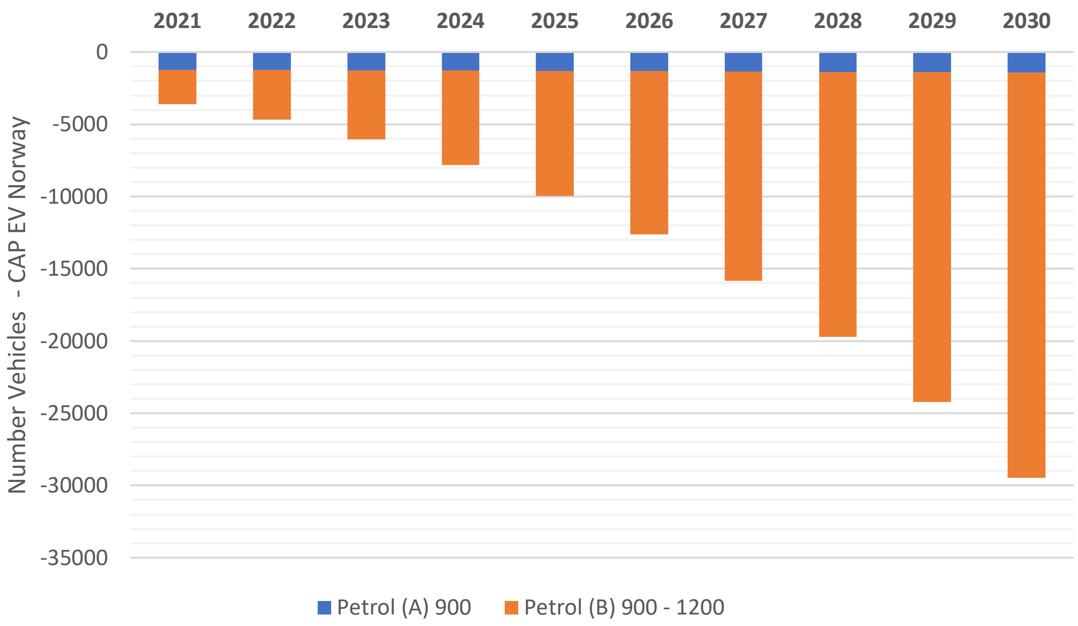


Figure 5-7 ICE Vehicle displacement: EV Norway scenario applied to Ireland (2021 – 2030)

5.3.3.2 Residential retrofitting assumptions

This section outlines the key assumptions utilised within the residential retrofitting scenarios. The diffusion rates simulate the total number of dwellings retrofitted in each year. The purpose of this study is to quantify the potential difference in emissions reductions across different implementation pathways, hence the early and delayed action scenarios assume an equal distribution of dwelling types with respect to retrofitting. The AdInS scenario utilises p and q values based on the work of Collins and Curtis (2017a), where the impact of advertising and investment spill over is explored in an Irish context.

This study provides insights into the impact on carbon budgets due to varying diffusion rates – based on the CAP target of 500,000 dwelling retrofits, including 400,000 heat pump installations.

Dwelling retrofit assumptions

Figure 5-8, Figure 5-9, and Figure 5-10 indicate the number and type of residential archetypes retrofitted in each period of analysis. Dwelling numbers differentiate between retrofits which include heat pumps and those which do not e.g. Terraced_CD_wHP indicates the annual number of terraced dwellings with an initial BER rating of C or D, retrofitted to a minimum standard of 100 kWh/m^2 year (B2 standard) including an electric heat pump. The p, q values indicated for each scenario dictate the diffusion rate and total number of dwelling retrofits which deliver 500,000 retrofits by 2030, while the AdInS scenario delivers 235,000 retrofits by 2030..

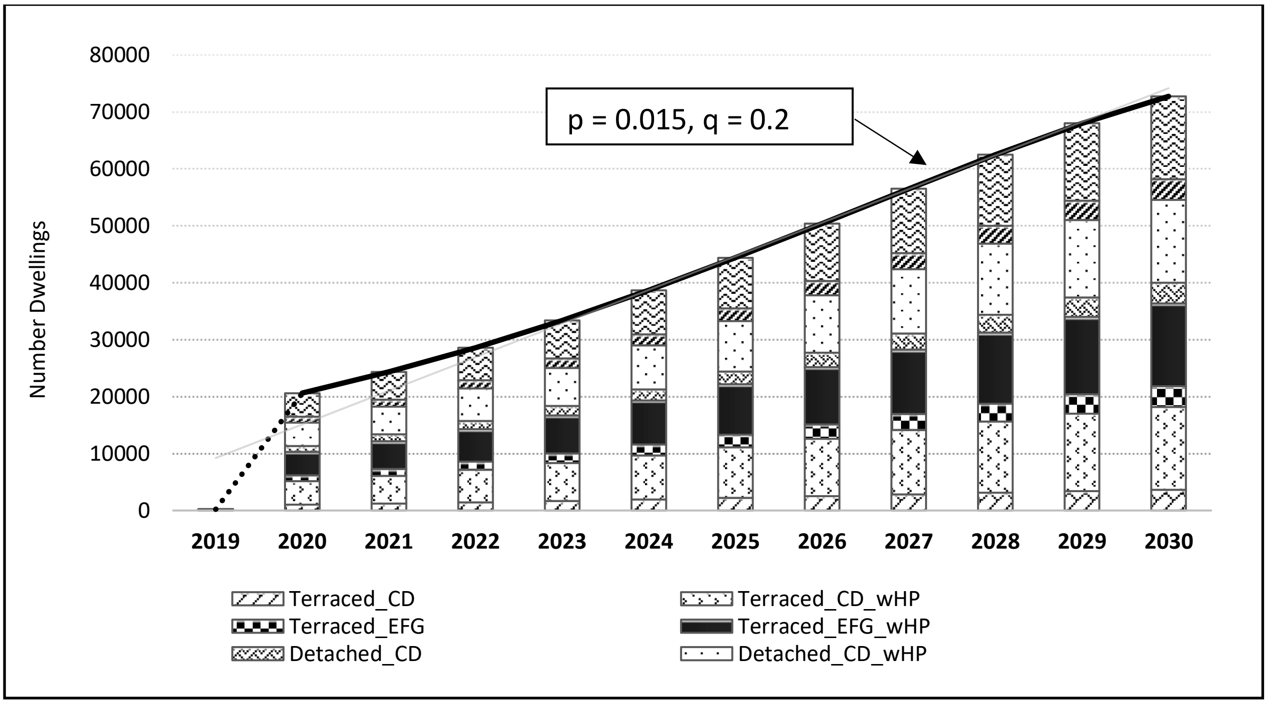


Figure 5-8 Residential retrofit delayed action scenario- number dwellings retrofitted per annum by archetype, including scenario p, q values

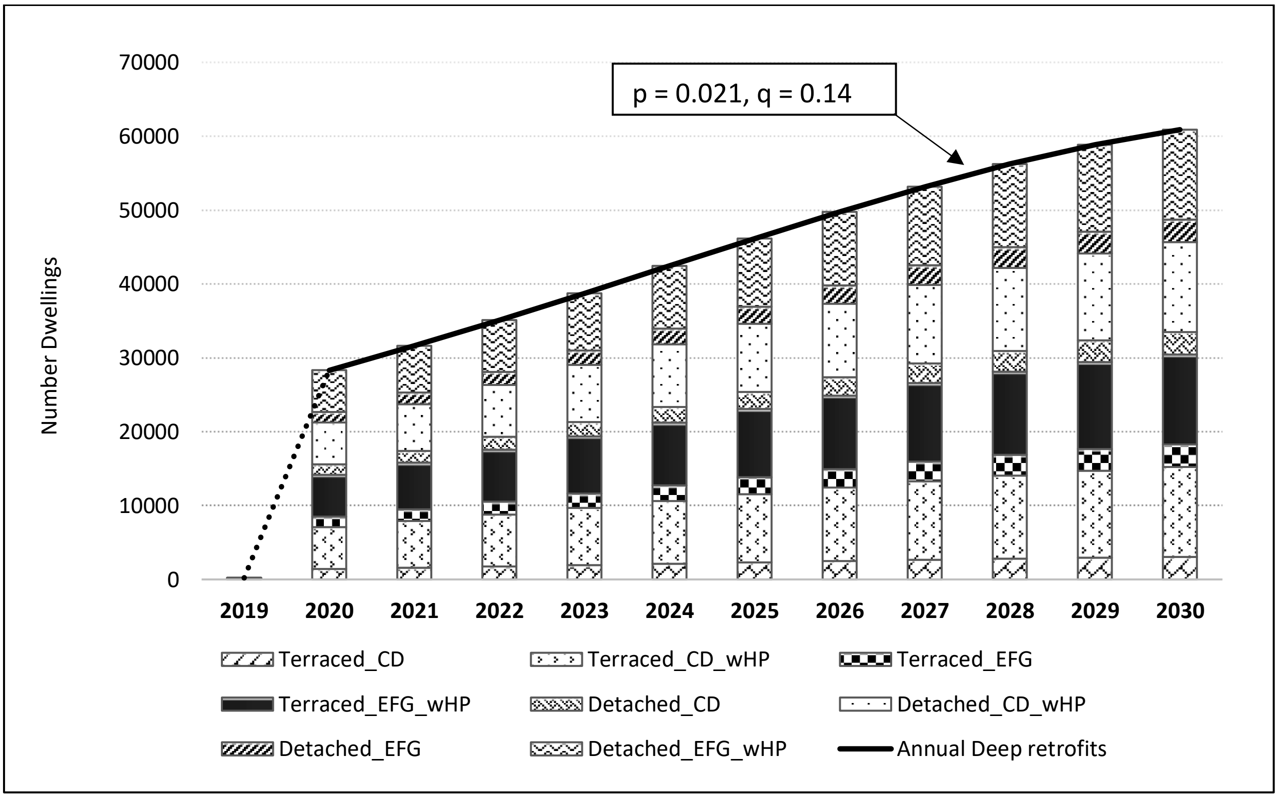


Figure 5-9 Residential retrofit early action scenario - number dwellings retrofitted per annum by archetype, including scenario p, q values

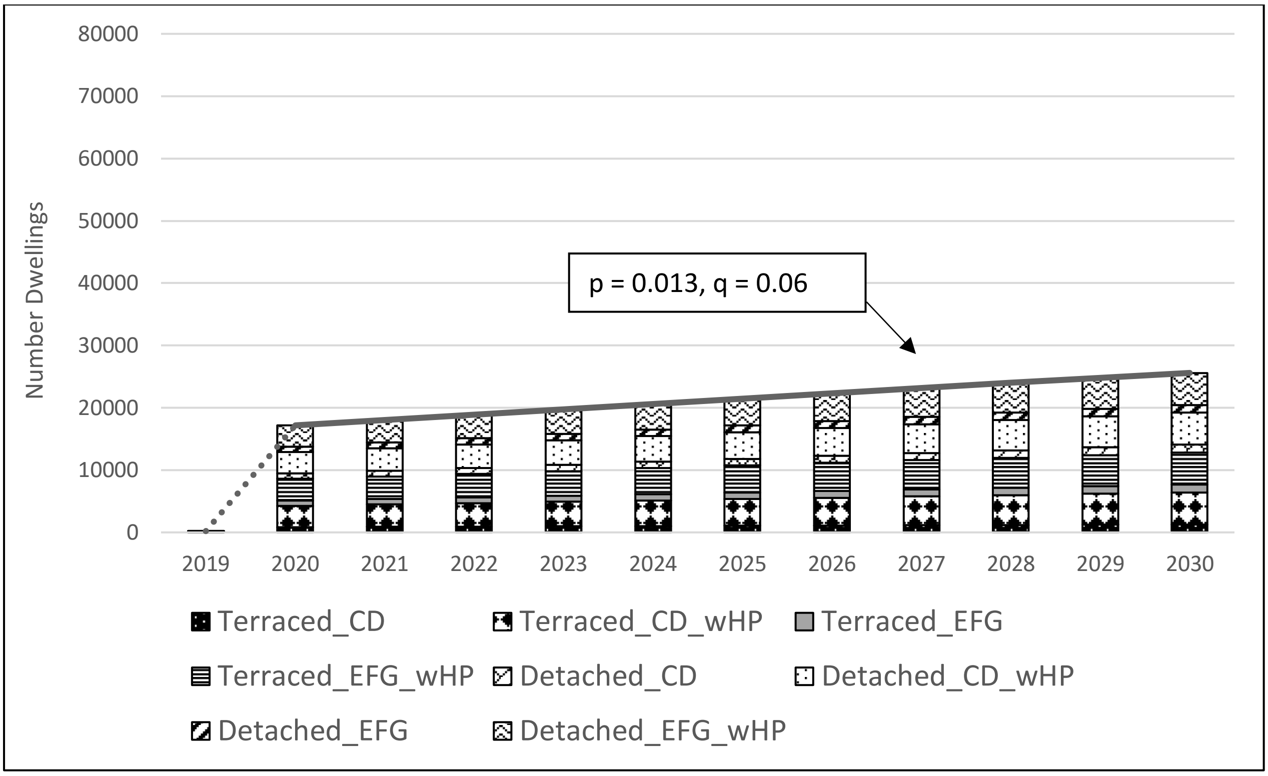


Figure 5-10 AdInS scenario - number dwellings retrofitted per annum by archetype, including scenario p, q values

5.4 Results

This section outlines the results of the early/ late target compliance scenarios as they apply to the diffusion of EV's within private passenger transport and the retrofitting and installation of residential dwellings. The results have been grouped by relevant scenarios and highlight what technologies are introduced in each, for each scenario. The EV Norway scenario provides insight into the scale of the challenge with respect to achieving the 2030 EV target outlined in the CAP scenarios.

5.4.1 Private passenger transport – Electric Vehicle diffusion

Each CAP compliant scenario described achieves the target of 840,000 EV's by 2030. The variable is the diffusion rate. In all cases the smallest capacity engines are replaced first, in favour of battery electric vehicles and plug-in hybrid electric vehicles. The EV Norway scenario achieves a total of approx. 200,000 EVs by 2030. Each figure also includes the 2030 EV percentage share of new vehicle sales. Figure 5-11 and Figure 5-12 show the number of EVs being added to the system in each year between 2021 – 2030, they also show the cumulative emissions reduction for each scenario. Figure 5-13 shows the annual EV diffusion and cumulative emissions reduction as a result of the EV Norway scenario. There is a range of emissions reductions across all scenarios:

1. 7.50 MtCO2 – Early action, Figure 5-11
2. 6.28 MtCO2 – Delayed action, Figure 5-12
3. 0.64 MtCO2 – EV Norway, Figure 5-13

The difference between delayed action emissions reduction: this additional 1.23 MtCO2eq represents an additional 19.5% reduction, relative to the least ambitious, target compliant, implementation pathway. The delayed action scenario achieves approximately 10 times more emissions reduction than the EV Norway scenario.

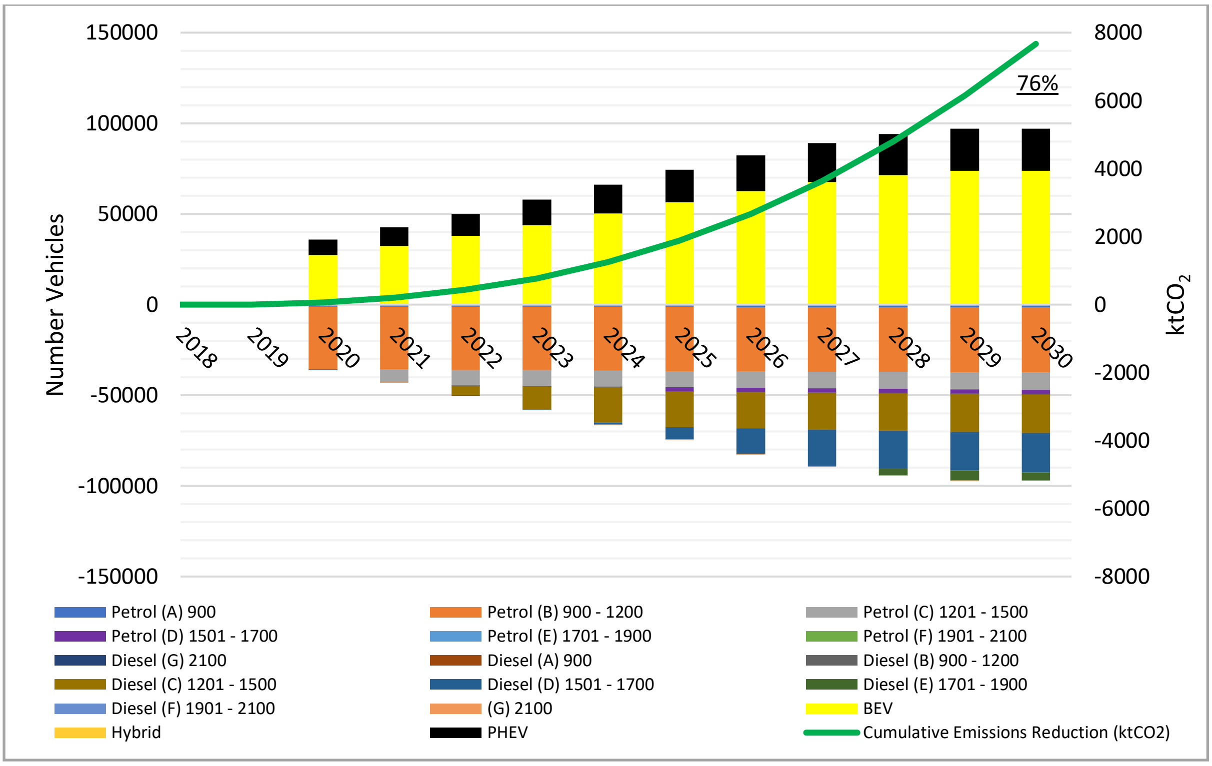


Figure 5-11 Electric Vehicle Early Action Target Compliance, Vehicle Sales and Cumulative Emissions Reduction (ktCO2)

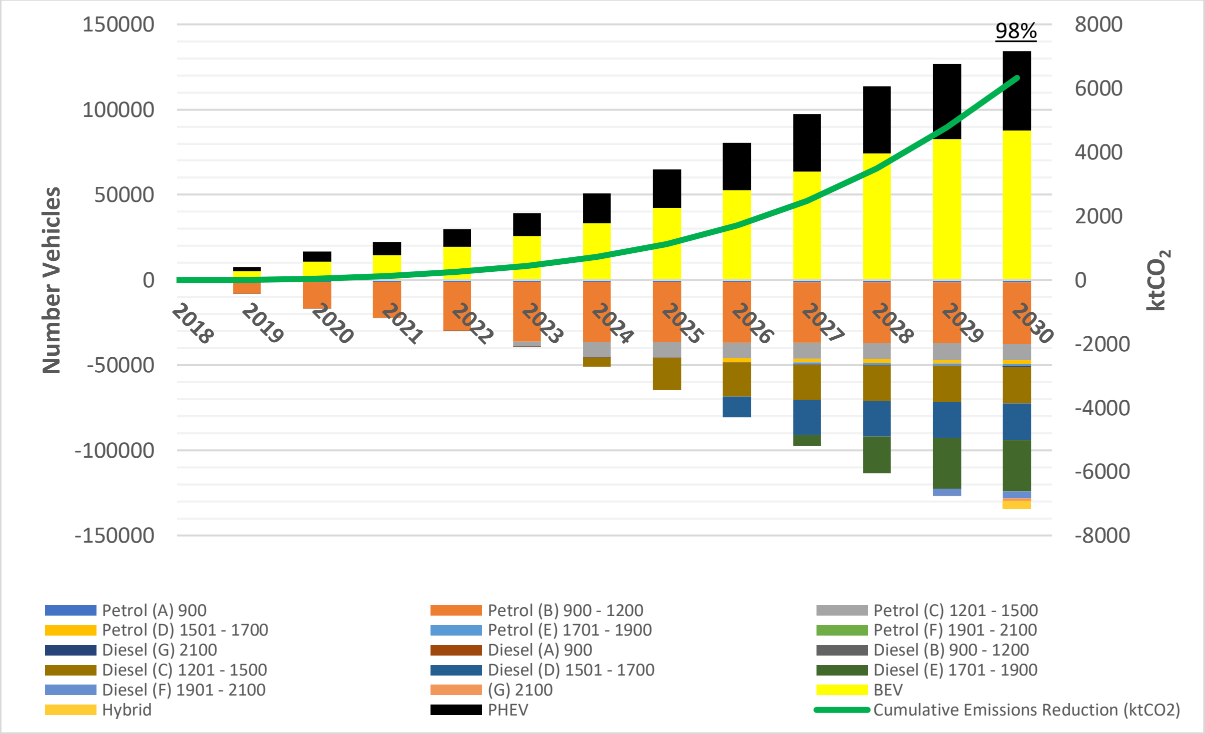


Figure 5-12 Electric Vehicle Delayed Action Target Compliance, Vehicle Sales and Cumulative Emissions Reduction (ktCO2)

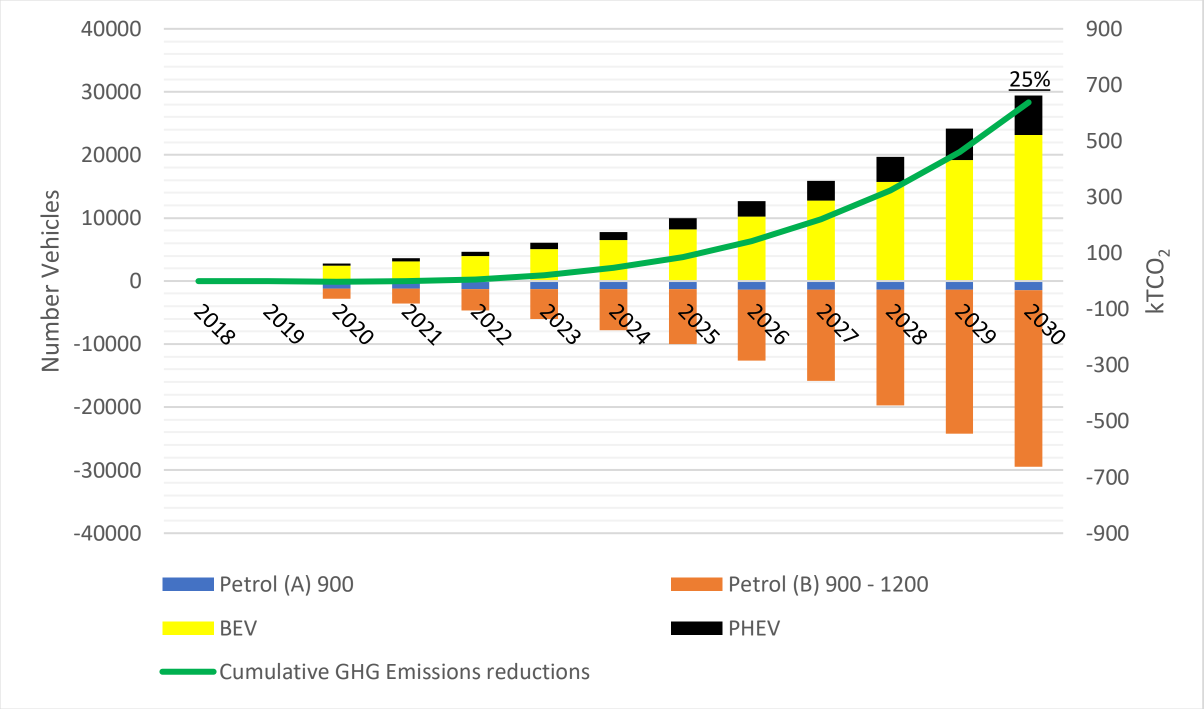


Figure 5-13 Electric Vehicles – Norway scenario, Vehicle Sales and Cumulative Emissions Reduction (ktCO2)

Note the engine capacity of the vehicles being removed from the system. The delayed action scenario requires a higher percentage share of total vehicles sales to be electric by 2030 (98% of all new vehicle sales), relative to the early action scenario which rises to a higher share earlier (53% sales by 2024) but tapers out slowly to 2030, occupying a 72% share of total new car sales in 2030. This scenario requires early action but facilitates a slower phasing out of petrol/ diesel alternatives while still delivering greater GHG emissions reductions over the period 2021 – 2030.

Section 5.3.3.1 provides details on the specific ICE vehicles being replaced in each scenario. Vehicles are indicated by fuel type and engine size for each year in the period of analysis. Table 5-6 indicates the number of BEV/ PHEV introduced within each scenario, for several simulation years.

Scenario	*Technology*	*2020*	*2022*	*2024*	*2026*	*2028*	*2030*
Early Action Target Compliance	BEV	16226	35748	46632	55275	63976	71560
	PHEV	8737	19289	25038	29753	34449	38532
Delayed Action Target Compliance	BEV	12482	21603	35902	55821	77897	92129
	PHEV	6740	11702	19342	30026	41901	49541
CAP EV Norway	BEV	4105	6144	9133	13432	19448	27520
	PHEV	1368	2048	3044	4477	6483	9173

Table 5-6 BEV and PHEV stock change by scenario

5.4.2 Residential Dwellings – retrofitting and heat pump installation

Each scenario described for the residential sector achieves the CAP target of 500,000 dwelling retrofits, including the installation of 400,000 heat pumps. Each scenario assumes retrofits are completed evenly across terraced and detached dwellings of both EFG and CD pre-works energy efficiency standard. The variable is the rate at which the dwellings are retrofitted, see Figure 5-8 and Figure 5-9. Figure 5-14 and Figure 5-15 show the total emissions reduction for the analysis period 2021 to 2030 for the early and delayed action scenarios respectively . There is a range of cumulative emissions reductions across each scenario:

1. 12.8 MtCO2 – Early Action Scenario.
2. 12.0 MtCO2 – Delayed Action Scenario.
3. 4.0 MtCO2 – Retrofit AdInS Scenario

There is a difference between early/ delayed action emissions reduction: this additional 0.8 MtCO2eq represents an additional 6.3% reduction, relative to the least ambitious, target compliant, implementation pathway. Figure 5-16 shows the cumulative emissions reduction associated with the retrofit AdInS scenario, equating to 4 MtCO2 eq cumulative emissions reduction by 2030.

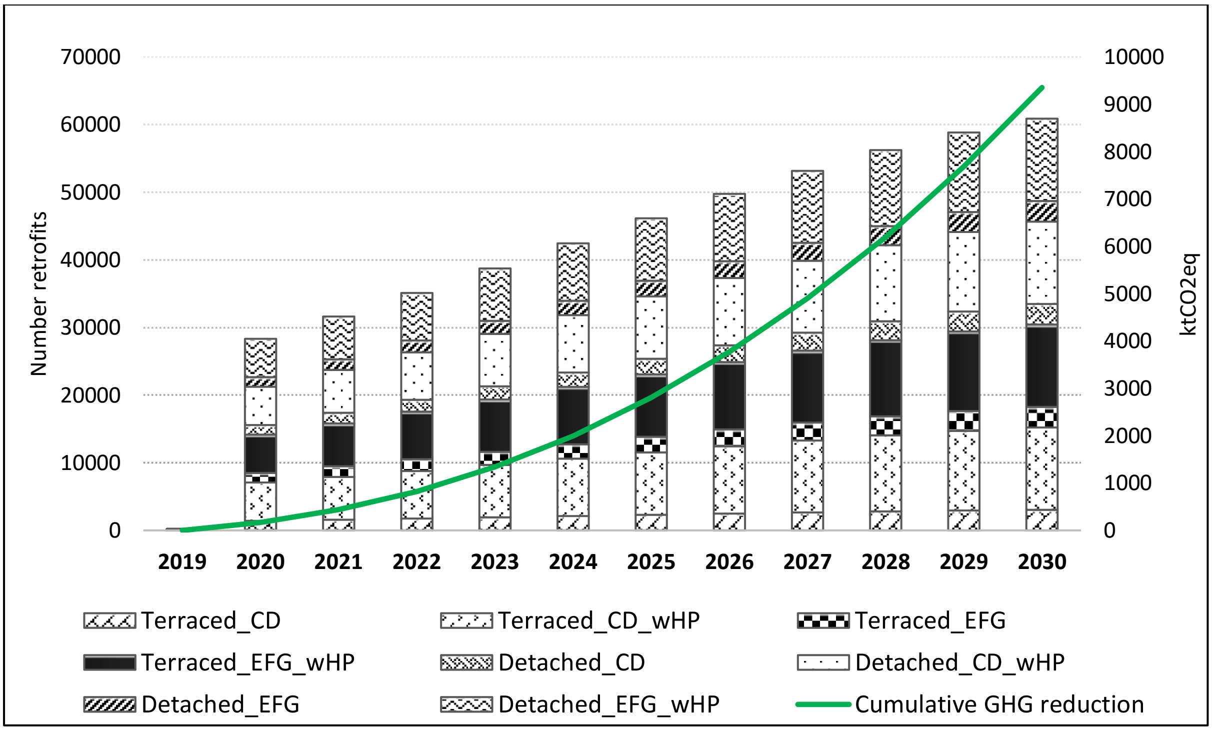


Figure 5-14 Residential retrofitting early action target Compliance, dwelling archetype retrofits and Cumulative Emissions Reduction (ktCO2)

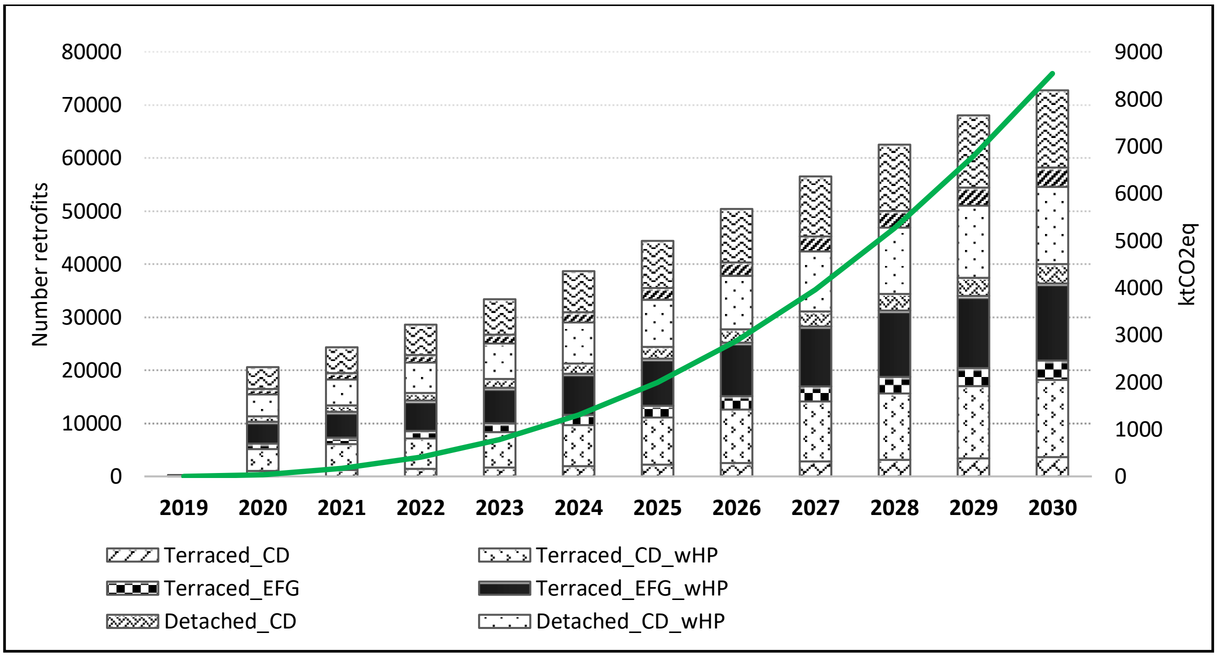


Figure 5-15 Residential retrofitting delayed action target Compliance, dwelling archetype retrofits and Cumulative Emissions Reduction (ktCO2)

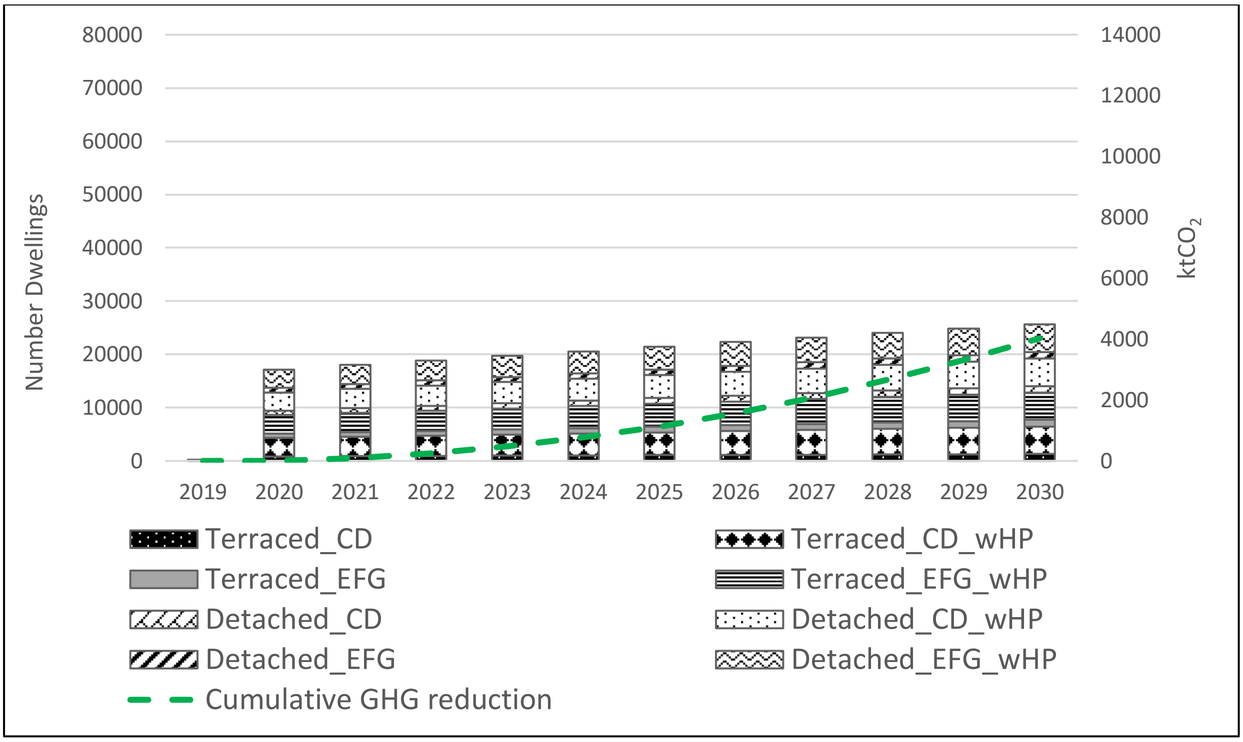


Figure 5-16 AdInS Scenario, dwelling archetype retrofits and Cumulative Emissions Reduction (ktCO2)

Section 5.3.3.2 provides details on the specific number of dwellings retrofitted in each year, by type and energy efficiency rating. **Error! Reference source not found.** indicates the total number of retrofits for each scenario.

Scenario	***Sector***	***Metric***	***2021***	***2030***	***Description***
Reference	Residential	Terraced_CD	131.5	460	Low Growth Deep retrofit uptake
		Terraced_EFG	131.5	460	
		Detached_CD	131.5	460	
		Detached_EFG	131.5	460	
CAP Retrofit Early Action	Residential	Terraced_CD	7908	15223	Rapid Early growth in Deep retrofit uptake achieving 2030 target
		Terraced_EFG	7908	15223	
		Detached_CD	7908	15223	
		Detached_EFG	7908	15223	
CAP Retrofit Delayed Action	Residential	Terraced_CD	6084	18187	Delayed Growth in Deep retrofit uptake, achieving 2030 target
		Terraced_EFG	6084	18187	
		Detached_CD	6084	18187	
		Detached_EFG	6084	18187	
AdInS Scenario	Residential	Terraced_CD	4500	6398	Retrofit uptake and diffusion potential based on (M. Collins and Curtis 2017a)
		Terraced_EFG	4500	6398	
		Detached_CD	4500	6398	
		Detached_EFG	4500	6398	

Table 5-7 LEAP IE Residential retrofit scenario assumptions (2021 – 2030)

5.4.3 Supply side influence

There is an intrinsic link between the emissions savings associated with the demand side emissions reduction policies discussed and the potential for an increase in supply side emissions (due to increased electricity demand and fuel switching). In practice, any policies which present a transformative shift towards the use of electricity as a transport or residential heating fuel, should be coupled with measures to ensure the decarbonisation of the electricity supply. No specific supply side decarbonisation scenarios were explored as part of this chapter, hence any discussion relating to the impact of increased supply side emissions is not truly reflective of current policy in Ireland. However, the LEAP Ireland GHG model does have a supply side module and allows some insight into the impact of increased emissions due to the introduction of 840,000 electric vehicles and 400,000 heat pumps. Figure 5-17 shows the percentage reduction in emissions savings when increasing supply side emissions are factored into overall demand side emissions. The range of 6 – 99% illustrates the scale of the challenge and the need to consider supply side measures in parallel to demand side ones. The EV Norway scenario delivers a relatively small cumulative emissions reduction during the period 2021 – 2030. In the absence of supply side emissions reductions, the cumulative savings are effectively cancelled out.

Scenario	***% reduction***
CAP EV Early_action	42%
CAP EV Delayed_action	43%
EV Norway	99%
CAP Retrofit Early_action	18%
CAP Retrofit Delayed_action	15%
Retrofit AdInS	6%

Figure 5-17 reduction in emissions savings due to increase in supply side emissions, by scenario

While there is value in analysing the impact of this “model-wide” approach to scenario analysis, there is further work needed to model the supply side generation profile more accurately. Work is on-going to complete a more granular representation of electricity generators in Ireland in LEAP, which will have an improved temporal resolution for each generation node.

5.5 Conclusions and Policy Implications

In this chapter I introduced a novel use of the Bass diffusion model, in conjunction with a new greenhouse gas emissions model for Ireland. I have shown the relevance of this multi-model approach by simulating two key policy goals for the period 2021-2030. The primary results of these pathways are shown in Figures 11 – 16. I argue that diffusion pathways and associated adopter categories illustrate four key insights.

First, implementation pathways matter for cumulative emissions savings and serve as a vital complement to end-year targets. The use of diffusion pathways with a bottom-up simulation model provides detailed insights into the steps required to realise targets e.g. which cars or homes are replaced or retrofitted in each year. Additionally, it aids monitoring progress to targets, improving implementation accountability and bridging the gap between current progress and future targets, providing a means to quantifiably assess aspirational policy targets.

Second, the quantification of early action shows it is possible to achieve 6 – 19% additional emission savings, relative to delayed action, in these scenarios. The results show that the most ambitious, CAP compliant, EV diffusion scenario can deliver an additional 1.23 MtCO2 eq. Regarding retrofitting, an additional 0.8 MtCO2eq reduction can be achieved through early adoption. Additionally, beyond the potential improved CO2 reductions, early action facilitates a slower phasing out of incumbent technologies, enabling more continuity in the shift away from petrol/ diesel alternatives over the period 2021 – 2030. For EVs, there is a need to significantly scale-up their percentage share of new vehicle sales immediately. The early adoption rate means that the scenario requires less EV penetration in later years, requiring 76% share of new vehicle sales by 2030 – relative to a 98% share of new vehicle sales in the late adoption scenario. For retrofitting, early adoption means the total number of retrofits does not exceed 61,000 per annum – relative to 72,000 per annum by 2030 in the late adoption scenario. Given the scale of the challenge to deliver these ambitious targets, the early introduction, coupled with a less disruptive transition, will reduce the pressure on the relatively new markets and place less strain on target delivery overall.

Third, the results of the precedent scenarios highlight the scale of the challenge and the unprecedented diffusion required to meet the 2030 targets. For EVs, effort which surpasses that of the most successful EV diffusion examples would be required to deliver CAP EV targets. The EV Norway scenario delivers 197,601 EVs (23.5% of CAP target), reaching a 25% share of new vehicle sales by 2030. The retrofitting scenario that delivers 235,000 deep retrofits (47% of CAP target) is at a scale that is substantially higher than has been achieved to date.

Fourth, the differences between early market and mainstream market adopters have consequences for appropriate policy design and the feasibility of achieving targets. The introduction of diffusion rates and adopter categories provides a mechanism to tailor policy formation to the specific characteristics of these target actor categories.

For EVs, early adopters are less motivated by financial incentives, which unfortunately means there are likely to be many free riders who benefitted from grant subsidies among the current cohort of EV owners. There are multiple policy implications as we seek to normalise the adoption of EVs and gain access to mainstream market actors, who are typically more influenced by financial incentives. Recent EV policy discourse has mentioned that the current grant subsidy scheme has a limited lifetime. Given the policy target of increased EV penetration, and the potential for less financial incentives, this presents a challenge for finding an effective policy mix which encourages widespread adoption of the new technology. Additionally, mainstream market actors are influenced by peers and external sources of authority, therefore endorsement by influential figures and the introduction of policies to actively manage the phase out of petrol and diesel incumbents is likely to be consequential.

For deep retrofitting, the limited data relating to early adopters presents a policy challenge, as it is likely many free riders exist within the 325 homes which participated in PDRG during the period 2017 – 2019. Additionally, as the average energy efficiency achieved as part of the PDRG is significantly greater (≤ 75 kWh/m2/year) than that expected within the current CAP target (≤ 100 kWh/m2/year), it is difficult to expect a similar policy to function as a useful means of moving beyond innovators and accessing early adopters. Given that mainstream market actors are more sensitive to price, the financial contribution from the State will have to (as a minimum) sustain or (in order to achieve higher diffusion) possibly grow, to support the continued roll-out of deep retrofits. As information campaigns are unlikely to motivate change among mainstream actors, a need for regulations as part of the policy mix for retrofitting should to be considered. Additionally, the preference among mainstream market actors is for standard solutions. Given the normally bespoke nature of retrofitting, this will be an enormous challenge for large scale uptake. Widespread retrofitting of homes is unlikely to happen until large-scale peer-to-peer examples displace the perception of retrofitting as a costly and disruptive event with limited benefits.

In theory, policies achieve maximum benefits because 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 the additional co-benefits of prioritising the least energy efficient dwellings. Future analysis within the transport sector could include the impact of modal shift within private passenger transport as ever increasing shares of EV penetration present a simplified solution to the decarbonisation of transport and ignores other important areas of concern such as congestion, equitable access to mobility, and the broader health benefits associated with cleaner air. This chapter and associated methodology can support the decision-making process and aid in policy prioritisation and resource allocation. While I acknowledge that the key assumptions and diffusion rates are exploratory, the analysis provides a pragmatic perspective on the implicit diffusion rates associated with existing end year targets.

6 Conclusions

This thesis aimed to enhance the capacity of energy policy simulation modelling and generate new knowledge to understand past and inform future climate action in Ireland. This section outlines the thesis conclusions as they apply to methodological developments and insights from ex-post/ ex-ante evidence-based policy analyses and recommendations. This thesis addressed the researched questions outlined in section 5. Each question is outlined below and addressed in brief, with reference to the appropriate chapter which further investigates the same:

(1) What analytical tools are suitable to address the diverse range of challenges facing energy system models in the 21st century?

In chapter 2 I explored the analytical tools developed as part of this thesis. I explored the concepts of ex-post and ex-ante analysis and the tools required to exploit them. Modern energy system models are tasked with addressing a broad range of modelling concerns such as complexity, uncertainty, interdisciplinarity, utilization, and scientific standards. The effective simulation of climate policy requires the set of tools which satisfy the planning, implementation, and review phases of the policy evaluation lifecycle. The tools I developed as part of this thesis serve to address these phases and some of the challenges identified for modern energy system models. In chapters 2 and 4 I present the new residential retrofit model (ArDEM-SQL), which I used to conduct an ex-post analysis of a retrofit support scheme (Mac Uidhir et al. 2019b; 2019a). I present the Application Script Editing Tool (ASET) alongside the newly developed LEAP Ireland GHG tool. These tools have been shown to fulfil the policy evaluation lifecycle and have been made available online to the broader energy modelling community and policy-makers. Lopion et al. (2018) established a set of three minimum requirements which must be satisfied for modelling tools to support governments with strategic decision making, including (1) national geographic coverage, (2) applicability to all energy sectors, and (3) supportive of the governmental decision making process. It is worth expanding the definition of the third criteria as there are many ways in which an energy system model can support the decision making process. Support should be defined here as improvements to model accessibility, data transparency, and improvements to a governments capacity to understand and operate an energy model. Ultimately the ArDEM-SQL and ASET tools have facilitated the development of the LEAP Ireland GHG tool, which satisfies this set of minimum criteria as it includes an energy system model on a national scale, all energy (and non-energy) sectors of the economy and has been made available to the national Environmental Protection Agency as part of its dissemination through training workshops and online[13], in response to the minimum criteria as defined by Lopion et al (2018).

(2) What enhancements can be made in energy policy simulation modelling to enhance modelling capability while simultaneously improving transparency?

In chapter 3 I presented a new methodology for the development of LEAP model structures and a means of conducting sensitivity analysis of key variables using the newly developed Application Script Editing Tool (ASET) interface. ASET utilises a series of accessible VBA interfaces to leverage advanced API scripting functionality in LEAP, allowing for easier sensitivity analysis of key variables and batch generation of scenarios. I presented a comparative case study to demonstrate the new tool, which explored some of the key differences, in terms of functionality and interaction, between the existing LEAP and ASET user interfaces. In chapters 2 and 4 I presented the new ArDEM-SQL, residential energy demand modelling tool, which I used to quantify the impact of a range of retrofit combinations and suggest a new method which could deliver increased emission reductions. In chapter 5 I presented the new LEAP Ireland GHG tool, a multi-sectoral model of energy, and non-energy demand and emissions for Ireland. Energy policy simulation modelling can be enhanced by introducing new functionality in a format which can be delivered through and accessible interface. There is an inherent trade-off between increased complexity

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[13] https://github.com/MaREI-EPMG/LEAP_Ireland

(often associated with new functionality), and the transparency of the modelling process. I utilised an established qualitative evaluation method in chapter 3 to show that the ASET tool improves the accessibility and repeatability of the LEAP modelling framework. These enhancements also apply to the ArDEM-SQL modelling tool. In response to the call from Wiese et al. (2018) for enhanced transparency in model development, these analytical tools, and their underlying data, have been made available online, improving the transparency of the modelling process, contributing to an open-source philosophy of energy system modelling, and progressing the scientific standard of the models in question.

(3) How can the ex-post evaluation of energy efficiency policies be used to understand past performance and deliver increased emission reductions in the future?

In chapter 4 I conducted an ex-post analysis of an existing residential retrofit scheme in Ireland, quantifying the emissions reduction associated with the number of known retrofits completed. In this analysis I identified potential alternative retrofit combinations within the retrofit scheme and quantified the impact of these changes. I utilised the new bespoke simulation modelling tool (ArDEM-SQL) to simulate the technical energy efficiency improvements associated with a range of retrofit combinations, as they apply to nine distinct building archetypes. I found that an additional 86% energy savings could have been technically achieved from the retrofit scheme through the implementation of bespoke retrofit combinations which adequately account for the pre-works condition of a dwelling. Energy efficiency policies were explored in the context of a retrofit scheme in Ireland. This analysis responds to the call of Hull et al. (2009) for additional ex-post assessment of energy efficiency policies. The ex-post evaluation of the retrofit activity to date identified that suboptimal retrofits are being completed on dwellings at present. I found that retrofit policies could deliver improved outcomes by adopting an output-based system in place of a measure-based system. The ArDEM-SQL tool, and underlying data, have been made available online. This improves the model transparency and supports the repeatability the work in the wider modelling community.

(4) How can the ex-ante evaluation of specific climate policies be used to gain greater insight into the steps required to deliver ambitious climate goals?

In chapter 5 I utilised a novel use of the Bass diffusion model (Bass 1969), in combination with the LEAP Ireland GHG model, to explore the impact of key national climate mitigation policies in Ireland. I examined the feasibility of these targets using precedent scenarios and a comparison between early and late diffusion pathways which deliver end-year targets for 2030. I found that the early diffusion of electric vehicles and residential retrofitting can deliver an additional 11% GHG reduction, relative to delayed action diffusion pathways. I leveraged the concept of diffusion of innovation and the Bass diffusion model to quantify an additional 2 $MtCO2_{eq}$ GHG reduction potential through different diffusion pathways. Scenario analysis provided a useful sense-check and warned against indiscriminately increasing ambition in the absence of robust evidence-based policy support which is underpinned by replicable energy models. The multi-model approach I employed allowed insight into the potential for the categorisation of adopter types, as they apply to the diffusion of EVs and residential retrofits. I leveraged the aggregated adopter categories defined by Egmond et al (2006) to explore adopter specific policy implications for the measures considered, highlighting the implications of existing and future interventions intended to deliver ambitious levels of EV adoption and residential retrofitting.

6.1 Methodological developments

This subsection describes each of the primary methodological developments and new simulation modelling tools completed as part of this thesis. Each newly developed methodology/ tool was designed to either add value to an existing energy system model or fulfil an identified gap in the current suite of available tools. Wiese et al. (2018) describe transparency of methods, code and data as the foundation of building upon existing scientific work in the field of energy systems modelling. While the policy insights presented in this thesis are interesting, the broader methodological developments, and new tools, serve to improve the scientific standard of energy systems modelling by improving transparency, access to the tools, and allowing for scrutiny of all methods employed. The ASET, ArDEM-SQL, and LEAP Ireland GHG modelling tools have all been made available as part of this thesis. Each new method is explored in more detail below e.g. Application Script Editing Tool (ASET) topology development and the Archetype Dwelling Energy Model – SQL (ArDEM-SQL). New simulation modelling tools include the LEAP Ireland GHG model and the sensitivity analysis functionality developed within ASET.

6.1.1 The Application Script Editing Tool

I developed the Application Script Editing Tool (ASET) to aid in the rapid creation of LEAP model structures and to populate data. The tool was needed to incorporate large datasets and more complex model topologies into the final LEAP Ireland GHG model. In addition, ASET functions as a means of conducting sensitivity analysis on key assumption in any LEAP model. This functionality provides a better understanding of the impact which key assumption have on final modelling results. The ability to define a minimum, maximum and step interval to conduct sensitivity analysis was not previously possible with LEAP and presents a novel approach to interrogating LEAP model key assumptions. ASET allows *most* features in LEAP to be controlled programmatically, offering powerful functionality which leverages the built-in Application Interface (API). The ASET tool represents an improvement to the scientific standard of the LEAP modelling framework as it improves the modelling transparency, replicability and open-access nature of the model, as defined by Wiese et al. (2018).

ASET utilises Microsoft (MS) Visual Basic for Applications (VBA) programming to generate simplified user interfaces (UI) for end users. These simplified UI's function to improve the model's utility and accessibility. The methodology allows LEAP energy system models to be created/ modified more efficiently than previously possible. This improves the LEAP modelling community's capacity to incorporate new data sets and to modify model structures appropriately, ensuring model structures are designed appropriately for the research questions they are investigating. This has previously been difficult and time consuming in LEAP due to use of the GUI alone. The development of more robust, powerful, and transparent energy models has advanced the relationship between energy models and the design of energy policy, especially with respect to their use in the exploration of ambitious energy and climate policy targets (Süsser et al. 2021). ASET's ability to rapidly update and even redesign LEAP models enables the ever-increasing need to support the interaction between energy models and energy policy. ASET was designed to provide for an entirely new means of creating/ interacting with a LEAP model. The tool leverages a limited subset of possible API functions to add the new features described here and in chapters 2 and 3 of this thesis.

6.1.2 Archetype Dwelling Energy Model – SQL

The newly developed Archetype Dwelling Energy Model – SQL (ArDEM-SQL) is a new simulation modelling tool, developed on the foundation of the IS EN 13790 - Dwelling Energy Assessment Protocol (DEAP) - (SEAI 2008). DEAP provides calculation methods for annual energy consumption of space/ water heating, lighting, pumps and fans. The ArDEM-SQL tool utilises a range of building input data from the BER database including, dwelling type, size and geometry, thermal insulation properties, building orientation data, end-use and fuel type information for space/ water heating and heating system efficiency. A detailed description of the BER database is included in Appendix A – Data in Brief Article, a published Data in Brief article (Mac Uidhir et al. 2019a) which was developed as part of this thesis. The methodological improvements and conversion to the Microsoft SQL platform allows the use of all 700,000 + BER records. The BER database has grown to more than 950,000 records since the publication of the ArDEM-SQL tool and its underlying data in 2020. This highlights the need for flexible tools which can accommodate changing datasets over time, a trend in energy system models observed by Lopion et al. (2018). The new simulation framework also improves model transparency as all governing demand calculations are explicitly visible in the ArDEM-SQL code. The ArDEM-SQL model (Mac Uidhir et al. 2019b), and all underlying data (Mac Uidhir et al. 2019a) are published and available online for the wider modelling community. The publication of the new model and underlying data builds on the work of Dineen et al. (2015), improving the capability of the modelling framework to analyse the complete BER database, and the transparency of the modelling process and assumptions.

6.1.3 LEAP Ireland Techno Economic GHG model

The LEAP Ireland GHG model presented in chapter 5 demonstrates a national model which provides for evidence-based policy support across multiple sectors of the Irish economy. The model contains a detailed technological representation of transport, residential, commercial services and non-energy agricultural demand and emissions for the period 2016 to 2050. The LEAP Ireland GHG model demonstrates the capacity to consider specific policy measures from the viewpoint of a carbon budget, shifting away from current policy design which tends to focus on end-year targets. Understanding specific policies from a carbon budget perspective highlights the need to understand cumulative carbon emissions in the context of deep decarbonisation strategies for Ireland. This model provides a sufficient level of technical detail to contribute useful policy insights and implementation pathways, presented on an accessible platform which can be used by both policymakers and energy modellers alike. The accessible platform and the models national coverage of all energy and non-energy sectors responds to Lopion’s set of three minimum requirements to usefully support governments with decision making (Lopion et al. 2018). The LEAP

Ireland GHG model (Mac Uidhir et al. 2020) is published online including access to all underlying data[14]. The publication of the new LEAP Ireland GHG model and underlying data builds on the work of Rogan et al. (2014) by (1) improving the data granularity of subsectors, (2) including new sectors not previously available e.g. non-energy GHG emissions, (3) significantly improving the transparency of the modelling tool as it has been made available online, (4) supporting the improved institutional capacity of the EPA to operate the tool via workshops, and (5) the development of new key policy insights e.g. the diffusion of electric vehicles and large-scale residential retrofitting in Ireland.

6.1.4 Bass model diffusion and exploratory coefficients

Chapter 5 investigated the impact of the diffusion of innovation within policy, leveraging the Bass model formula (Bass 1969) with exploratory innovation (p) and imitation (q) coefficients. This method provided insights into the required levels of diffusion necessary to deliver key policy targets in Ireland. The methodology was leveraged to conduct comparative “precedent scenarios” which explored the policy outcomes associated with known p, q values for electric vehicles (Massiani and Gohs 2015; Jensen et al. 2016), and residential retrofitting (M. Collins and Curtis 2017a). The range of scenarios serve to highlight the scale of the challenge with respect to delivering 2030 targets and provide for alternative implementation pathways which deliver these targets. The additional benefits associated with early implementation pathways were also explored using this methodology.

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[14] LEAP Ireland GHG, source: https://github.com/MaREI-EPMG/LEAP_Ireland

6.2 Value added

This thesis has presented a number of improvements and outputs which are beneficial to number of actors, including model developers, users and policy- makers. As these methodological improvements and outputs are of varying levels of significance to different actors, this section explores their value added within the context of the energy modelling community and beyond.

Firstly, for model developers, the ASET tool represents a step-change in the time taken to construct complex LEAP model topologies, reducing the time taken to develop new model structures from weeks and months to hours and days. Additionally, ASET represents an improvement in the open-source philosophy associated with the development of LEAP models and will facilitate other model developers to create new modular, bespoke plugins based on a range of future modelling needs. The ArDEM-SQL code and underlying data has been made available online and can be replicated in other regions with similar energy efficiency data of building stocks. The ArDEM-SQL model represents a significant improvement on the pre-existing ArDEM model both in terms of model transparency and utility. The LEAP Ireland GHG model has also been made available online, including underlying data and assumptions. This new national energy demand and emissions model represents a useful resource to model developers, facilitating model transparency and scrutiny in its on-going use to provide evidence based policy support in Ireland.

Secondly, for model users, the tools developed as part of this thesis provide new functionality previously unavailable. ASET allows for sensitivity analysis of key variables, without any knowledge of the underlying code which would be of more interest to model developers. The LEAP Ireland GHG model is provided on an accessible platform (LEAP), meaning users can interrogate model assumptions, data, and results in one coherent platform – without the need for advanced modelling skills.

Finally, for policy-makers, the LEAP Ireland GHG tool and the ex-post/ante analysis provide a means to bridge the gap between siloed simulation models such as CarSTOCK and ArDEM-SQL, presenting a single coherent modelling platform which can be easily understood and leveraged to gain insights into specific policy concerns e.g. residential retrofit pathways and the rapid diffusion of electric vehicles in Ireland. The analysis presented here questions the suitability of current retrofit supports and suggests a means to improve them. The consequences of bespoke policy design are explored in the context of early and mainstream market actors and the feasibility of achieving ambitious climate targets is also addressed. Policy-makers can continue to utilise the LEAP Ireland GHG tool to analyse future policy options, supporting the decision making process and transparency.

Wiese et al. (2018) discuss the advantages associated with the “openness” of a modelling framework, stating that “an open-source approach is a fundamental condition for complying with scientific standards”. The sharing of the modelling tools which I have developed is intended to answer this need for openness and framework sharing, with the goal of improving scientific standards within energy system simulation modelling. The new functionality of the tools developed serve to improve the utility of the modelling frameworks discussed. The ASET tool adds new functionality to LEAP while ArDEM-SQL leveraged an improved scripting platform to enable advanced ex-post analysis which was previously not possible (Uidhir et al. 2019). The LEAP Ireland GHG tool presented an analyst focused output which considered policy implementation pathways in place of end of year targets (Mac Uidhir, Rogan, and Gallachóir 2020). These ex-post and ex-ante analyses help to bridge the gap between model users and analysts, who are not always the same. Policy analysts need access to more accessible evidence-based modelling outputs which can be used to underpin future policy planning without the need for advanced modelling skills (Giannakidis et al. 2018).

6.3 Ex-Post Analysis

I conducted an ex-post analysis in chapter 4 which investigated the impact of the existing retrofit grant scheme known as the Better Energy Homes (BEH) for the period 2010 – 2015. Each grant was applied to one of nine distinct building archetypes for Irelands residential building stock. The analysis adds to the limited examples of ex-post analysis of residential energy efficiency policies in Ireland (Scheer et al. (2013); Dineen et al. (2015)) and responds to the call of (Hull et al. (2009) for additional ex-post assessment of energy efficiency policies. This analysis presented a new simulation model known as the Archetype Dwelling Energy Model-SQL (ArDEM-SQL) and quantified the additional energy saving which could have been achieved in an alternate set of retrofit combinations, applied to 112,000 known dwelling retrofits for this period of analysis (Uidhir et al. 2019). The simulation model utilised in excess of 700,000 records contained within the Building Energy Rating (BER) (SEAI 2019e) database to calibrate and simulate the alternate set of retrofit scenarios. The findings show that residential dwellings are undertaking sub-optimal retrofit measures and there are 86% additional energy savings which could be achieved using the alternate set of retrofit measures. The high frequency of sub-optimal retrofits has been shown in Ireland (Collins et al. 2016) and abroad (Gamtessa 2013). This analysis showed the need for a robust pre-works assessment of a buildings energy efficiency which could guide homeowners in choosing retrofit combinations that deliver improved energy savings and thermal comfort.

In addition to the quantification of the historic energy savings, this analysis provided for a new retrofit structure to aid in designing alternative archetype retrofit schemes which are output based, i.e. grants which are paid for achieving verified savings per unit grant in place of the current measure based grant system. The need to adequately account for the pre-works condition of a residential dwelling is also highlighted in this section.

6.4 Ex-Ante Analysis

The ex-ante analysis quantified the additional emission reductions which are technically achievable based on differing implementation pathways for key climate policy in Ireland. This analysis presented a novel use of the Bass diffusion model (Bass 1969) with the newly developed LEAP Ireland GHG model (Mac Uidhir et al. 2020), described in chapters 2 and 5, to investigate different technology diffusion rates associated with the large-scale introduction of electric vehicles (840,000 by 2030) and the retrofitting of residential dwellings (500,000 by 2030), including the installation of 400,000 heat pumps. The scenarios are all target compliant, i.e. reach the currently stated 2030 target – following different pathways. The results showed that the most ambitious early action scenario achieved an additional 2 MtCO2 reduction over the period 2020 – 2030, relative the least ambitious delayed action scenario.

This analysis explores the added benefits associated with early action and aids in provides for a more complete understanding of the full implications associated with approaching climate policy as part of a carbon budget and not simply an end year target. While there is uncertainty associated with carbon budgets, they represent a robust upper bound to the remaining CO2 which can be emitted during a certain period which aids in understanding the scale of the climate mitigation challenge (Matthews et al. 2017).

6.5 Recommendations

This section described the recommendations identified as part of the development of this thesis. These recommendations are considered in relation to (1) data gathering, (2) energy modelling, and (3) policy insights. Each of these recommendations is considered individually for clarity. Data Gathering

6.5.1 Data gathering

The effectiveness of an energy model to provide robust evidence-based policy support depends on the quality and granularity of data available. In short, an energy model is only as useful as the underlying data. In section 1.3 I presented a review of energy model classifications, which shows the *data requirements* of any energy model as a key defining characteristic (Van Beeck 1999; Hall and Buckley 2016). This subsection recommends improvements in data gathering which will support the on-going development and improvement of the LEAP Ireland GHG model as more complex and ambitious climate mitigation targets are considered across all sectors. The process of development for the LEAP Ireland GHG model highlighted specific areas/ subsectors where data collection can be improved.

This thesis has quantified the impact of a residential retrofit scheme due to the level of granular data available for the existing building stock and historic retrofit activity. While this provides useful insights into the potential for additional energy savings due to energy efficiency improvements, it could be improved if the associated BER database expanded the range of gathered information e.g. wall structure and metered energy consumption data for space/ water heating. There are clear gaps in the gathering of industry end-use data in Ireland. This thesis leveraged data from the UK DECC Industry end-use survey to provide energy balance consistent *estimates* for energy end-use within Irish industries. This data could be significantly improved for Ireland, improving the useful insights into alternative climate mitigation pathways for the industry sector. Detailed subsectoral data on public services such as annual building archetype energy demand by fuel type, similar to the commercial services section described in chapter 5 of this thesis, would represent a substantial improvement on the existing data available. The public transport subsector would benefit from additional data gathering activity on demand drivers such as public transport passenger-km by mode and the potential for active modes such as walking and cycling to offset the continued growth of carbon intensive private passenger transportation modes such as ICE vehicles.

6.5.2 Energy Modelling

Energy modelling activity has evolved over time to incorporate larger datasets and conduct more complex scenario analysis (Dodds et al. 2015; Lopion et al. 2018). Evidence based policy support depends on detailed bottom-up energy system models which can adequately simulate the effects of individual policy measures. Understanding the relationship between research question and the underlying capabilities of a specific energy model lies at the core for determining the choice of an appropriate model choice (Connolly et al. 2010). There is a need to continually review model structures and data availability to ensure the correct model is utilised, depending on the research scope.

LEAP provides a flexible modelling structure which can accommodate top-down and bottom-up modelling methodologies, incorporating different types of available data and presenting a coherent national model which incorporates all economic sectors. This flexibility is presented as part of a stable software package which is accessible to all users.

6.5.3 Policy Insights

The key policy insights from this thesis are rooted in the ex-post and ex-ante analyses conducted in chapters 4 and 5 respectively. There is a need for more robust ex-post analysis of government climate policy (Hull et al. 2009), understanding and evaluating the causes of policy success and failure is critical to producing effective evidence-based policy going forward. Policy insights from chapter 4 underpin recommendations for new methods of developing appropriate model structures which can address bespoke research questions in a timely fashion. The following key policy insights and recommendations from this thesis are summarised as follows:

- Energy models which provide evidence-based policy support need to be accessible and robust. If energy system models are to continue to address the emerging challenges facing climate policy formation then it is essential that they improve the transparency of their methodologies and underlying data assumptions, in line with scientific standards of repeatability and scrutiny.
- Many energy system models entail steep learning curves which make their findings/results inaccessible to policymakers. LEAP serves as an accessible bottom-up modelling tool which can effectively simulate individual policy measures and translate results to policymakers. This final step of result communication is often overlooked and undervalued in the energy modelling community.

C2/3

- Retrofit support schemes can be substantially improved through the implementation of bespoke dwelling retrofit supports based on the pre-works condition of a structure. A grant scheme which rewards verified savings instead of list of approved measures would deliver greater energy savings.
- Ex-post analysis of retrofit supports indicates there is a potential to improve energy savings by up to 86%, based on alternative simulated retrofit combinations.

C4

- Publication of energy system models and their underlying data aid in improving methodological transparency and encourage scrutiny of modelling results.
- The multi-model approach to assess the diffusion of electric vehicles and residential retrofitting suggests that 2030 Climate Action Plan (CAP) targets (840,000 EVs and 500,000 retrofits present significant challenges in terms of achievability. The required diffusion rates suggest that it would involve an unprecedented level of investment and commitment to deliver.
- Ex-ante evaluation of CAP targets and scenario analysis of potential carbon budgets indicate multiple benefits associated with early action. Early action and investment is important; emission reductions in the early delivery of EVs can achieve an additional 1.23 $MtCO_{2\ eq}$ savings, relative to a delayed action target compliant scenario, between 2020 and 2030. Similarly, the early delivery of dwelling retrofits can achieve an additional reduction of 0.8 $MtCO_{2\ eq}$ for the period 2020 – 2030.
- Precedent scenarios highlight the challenges associated with setting distant end of period targets without considering cumulative carbon budgets over a period of analysis.
- There is a difference between early market and mainstream market actors when considering public response to climate policy. The introduction of diffusion rates and adopter categories provides a mechanism to tailor policy formation to the specific characteristics of these target actor categories. Chapter 5 explored these policy types and discussed the implications for the diffusion of EVs and retrofitting at scale in Ireland.
- Early action in the delivery of EVs can achieve greater GHG reductions in the period 2020 – 2030 while simultaneously facilitating a more gradual transition away from existing petrol/ diesel engines.

C5

As Ireland continues to develop *no regret* solutions to the acknowledged climate crisis, we can rest assured that early action and the rapid deployment (at scale) of retrofitting and EVs is in the best interest of the climate and society. The evidence in this thesis supports these policies and suggests their adoption will have an overall net benefit to society. The development and publication of the simulation tools presented here support an improved transparency of modelling methods, data, and code. This forms the foundation to build upon an open-source philosophy of energy system modelling and contribute to the improvement of scientific standards and progress as defined by Wiese et al. (2018) and Lopion et al. (2018).

6.6 Future Research

This section outlines areas of future research which will support further improvement to the planning, implementation and evaluation stages within the policy simulation lifecycle outlined in section 2.1. Each stage will be inherently supported by further improving the subsectoral descriptions within the LEAP Ireland GHG model described below.

6.6.1 Improve LEAP sectoral descriptions

Policy planning will be improved through ongoing engagement with key government stakeholders to provide for bespoke sectoral representations within the LEAP Ireland GHG model and deliver robust Ex-Ante simulations of planned future policy (DCCAE 2017c). All energy models can benefit from improved descriptions of economic sectors and future research utilising the LEAP Ireland GHG model should continue to evaluate the best available data and endeavour to incorporate new information into the model description (Connolly et al. 2010). While this is true for all sectors, future work to improve the description of the Industry and Public services subsectors should be prioritised as recent changes in the publication of business energy data has resulted in changes to historic services and industry figures in Irelands energy balance (SEAI 2020b).

More robust data gathering within the Industrial sector – in line with the superimposed UK DECC data utilised within this thesis, would allow for sectoral specific energy efficiency measures which target individual subsectors by NACE category. At present the data gathered within the Business energy use survey does not allow for this type of analysis. Gathering this detailed industrial sector data will support the evaluation of existing Industry policy supports through an Ex-Post analysis of the Large Industry Energy Network (LIEN) and the Excellence in Energy Efficiency Design (EXEED) programmes.

Public Services would benefit from additional data gathering activity as energy end-use within this sector is not transparent. While data related to total residential dwelling activity is quite comprehensive, an in-depth survey of residential appliance energy use would also provide useful data for future research. It would be useful if this data were linked directly with the information already contained within the BER database. This data would aid in a deeper understanding of appliance energy use, applied to distinct archetypes already in use within LEAP.

Improved representation of supply side, electricity generation portfolios in LEAP would facilitate a better understanding of the supply-side impact of policies that rely on large scale electrification e.g., electric vehicles and heat pumps. At present, section 5.4.3 highlights the results of such an analysis, based on two key climate policies in an Irish context. Given the goal of achieving 70% RES-E by 2030, this more granular, detailed representation of the electricity generation profile is important.

The continued development and improvement of sectoral representations will continue as part of the Climate Action Modelling Group (CAMG), guided by the requirements to provide evidence-based policy support to deliver the Climate Action Plan. The LEAP Ireland GHG model will support the ongoing implementation of Ireland’s existing Climate Action Plan (Government of Ireland 2019), and future iterations of the same, through continual engagement, evaluation, and appropriate updating. This will also support the continued capacity development within government.

6.6.2 Extend scenario analysis

In addition to the CAP EV and residential retrofitting policy scenarios included with the developed LEAP Ireland GHG model there is a need to extend the range of scenarios to include additional policies outlined within the Climate Action Plan. These scenarios could include the potential for emissions reductions due to increased public transport, changes in agricultural livestock demographics, increased RES-E targets, and the broader impacts associated with LULUCF.

LEAPs integrated support to analyse the associated health benefits due to the effects of air pollutants and particulate matter could be utilised in a range of future scenarios. This research would provide important insights into the long-term health benefits associated with decarbonisation scenarios as there are currently 1,300 premature deaths reported annually in Ireland as a result of fine particulate matter (PM 2.5) (EPA 2020b). Use of this functionality would require further model development to include these air pollutants and particulate matter for each sector.

6.6.3 Extend LEAP 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 model to utilise the LEAP marginal abatement cost curve tool developed within UCC. Hall and Buckley (2016) state that the inclusion of cost is important to help define the econometric nature of any energy system model. The inclusion of cost would also aid in linking the LEAP Ireland GHG models to other energy system optimisation models which rely heavily on cost figures e.g. the Irish TIMES model (Ó Gallachóir et al. 2012).

6.6.4 Improve documentation

On-going development and improvement to the documentation associated with ASET, ArDEM-SQL, and the LEAP Ireland GHG tool should be prioritised. Improved documentation which goes beyond the *usability* of the tools (see section 3.4 for ASET comparison) will support an open-source philosophy in the on-going development of these tools, supporting transparency, repeatability, and scrutiny of these models, ultimately improving the scientific standards within the energy modelling community and delivering improved evidence-based support to decision-makers (Wiese et al. 2018).

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Appendices

Appendix A – Data in Brief Article

Title: Residential stock data and dataset on energy efficiency characteristics of residential building fabrics in Ireland

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Abstract

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)(Mac Uidhir et al. 2019b). 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)(EU Parliament and the Council of the EU 2010). Data is collected using the Dwelling Energy Assessment Procedure (DEAP) (SEAI 2008). DEAP is used to produce energy performance certificates known as Building Energy Ratings (BER). A BER indicates a buildings 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

Keywords

Residential Energy Efficiency Database, Building Energy Rating, Energy Performance Certificates, Dwelling Energy Assessment Procedure

Specifications Table

Subject	Engineering (General)
Specific subject area	Residential dwelling energy performance characteristics and stock for Ireland.
Type of data	Microsoft SQL Database, Excel Spreadsheet with supplementary tables
How data were acquired	• BER database information was acquired from the Sustainable Energy Authority of Ireland (SEAI). Provided as unfiltered database of all BER records. Microsoft SQL used to process/ query this database. • PWBER data acquired from SEAI. • National building census data gathered from Central statistics office (CSO).
Data format	Filtered model input data, SQL format Raw Model Input data
Parameters for data collection	All data on construction characteristics impacting energy performance of residential dwellings in Ireland.
Description of data collection	Data made available by the Sustainable Energy Authority of Ireland. Stored in SQL database and filtered using data collection parameters specified in section 2.1.4. CSO National Stock acquired from the Central Statistics Office (CSO)

Data source location	CSO/ PWBER data related to Ireland, BER data provided provide at postal code level for Dublin and City/County level for all other counties.
Data accessibility	*Data is provided with this article in the following formats:* • BER Database is provided with the article in the form of SQL database attachment. • PWBER Data provided as supplementary Excel file • CSO data is provided within this article
Related research article	T. Mac Uidhir, F. Rogan, M. Collins, J. Curtis, B. Ó Gallachóir. Improving energy savings from a residential retrofit policy: a new model to inform better retrofit decisions. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2019.109656 (Mac Uidhir et al. 2019b)

Value of the Data

- This data provides transparency to model input parameters used in the evaluation of energy efficiency measures for residential dwellings in Ireland. The data provides a detailed source of building fabric information in a queryable format.

- Energy analysts can benefit from the detailed building fabric information, serving to aid in replication of residential energy efficiency analyses. Policymakers can also benefit from detailed analyses underpinning evidence-based policy support.

- This data can be used to gain insights into the link between energy performance of specific building fabrics and the associated net improvement to building energy efficiency.

1. Data

The supplementary SQL database attachment provided with this article contains detailed building fabric performance characteristics for 735,906 dwelling records. Informational data is provided for each record in the form of a description of the dwelling type (Apartment, Basement Dwelling, Detached house, End of terrace house, Ground-floor apartment, House, Maisonette, Mid-floor apartment, Mid-terrace house, Semi-detached house, Top-floor apartment), year of construction, dwelling location (postal code for Dublin and City/County description for all other counties), date/ purpose of the BER assessment (Grant Support, New Dwelling, Private Letting, Sale, Social Housing Letting, Unknown, Other). Building fabric data is provided in the form of U-Values (W/m^2 K) and surface area (m^2) for each dwelling's walls, roof, floors, windows, and doors. The number of building stories, ground floor area (m^2), heating system efficiency and the main/ secondary space/ water heating fuels are also provided for each record.

The datasets within this article provide CSO census (CSO 2016) and BER data on the number of dwellings by type, year of construction and BER grade category (table 2). This data is presented in table 1 and table 2.

Data specifying the total number of dwelling types, by year of construction, is presented in table 1. This data was collected as part of the national census completed in 2016. The energy performance of building types is not included in this data.

Table 0-1 CSO Census data, number dwellings by type and year of construction

House Type	**< 1919**	**1919 to 1945**	**1946 to 1960**	**1961 to 1970**	**1971 to 1980**	**1981 to 1990**	**1991 to 2000**	**2001 to 2005**	**> 2006**
Detached house	74125	46847	42427	42221	97698	86491	111455	175223	18050
Semi-detached house	15478	25149	39121	43364	71056	49522	80437	115869	5900
Terraced house	36956	31594	38410	24370	36397	23557	19161	51682	3127
Flat or apartment in a purpose-built block	3159	2434	3415	4039	5873	9310	27108	84521	5717
Apartment in converted	9575	2653	1745	1186	1176	1039	1530	2247	365

house/commercial building									
Bed-sit	972	306	229	195	152	136	142	152	42
Not stated	935	685	760	666	1121	989	978	2069	235

Data specifying the total number of building archetypes, by year of construction and energy performance grouping is presented in table 2. This dataset is collected as part of Building Energy Rating (BER) programme operated by SEAI. A BER is compulsory for all new dwellings, dwellings being sold/ rented, dwellings in receipt of an SEAI energy efficiency grant.

Table 0-2 BER data: Number of dwelling archetypes by type, year of construction and BER group

Building Archetype	**< 1919**	**1919 to 1945**	**1946 to 1960**	**1961 to 1970**	**1971 to 1980**	**1981 to 1990**	**1991 to 2000**	**2000 to 2005**	**>2006**
Apartment AB	132	296	185	422	249	180	964	6407	22054
Apartment CD	1769	1065	1044	1450	2442	4091	17611	31561	19926
Apartment EFG	7216	2371	1615	1500	1963	3187	8587	6397	2212
Terrace AB	644	893	1198	904	1757	1759	2796	4909	31761
Terrace CD	6401	9590	12820	12818	30992	30395	45837	50996	22915
Terrace EFG	13929	13619	15040	8137	13195	7499	7831	3727	1088
Detached AB	393	355	404	400	944	1195	3173	4929	15399
Detached CD	3777	3118	3598	4883	16510	18647	31420	26730	9761
Detached EFG	11400	8329	6755	5432	9209	4881	3163	1149	573
All Types	45661	39636	42659	35946	77261	71834	121382	136805	125689

The BER database, included as supplementary material, represents a range of 140 individual building characteristics as they apply to 735,906 dwellings. The average U-Value (W/m^{2}K) for walls, roof and windows, for each of the nine dwelling archetypes and year of construction bracket, is shown in tables 3,4 and 5 respectively. A complete list of building characteristics is included and further described in table 7.

Table 0-3 BER data: average U-value (W/m^{2}K) for ***external walls*** *by dwelling type, BER category and year of construction grouping*

Building Archetype	< 1919	1919 to 1945	1946 to 1960	1961 to 1970	1971 to 1980	1981 to 1990	1991 to 2000	2000 to 2005	>2006
Apartment AB	0.50	0.38	0.37	0.65	0.48	0.46	0.52	0.47	0.34
Apartment CD	1.06	0.98	0.99	0.96	0.78	0.55	0.57	0.54	0.43
Apartment EFG	1.59	1.59	1.64	1.52	1.20	0.64	0.64	0.58	0.54
Terrace AB	0.38	0.34	0.33	0.34	0.38	0.38	0.38	0.38	0.24
Terrace CD	1.12	0.92	0.94	0.85	0.72	0.48	0.47	0.45	0.35
Terrace EFG	1.77	1.73	1.76	1.62	1.32	0.54	0.44	0.39	0.37
Detached AB	0.36	0.31	0.30	0.30	0.33	0.35	0.38	0.37	0.25
Detached CD	0.95	0.81	0.70	0.67	0.60	0.46	0.44	0.44	0.35
Detached EFG	1.70	1.65	1.53	1.36	1.13	0.58	0.49	0.45	0.44

Table 0-4 average U-value (W/m^{2}K) for ***roof*** *by dwelling type, BER category and year of construction grouping*

Building Archetype	< 1919	1919 to 1945	1946 to 1960	1961 to 1970	1971 to 1980	1981 to 1990	1991 to 2000	2000 to 2005	>2006
Apartment AB	0.12	0.07	0.08	0.19	0.13	0.09	0.10	0.10	0.08
Apartment CD	0.29	0.24	0.29	0.46	0.22	0.15	0.15	0.14	0.12
Apartment EFG	0.94	0.98	0.92	0.84	0.50	0.23	0.21	0.18	0.18
Terrace AB	0.22	0.21	0.22	0.20	0.19	0.18	0.19	0.21	0.15
Terrace CD	0.57	0.45	0.42	0.39	0.28	0.25	0.27	0.25	0.21
Terrace EFG	1.46	1.15	1.00	0.84	0.58	0.31	0.26	0.22	0.48
Detached AB	0.21	0.20	0.20	0.21	0.20	0.22	0.24	0.23	0.17
Detached CD	0.47	0.41	0.36	0.36	0.28	0.25	0.27	0.27	0.25

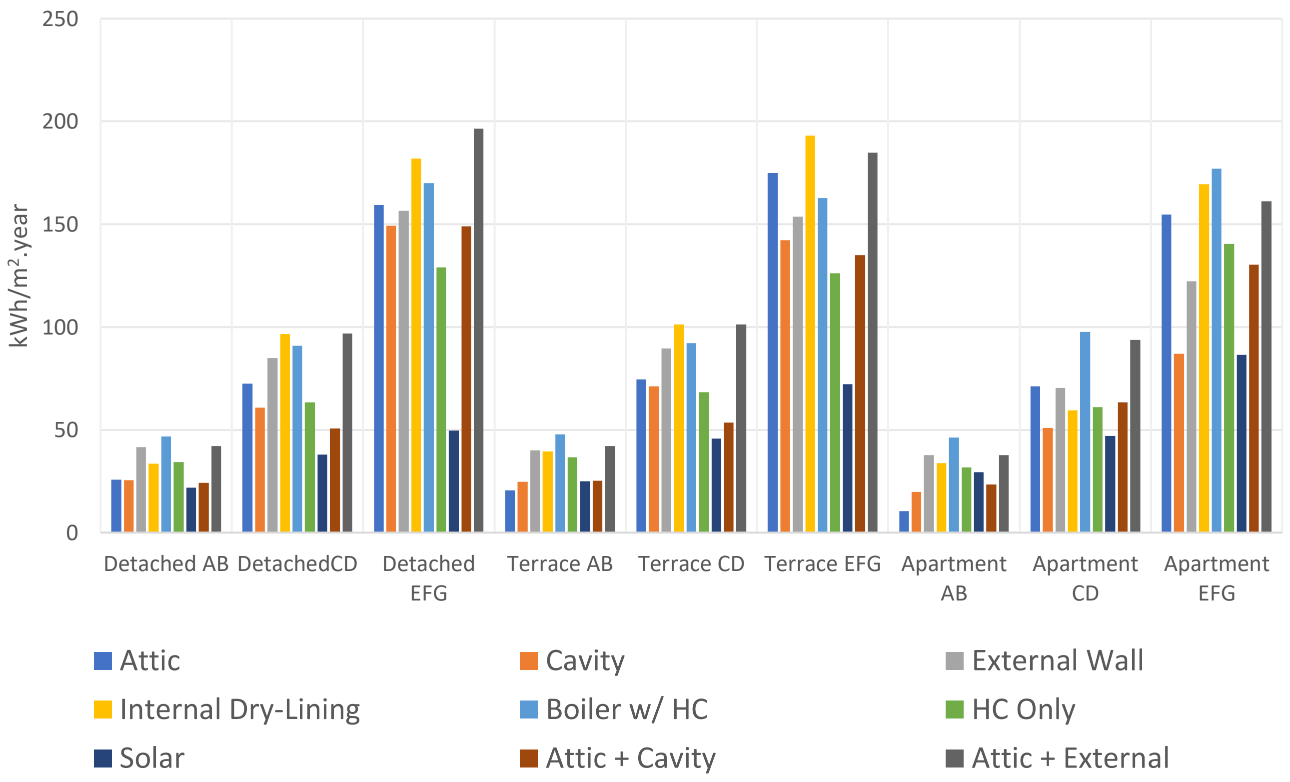
Detached EFG	1.30	1.15	0.95	0.77	0.57	0.36	0.34	0.41	0.74

Table 0-5 average U-value (W/m^{2}K) for ***windows*** *by dwelling type, BER category and year of construction grouping*

Building Archetype	**< 1919**	**1919 to 1945**	**1946 to 1960**	**1961 to 1970**	**1971 to 1980**	**1981 to 1990**	**1991 to 2000**	**2000 to 2005**	**>2006**
Apartment AB	2.60	2.35	2.22	2.31	2.05	2.62	2.63	2.40	1.85
Apartment CD	3.08	3.01	2.85	2.78	2.82	2.87	2.89	2.60	2.25
Apartment EFG	3.53	3.44	3.39	3.39	3.34	3.17	2.96	2.68	2.32
Terrace AB	2.08	1.97	1.91	2.25	2.23	2.31	2.33	2.38	1.62
Terrace CD	2.93	2.77	2.82	2.87	2.88	2.93	2.85	2.63	2.25
Terrace EFG	3.70	3.58	3.59	3.37	3.21	3.18	2.97	2.77	2.31
Detached AB	1.97	1.83	1.79	1.86	2.06	2.35	2.58	2.43	1.70
Detached CD	2.81	2.74	2.76	2.82	2.85	2.88	2.83	2.61	2.26
Detached EFG	3.57	3.47	3.45	3.36	3.29	3.32	2.99	2.75	2.33

The PWBER dataset included as supplementary material represents the average energy efficiency improvement (kWh/m^2 year), for a range of 50 retrofit combinations, as they apply to nine distinct building archetypes. These archetypes include energy performance groupings (AB, CD, EFG) applied to apartment, detached, and terraced dwellings. Figure 1 illustrates the average annual energy savings (kWh/ m2 year) associated with nine distinct retrofit combinations from the PWBER dataset.

Figure 0-1 PWBER Data: Average annual energy efficiency improvement by retrofit combination and dwelling archetype.



2. Experimental Design, Materials, and Methods

This section outlines the steps required to acquire, process, and analyse the data referenced in this article.

2.1 Census Data on Housing in Ireland

The CSO provide direct access to 2016 census results for building type by year of construction through an online portal (CSO 2016). CSO survey definitions for building type differ from other sources and are therefore aggregated into three building types (Detached, Terraced, Apartment), as shown below in table 6.

Table 0-6 CSO Dwelling Type Definitions - Census 2016

Dwelling Type (CSO)	**Dwelling Type Aggregated**
Detached House	Detached
Semi-Detached House	Terraced
Terraced House	
Flat or Apartment in purpose-built block	Apartment
Flat or Apartment in converted house or commercial building	
Bed-Sit	N/A
Not Stated	N/A

2.2 BER Database

This process describes the acquisition and filtering procedures to produce the included BER input database. Tables 2,3,4 and 5 are derived directly from the filtered BER database.

1.1.1 The Sustainable Energy Authority of Ireland host a public national depository of all BER records, available for download in excel format (SEAI 2019e). This format is not suitable for analysis and required further processing to produce queryable database in SQL format.

1.1.2 This Raw Data is imported into a blank Microsoft SQL database table using SQL Server Integration Services (SSIS). SSIS is used for complex data transformation and managing/ filtering data (Microsoft 2017a). This process allows all 735,906 records to be queried individually. A series of scripts are then utilised to manage and filter the database, adding unique record IDs for each record in the database and removing unwanted outliers. Each script is provided with this article and its function described here.

1.1.3 Using SQL Server Management studio (SSMS) (Microsoft 2017b). A unique ID is associated with each record in the BER database. Executing SQL Script 1 creates a new database table which includes a record ID column and inserts all other records accordingly. This record ID is used to track deleted records upon removal of outliers. The ID is helpful with respect to error handling and understanding the reason an individual record might be removed.

1.1.4 Outliers are removed from the database, removing any records which satisfy the following criteria; Results are provisional, Main floor area = 0m^2, Ground floor area <= 30m^2, Ground floor area > 1000m^2, Apartments/ Terraced Dwellings with floor area > 500m^2, Heating System Efficiency < 19%, Heating System Adjustment Factor < 0.7, Main Water Heating system efficiency > 450%, Main Water Heating system efficiency < 19%, Water Heating Efficiency Adjustment Factor < 0.7, Living Area Percentage > 90, Living Area Percentage < 5, Supplementary Heat Fraction $\notin \{0,0.1,0.15,0.2\}$, Declared Loss Factor > 20, Thermal Bridging Factor < 0, Thermal Bridging Factor > 0.15, Dwelling Type Description $\in$ {House, Basement Dwelling, Maisonette} – resulting in removal of 46,661 records.

Executing SQL Script 2 removes record outliers from the database, tracking the total number of records removed from the database for each criterion stated.

1.1.5 Executing SQL Script 3 creates the final table and inserts all relevant values from the processed database. This table forms the input data for use within the energy system model defined as the SQL Archetype Dwelling Energy Model (ArDEM-SQL) (Mac Uidhir et al. 2019b). Table 8 shows the complete list of input variables in this final table. The complete database backup is included as supplementary SQL backup (Backup.bak).

Table 0-7 Data input variables name and description

SQL input variable name	**SQL input variable description**

Record ID	Unique BER record identifier
CountyName	BER record geographical location (county)
DwellingTypeDescr	Description of dwelling type e.g. Detached, Apartment
Year_of_Construction	Building year of construction
TypeofRating	Nature of BER record, Final, Existing or Provisional
EnergyRating	Letter grade for energy performance e.g. A1, A2, A3, B1, B2, B3, C1, C2, C3, D1, D2, E1, E2, F, G
BerRating	Numerical energy performance rating (kWh/m^2.year)
GroundFloorArea(sq m)	Ground Floor Area (m^2)
UValueWall	Wall U-Value (W/m^{2}K)
UValueRoof	Roof U-Value (W/m^{2}K)
UValueFloor	Floor U-Value (W/m^{2}K)
UValueWindow	Window U-Value (W/m^{2}K)
UvalueDoor	Door U-Value (W/m^{2}K)
WallArea	Wall Area (m^2)
RoofArea	Roof Area (m^2)
FloorArea	Floor Area (m^2)
WindowArea	Window Area (m^2)
DoorArea	Door Area (m^2)
NoStoreys	Number Storeys per dwelling
CO2Rating	BER CO2 intensity rating (kgCO2/m$^{2\cdot}$yr)
MainSpaceHeatingFuel	Predominant fuel used for Main Space Heating
MainWaterHeatingFuel	Predominant fuel used for Main Water Heating

HSMainSystemEfficiency	Main Heating System Efficiency (%)
HSEffAdjFactor	Heating system energy efficiency adjustment factor
HSSupplHeatFraction	Supplementary Heating system fraction of heating requirement
HSSupplSystemEff	Supplementary heating system efficiency (%)
WHMainSystemEff	Main Water heating System Efficiency (%)
WHEffAdjFactor	Water Heating Efficiency Adjustment Factor
SupplSHFuel	Supplementary Space Heating fuel
SupplWHFuel	Supplementary Water Heating Fuel
NoOfChimneys	Number of Chimney stacks in dwelling
NoOfOpenFlues	Number of Open Flues in dwelling
NoOfFansAndVents	Number of fans and vents in dwelling
NoOfFluelessGasFires	Number of Gas Fires not including Flues
DraftLobby	Is a draft lobby present on entrance (yes/no)
VentilationMethod	Dwelling ventilation method e.g. Natural Ventilation
StructureType	Masonry, Timber or Steel frame
SuspendedWoodenFloor	Is there a suspended wooden floor in dwelling (yes/no)
PercentageDraughtStripped	Percentage of floor draught stripped (%)
NoOfSidesSheltered	Number of sheltered walls
PermeabilityTest	Was a permeability test performed (yes/no)
PermeabilityTestResult	Permeability test result (m^3/hour)
TempAdjustment	Applied space heating temperature adjustment - dependent on space heating control category (°C)

HeatSystemControlCat	Heating system control category ID
HeatSystemResponseCat	Heating system response category ID
NoCentralHeatingPumps	Number of central heating pumps
UndergroundHeating	Does dwelling utilise underfloor heating (yes/no)
GroundFloorUValue	Ground floor U-Value (W/m^{2}K)
DistributionLosses	Hot water heating distribution losses - dependent on hot water storage insulation (kWh/year)
StorageLosses	Hot water storage losses
SolarHotWaterHeating	Is solar water heating used in dwelling (yes/no)
ElecImmersionInSummer	Supplementary electric immersion used in summer months (yes/no)
CombiBoiler	Is Combi boiler used in dwelling (yes/no)
WaterStorageVolume	Hot water storage volume (L)
InsulationType	Hot water storage insulation type e.g. Loose Jacket
InsulationThickness	Hot water storage insulation thickness (mm)
PrimaryCircuitLoss	Hot water primary circuit losses (kWh/year)
GroundFloorArea	Total ground floor area (m^2)
GroundFloorHeight	Total ground floor height (m)
FirstFloorArea	Total first floor area (m^2)
FirstFloorHeight	Total first floor height (m)
SecondFloorArea	Total second floor area (m^2)
SecondFloorHeight	Total second floor height (m)
ThirdFloorArea	Total third floor area (m^2)
ThirdFloorHeight	Total third floor height (m)

ThermalBridgingFactor	Transmission heat loss due to thermal bridging (W/m^2.K)
ThermalMassCategory	Index of heat capacity required, rated ow, medium-low, medium, medium-high, or high
PredominantRoofTypeArea	Total area of main roof (m^2)
PredominantRoofType	Total main roof construction type
LowEnergyLightingPercent	Percentage of energy efficiency lighting installed (%)
LivingAreaPercent	Percentage of building used for living space (%)
RoomInRoofArea	Is attic converted to living space (yes/no)
MainFloorArea	Total dwelling floor area (m^2)
PurposeOfRating	Reason for BER assessment e.g. Sale, Retrofitting
DateOfAssessment	Date of BER assessment

Appendix B – Meteorological data for ArDEM-SQL simulation

Metric	Month	Value (°C)
Mean External Temperature	January	5.3
Mean External Temperature	February	5.5
Mean External Temperature	March	7
Mean External Temperature	April	8.3
Mean External Temperature	May	11
Mean External Temperature	June	13.5
Mean External Temperature	July	15.5
Mean External Temperature	August	15.2
Mean External Temperature	September	13.3
Mean External Temperature	October	10.4
Mean External Temperature	November	7.5
Mean External Temperature	December	6

Appendix C – ArDEM-SQL Simulation characteristics

ArDem (Columns)

	Insert Statement
RecordID	RecordID
DwellingType	@dwellingtype
YearOfConstruction	@yearofconstruction
TFA	@tfa
Volume	@volume
LivingAreaFraction	@livingareafraction
LivingArea	@livingarea
VHLTotal (m3/h)	@vhltotal
VHLTotal (ac/h)	@vhl_ach
OpeningInfiltration	@openinginfil
StructuralAirTightness	@structuralAirTightness
AirPermeabilityTest_Completed	@airpermtest
StructureType	@structuretype
WallType $^{\text{added}}$	@walltype
AirPermeabilityTest_Result	@airpermresult
WoodFloorSuspend_Result	@floorsuspendedinfil
DraughtStripped_Result	@DraughtStripped
StructuralInfiltration	@structuralinfil
Infiltration1	@infiltration_1
Infiltration_Final (ac/h)	@infiltration_Final
EffectiveAirChange(ac/h)	@effectiveairchange
VentilationHeatLoss(W/K)	@ventilationHeatLoss
EffectiveGlazedCollectingArea(m2)	@effectiveCollectingArea
GlazingRatio	@glazingratio
UValue_Window(W/m2K)	@Window_U_Final
FabricHeatLoss(W/K)	@FabricHeatLoss
HeatLossCoefficient_Final(W/K)	@HeatLossCoefficient_Final
HeatLossParamter_Final(W/Km2)	@HeatLossParameter
Occupancy	@occupancy
HotWaterUsage(V.eqLat60C)	@HotWaterUsage
HotWaterEnergyRequirement(kWh/y)	@HotWaterEnergyRequirement
HotWaterEnergyRequirement_AtTap(kWh/y)	@HotWaterEnergyRequirement_AtTap
DistributionLosses(kWh/y	@distlosses
StorageLosses_Final(kWh/y)	@storageloss_final
WaterCircuitloss(kWh/y)	@water_Cicuit_loss_occupancy
Water_Output_Total	@hotwateroutputbd
Output_Main_WaterHeater(kWh/y)	@waterheater_output_main
Output_Secondary_WaterHeater(kWh/y)	@waterheater_output_supplementary
HeatGains_WaterSystem(kWh/y)	@water_system_heat_Gains
HeatGains_WaterSystem_Watts(W)	@water_system_heat_gains_watts
Lighting_Basic(kWh/y)	@lightingconsumption_basic

LightingConsumption_Annual(kWh/y)	@lighting_consumption_annual
LightingInternalGains(W)	@lighting_internal_gains_Watts
InternalGains_All(W)	@internal_Gains_all
Dwelling_TimeConstant1(h)	@utilisation_factor_gains
ParameterA(h)	@ParameterA_final
Mean_Int_Temp_Week(C)	@mean_int_temp_per_week_C
HeatUse_HeatingSeason_Oct-May(kWh/y)	@HtUse_Heat_Use_HeatingSeason_Total_kWh_year
HeatUse_All_Year(kWh/y)	@HtUse_Heat_Use_FULLYear_Total_kWh_year
AdjustedInternalTemp	@SH_Living_Temp_Adjusted
Adjusted_NonLiving_Space_Temp	@SH_NON_Living_Space_Temperature
Mean_Internal_Temp_Heating_hours	@SH_Mean_Internal_Temp_Heating_hours
SH_Control_Related_Heat_Waste	@SH_Additional_Heat_emission_Due_to_non_ideal_Control
SH_GrossHeatEmissions	@SH_Gross_Heat_Emissions
Pumps&Fans_Elec_Consumption(kWh/y)	@SH_Pumps_Fans_Elec_Consumption_Total_kWh_y
Pumps&Fans_Heat_Gains(W)	@SH_Pumps_Fans_Heat_Gains_Total_Watts
SH_Avg_UtilisationFactor	@SH_Average_Utilisation_Factor
NetHeat_Emissions(kWh/y)	@HS_Net_heat_emissions_kWh_y
Additional_Floor_HeatLoss	@SH_Additional_Heat_Loss_Floor
SH_Requirement_Annual(kWh/y)	@SH_Annual_Requirement_kWh_y
SpaceHeatingRequirement_Main(kWh/y)	@ER_Energy_Required_Main_Space_Heating_kWh_y

Appendix D – Application Programming Interface command set for ASET

LEAP API Object	Type	Read/ Write	Description
ActiveArea	Variant	R/W	Get/Set active area
ActiveBranch	Variant	R/W	Get/set active branch
ActiveRegion	Variant	R/W	Get/Set active region
ActiveScenario	Variant	R/W	Get/set active scenario
ActiveScript	String	R	filename of active script
ActiveUnit	Variant	R/W	gets or sets active unit in the results
ActiveVariable	Variant	R/W	get/set active variable
ActiveView	Variant	R/W	get/set active view (e.g. Analysis, Results…)
ActiveYear	Integer	R/W	get/set active year in results
AddAggregateIntensity	Object	R/W	add new agg. Energy intensity category
AddCategory	Object	R/W	add a new demand category
AddFeedstock	Object	R/W	add a new feedstock branch
AddIndicator	Object	R/W	Adds indicator branch to specified tree
AddIndicatorCategory	Object	R/W	Add new indicator category
AddKeyAssumption	Object	R/W	Add new key assumption
AddKeyAssumptionCategory	Object	R/W	Add new key assumption category
AddModule	Object	R/W	Add new transformation module e.g. Elec Transformation & Distribution
AddNonEnergySectorCategory	Object	R/W	Add new non-energy sector category
AddNonEnergySectorEffect	Object	R/W	Add new non-energy sector effect
AddOutput	Object	R/W	Add new transformation output fuel
AddProcess	Object	R/W	Add new transformation process
AddSimpleProcess	Object	R/W	Add new simple process
AddTechnology	Object	R/W	Add new Demand technology

AddTEDEffects	Object	R/W	Add emission factors associated with TED ID
AddTotalTechnology	Object	R/W	Add new Total Technology
AddUsefulIntensity	Object	R/W	Add new useful energy intensity branch
AfterCalc	String	R/W	Get/set the filename for script that occurs after all calculations
AfterScenarioCalc	String	R/W	Get/set the filename for script that occurs after each scenario is calculated
AllowEfficienciesOver100	Boolean	R/W	Get/set whether LEAP allows efficiencies > 100%
AllowGrowthOnShares	Boolean	R/W	Get/set whether LEAP allows growth functions on Shares
AllowLaggedResults	Boolean	R/W	Get/ Set whether LEAP allows expressions to reference lagged results
AllResultsSaved	Boolean	R/W	Get/set save all results or only specified sets
AreaCountry	String	R/W	Get/set name of country associated with area
Areas	Object	R	Collection of all LEAP Areas on computer
AreaScale	Integer	R/W	Get/Set scale of an area
AssumeNoRegionalTrade	Boolean	R/W	Get set assumption on regional trade
BaseYear	Integer	R/W	Get/set base year for LEAP model
BDEInstalled	Boolean	R	Borland Database Engine (deprecated as of 2008)
BeforeCalc	String	R/W	Get/Set filename for script to run before calculation
BeforeScenarioCalc	String	R/W	Get/Set filename for script to run before scenario calculations
BeforeTransformationCalc	String	R/W	Get/ set filename for script to run before Transformation calculations
Branch(BranchName)	Object	R	Previously used to define branches - Obsolete use BRANCHES
Branches	Object	R/W	Returns Collection of visible branches in tree - use with ID
BranchVariable	Object	R/W	Gets LEAP variable for a branch - i.e. Energy Intensity etc.
BringToFront	Method	NA	Brings LEAP application (UI) window to the front of window stack

CalcPrimaryEnergy	Boolean	R/W	Get/ set whether additional calcs are used to allocate energy demand
Calculate(Calculate WEAP)	Method	R/W	Starts LEAP Calc - returns to Results, TRUE/FALSE for WEAP
CanQuit	Boolean	R	Gets whether LEAP can close down & preps for close down
CheckSurplusProduction	Boolean	R/W	Get/Set whether check for surplus production in Transformation calcs.
CheckUnmetRequirements	Boolean	R/W	Get/Set whether check for unmet requirements in Transformation calcs.
Clear	Method	NA	Clears PRINT messages in built in Script Editor
CLS	Method	NA	Clears PRINT messages in built in Script Editor
ComputerInfo	String	R	Gets system information for PC
CopyEnergyBalance Chart	Method	NA	Copies the current energy balance to Clipboard
CopyEnergyBalance Table	Method	NA	Copies the current energy balance TABLE to Clipboard
CopyFile	Method	NA	Copy a system file from one location to another
CopyResultsChart	Method	NA	Copies current results view chart to clipboard
CopyResultsTable	Method	NA	Copies current results view Table chart to clipboard
Countries	Object	R	Gets collection of all countries
CreateDirectory	Method	NA	Creates a system directory
DeleteFile	Method	NA	Delete file at specified directory
DictionaryDirectory	String	R	Get full path of LEAP Dictionary directory
DictionaryVersion	Integer	R	Gets LEAP Data dictionary version
Dimensions	Object	R	Gets collection of all dimensions
DisableControls	Method	NA	Disables LEAP Main user interface - allows for intensive data processing
DiscountRate	Floating Point	R/W	Get/ Set discount Rate (%)
DontCheckShares	Boolean	R/W	Get/Set whether LEAP should check share sum to 100% across branches
Effects	Object	R	Gets the collection of all effects

EnableControls	Method	NA	Enable the LEAP Main user interface - used in conjunction with DISABLE
EndYear	Integer	R/W	Get/Set analysis end year
EnergyBalanceColumns	Integer	R/W	Get/ set columns displayed in Energy balance table
ExportData	Method	NA	Export Data from LEAP TO excel
ExportEnergyBalanceCSV	Method	NA	Export current energy balance to CSV format at specified location
ExportEnergyBalanceXLS	Method	NA	Exoort current energy balance to EXCEL
ExportExpressions	Method	NA	Export ALL expressions from LEAP to EXCEL
ExportResults	Method	NA	Export Current results view chart
ExportResultsCSV	Method	NA	Export Current results view chart in CSV format
ExportResultsPPT	Method	NA	Export Current results view chart in PowerPoint Format
ExportResultsXLS	Method	NA	Export Current results view chart in Excel Format
Favorites	Object	R	Gets collection of all saved Favorite charts
FirstDepletionYear	Integer	R/W	Get/Set the first year in which fossil fuel resources are depleted
FirstSceanrioYear	Integer	R/W	Get/Set first scenario year in area
ForceCalculation	Method	NA	Force LEAP to calculate next time results requested - regardless of data change
FuelGroupSets	Object	R	Returns complete fuel group sets by Set ID
GNUMathProgInstalled	Boolean	R	Check is GNU Math prog installed - needed for OSeMOSYS
ImportExpressions	Method	NA	Import Expressions from Excel (see ExportExpressions)
IsCalculating	Boolean	R	True If LEAP is calculating
LandTypes	Object	R	Gets collection of all land types
MappingInstalled	Boolean	R	True if LEAP mapping components installed
MaxIterations	Integer	R/W	Get/Set max iterations to solve transformation calcs.
Minimize	Method	NA	Minimize LEAP application to windows taskbar
NumFuelGroupSets	Integer	R	Get number of fuel group sets in active area

NumRegionGroupSets	Integer	R	Get number of region group sets in active area
Print(Value)	Method	NA	Prints string, updating APIPrint.txt file
PrintToFile	Method	NA	Print specific string to specified text file location on system
ProgramDirectory	String	R	Get fill installation path for LEAP
ProgramStarted	Boolean	R	True if LEAP is started
Quote	String	R/W	Returns string wrapped in quotes
Refresh	Method	NA	Refresh screen display
RefreshResources	Method	NA	Refresh resources list
RegionGroupSets	Object	R	Returns one set of region groups
Regions	Object	R	Get the collection of all LEAP regions
Registered	Boolean	R	True if copy of LEAP running is fully registered & licensed
RegisteredOnline	Boolean	R	True if copy of LEAP running is registered online
RenameFile	Method	NA	Rename old file on system to new specified name
ResourceBranchFrom	Object	R	Get LEAP resource branch object corresponding to the specified fuel
Restore	Method	NA	Restore LEAP application window if minimised
ResultsEvery	Integer	R/W	get/ Set interval for calculation of results
ResultsLegend	Variant	R/W	Get/Set the dimension for the results chart legend
ResultsXAxis	Variant	R/W	Get/ Set the dimension for the results chart x-axis
ResultValue	Floating Point	R	Returns result value for specified branch in particular year
SaveArea	Method	NA	Save the current area
SaveFavorite	Object	R	Saves favorite to Favorite folder
SaveResultsChart	Method	NA	Save the current results view chart in a specified format
SaveVersion	Method	NA	Save a new backup version of current area
Scenarios	Object	R	Get collection of all LEAP scenarios
ShowAreaBranch	Boolean	R/W	Get/ Set visibility of top-level area branch in the Analysis view

ShowCalcProgress	Integer	R/W	Get/ Set whether LEAP shows calculation progress - slow calculations
ShowComplexEffects	Boolean	R/W	Get/ Set whether complex effects are included/ visible & inc. in calculations
ShowCosts	Boolean	R/W	Get/ Set whether cost variables are included/ visible & inc. in calculations
ShowEnergyEffects	Boolean	R/W	Get/ Set whether energy sector emissions are inc/ vis in calculations
ShowIBC	Boolean	R/W	Get/ Set whether IBC extension is included in calculations
ShowIndicators	Boolean	R/W	Get/ Set whether indicator branches are visible
ShowLandResources	Boolean	R/W	Get/ Set whether land-based resource data are visible/ inc. in calc
ShowNonEnergy	Boolean	R/W	Get/ Set whether non-energy sector emissions branches are visible/ inc. in calcs
ShowSplash	Boolean	R/W	Get/ Set the visibility of the splash screen
ShowStatDiffs	Boolean	R/W	Get/ Set whether statistical difference branches are vis/ inc. in calcs
ShowTransformation	Boolean	R/W	Get/ Set whether Transformation branches are visible
SoftwareVersion	String	R	Get current LEAP version e.g. 2015.XXX
SoftwareVersionValue	Floating Point	R	Get the LEAP software version
StatDiffBranchFromFuel	Object	R	Get the LEAP statistical difference branch object corresponding to specified fuel
Status	Boolean	R	For development only - not for normal use
StockChangeBranchFromFuel	Object	R	Gets the LEAP stock change branch corresponding to specified fuel
Tags	Object	R	Gets all area collection of tags
TEDTechnologies	Object	R	Get the collection of all TED Technologies
TECTechnology(TED ID)	Object	R	Returns a specific TED technology object given specific ID
TimeSlices	Object	R	Gets the collection of all LEAP timeslices
Units	Object	R	Get the collection of all units
UserName	String	R	Get the current registered username

UserVariables	Object	R	Get the collection of all user variables
Verbose	Integer	R/W	Get/ Set message types during LEAP automation
Versions	Object	R	Get the collection of all LEAP versions in active area
Views	Object	R	Get the collection all LEAP views
Visible	Boolean	R/W	Get/ Set whether the LEAP application is visible
WEAPInstalled	Boolean	R	Get whether WEAP is installed
WEAPLinkage	Object	R	Gets the linkage to WEAP
WorkingDirectory	String	R	Gets the full path of LEAP working directory
YearlyShapes	Object	R	Get the collection of yearly shapes defined for the area

Collections

Collections	**Type**	**Read/Write**	**Description**
Areas			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch
Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
Branches			
Count	Integer	R	Count Collection Items in Branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
Countries			
Count	Integer	R	Count Collection Items in Branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
Dimensions			
Count	Integer	R	Count Collection Items in Branch

Item	Object	R	Get collection Item by name, using index ID
Effects			
Count	Integer	R	Count Collection Items in Branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
Favorites			
Count	Integer	R	Count Collection Items in Branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
Fuels			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch
Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
FuelGroups			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch
Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
Name	String	R/W	Name of current collection item
Order	Integer	R/W	Display order of collection items
LandTypes			
Count	Integer	R	Count Collection Items in Branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
Regions			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch

Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
RegionGroups			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch
Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
Name	String	R/W	Name of current collection item
Order	Integer	R/W	Display order of collection items
Scenarios			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch
Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
ResultsShown	Method	R/W	Get/Set whether results shown for All scenarios
Tags			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch
Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
TagGroups			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch

Delete	Method	R/W	Delete specified Item from branch
Exists	Boolean	R	Check if collection item exists
Init	Method	NA	
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
TEDTechnologies			
Count	Integer	R	Count Collection Items in Branch
Item	Object	R	Get collection Item by name, using index ID
TimeSlices			
Count	Integer	R	Count Collection Items in Branch
Item	Object	R	Get collection Item by name, using index ID
Units			
Count	Integer	R	Count Collection Items in Branch
Exists	Boolean	R	Check if collection item exists
Item	Object	R	Get collection Item by name, using index ID
MaxID	Integer	R	Check maxID in collection
UserVariables			
Add	Object	NA	Add Collection Item
Count	Integer	R	Count Collection Items in Branch
Delete	Method	R/W	Delete specified Item from branch
Item	Object	R	Get collection Item by name, using index ID
Variables			
Count	Integer	R	Count Collection Items in Branch
Item	Object	R	Get collection Item by name, using index ID
Versions			
Count	Integer	R	Count Collection Items in Branch
Item	Object	R	Get collection Item by name, using index ID
Views			
Count	Integer	R	Count Collection Items in Branch
Item	Object	R	Get collection Item by name, using index ID
YearlyShapes			

Count	Integer	R	Count Collection Items in Branch
Item	Object	R	Get collection Item by name, using index ID

Objects	**Type**	**Read/Write**	**Description**
Area			
Active	Boolean	R/W	Check if Object IS active in area
Archived	Boolean	R	Check if Object IS archived
Backup	Boolean	R	Backup Area to specific location
CopyFulesFrom	Method	NA	Copies fuels from another specified area
CountryCode2	String	R	Get 2 Letter country code of area
CountryCode3	String	R	Get 3 Letter country code of area
CountryName	String	R	Get Country Name of area
Directory	String	R	Get Area folder name
Name	String	R	Get object name
Open	Method	NA	Open Object type
Pre2011	Boolean	R	Indicates if area is pre 2011 format
ReadOnly	Boolean	R	Returns whether area is marked RO
Save	Method	NA	Save the Area
Branch			
Active	Boolean	R/W	Check if Object IS active in area
BranchID	Integer	R	Get unique branch ID
BranchType	Integer	R	Get branch type
BranchTypeName	String	R	Get branch type name
Children	Object	R	Get collection of child branches to parent object
Delete	Method	NA	Delete specified object
DemandMethod	Integer	R	Get Demand Method e.g. Stock Turnover etc
Expand	Method	NA	Expand Lower branches
Expanded	Boolean	R/W	Get Set expanded status of branch
Fuel	Object	R	Return fuel object
FullName	String	R	Full Path Name for specified object

ID	Integer	R	Unique Object ID
Image	Integer	R	Image ID for identified object
Index	Integer	R	Returns index number of object
IPCCTEDTechnology	Object	R	Returns TED Tech containing best IPCC Tier 1 values for object
IsEndUseIntensity	Boolean	R	True if end use intensity branch type
IsFinalInCurrentAccounts	Boolean	R	True if end use intensity is set to use final energy intensities
IsUseful	Boolean	R	True if branch is useful energy demand
Level	Integer	R	Returns depth of current branch in Tree
MoveDown	Method	NA	Move a bracnch relative to current position in tree
MoveUp	Method	NA	Move a bracnch relative to current position in tree
Name	String	R	Get object name
Notes	String	R/W	Get/ Set object notes
Order	Integer	R	Returns Branch order
Parent	Object	R	Returns branch parent
Tags	Object	R	Get collection of tags associated with object
Variable	Object	R	Get specified variable object
VariableExists	Boolean	R	Check if variable exists within object
Variables	Object	R	Get collection of all variables belonging to object
Visible	Boolean	R/W	Get/Set visibility of current object
Country			
Abbreviation	String	R	Get Object abbreviation
Code2	String	R	Get 2 Letter country code of area
Code3	String	R	Get 3 Letter country code of area
CodeNum	Integer	R	Get the ISO numeric country code
Developing	Boolean	R	Is this a developing country
IBC_O3Health	Boolean	R	Does IBC support analysis of ozone health impacts
IBC_O3Vegetation	Boolean	R	Does IBC support analysis of ozone impacts on vegetation
IBC_PM25	Boolean	R	Does IBC support analysis of PM2.5
ID	Integer	R	Unique Object ID

Latitude	Floating Point	R	Object central point latitude
Longitude	Floating Point	R	Object central point longitude
LongName	String	R	Formal long name of country object
Name	String	R	Get object name
Region	String	R	Get 2 letter country abbreviation of region
Zoom	Integer	R	Get default zoom factor for showing country/region on map
Dimension			
Active	Boolean	R/W	Check if Object IS active in area
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
Name	String	R	Get object name
Effect			
Abbreviation	String	R	Get Object abbreviation
GWP100	Floating Point	R/W	100 year global warming potential
GWP20	Floating Point	R/W	20 year global warming potential
GWP500	Floating Point	R/W	500 year global warming potential
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
Name	String	R	Get object name
UnitID	Integer	R/W	Get/Set ID of unit in which the effect is measured
Favorite			
Activate	Method	NA	Set favorite chart to be active
FaveName	String	R	Get name of favorite
FolderName	String	R	Get name of favorite folder
Name	String	R	Get object name
Fuel	Object	R	Return fuel object

Density	Floating Point	R/W	Get/ Set fuel density (kg/liter)
EnergyContent	String	R	Get Energy content of fuel (energy units per physical unit)
Fueltype	String	R	Get Fuel Type e.g. fossil, renewable
Group	Object	R/W	Get/ Set one of the fuel groupings
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
LhvHhvRation	Floating Point	R/W	Get/ Set Lower to Higher Heating value ratio
Name	String	R	Get object name
PercentAsh	Floating Point	R/W	Get/ Set chemical composition of fuel
PercentCarbon	Floating Point	R/W	Get/ Set percent carbon by weight
PercentLead	Floating Point	R/W	Get/ Set percent lead by weight
PercentMoisture	Floating Point	R/W	Get/ Set Percent moisture by weight
PercentNitrogen	Floating Point	R/W	Get/ Set Percent Nitrogen by weight
PercentOxidized	Floating Point	R/W	Get/ Set percent of fuel oxidized during combustion by energy content
PercentSulfur	Floating Point	R/W	Get/ Set percent sulfur by weight
State	String	R	Get fuel state as text
UsedInArea	Boolean	R	True if fuel used in current area
User1	Floating Point	R/W	One of three floating point variables for use by modeller
User2	Floating Point	R/W	One of three floating point variables for use by modeller
User3	Floating Point	R/W	One of three floating point variables for use by modeller
FuelGroup			
ID	Integer	R	Unique Object ID

Name	String	R	Get object name
Order	Integer	R	Returns Branch order
LandType			
Abbreviation	String	R	Get Object abbreviation
ID	Integer	R	Unique Object ID
Name	String	R	Get object name
Order	Integer	R	Returns Branch order
Region	String	R	Get 2 letter country abbreviation of region
Abbreviation	String	R	Get Object abbreviation
Active	Boolean	R/W	Check if Object IS active in area
CountryCode	Integer	R	Get 3 digit numeric code for region
CountryID	Integer	R	Get LEAPs internal country ID for region
Group	Object	R/W	Get/ Set one of the fuel groupings
Grouping	String	R	Obsolete
IBC_O3Health	Boolean	R	Does IBC support analysis of ozone health impacts
IBC_O3Vegetation	Boolean	R	Does IBC support analysis of ozone impacts on vegetation
IBC_PM25	Boolean	R	Does IBC support analysis of PM2.5
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
InheritsFromRegion	Object	R/W	Get/ Set a region to inherit expressions from
IsDeveloping	Boolean	R	Gets if region is currently low/middle income
Latitude	Floating Point	R	Object central point latitude
Longitude	Floating Point	R	Object central point longitude
Name	String	R	Get object name
ResultsShown	Method	R/W	Get/Set whether results shown for All scenarios
User1	Floating Point	R/W	One of three floating point variables for use by modeller
User2	Floating Point	R/W	One of three floating point variables for use by modeller

User3	Floating Point	R/W	One of three floating point variables for use by modeller
Zoom	Integer	R	Get default zoom factor for showing country/region on map
RegionGroup			
ID	Integer	R	Unique Object ID
Name	String	R	Get object name
Order	Integer	R	Returns Branch order
Scenario			
Abbreviation	String	R	Get Object abbreviation
Active	Boolean	R/W	Check if Object IS active in area
AddAdditional	Method	NA	Add additional scenario
AdditionalScenarios	Object	R	Get collection of additional scenarios beloning to given scenario
DemoteAdditional	Method	NA	Demote additional scenario in list of current additional scenarios
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
IsCurrentAccount	Boolean	R	Get/Set whether results shown for the scenario
LastCalculated	Date	R	Get date/time scenario last calculated
LastChanged	Date	R	Get date/time scenario last edited
Name	String	R	Get object name
NeedsCalculation	Boolean	R	Returns whether scenario needs to be calculated
Parent	Object	R	Returns branch parent
PromoteAdditional	Method	NA	Promote additional scenario in list of current additional scenarios
RemoveAdditional	Method	NA	Remove additional scenario in list of current additional scenarios
ResultsShown	Method	R/W	Get/Set whether results shown for All scenarios
Tags	Object	R	Get collection of tags associated with object
Branches	Object	R	Get collection of branches with this tag
Color	String	R/W	Get/ Set the color of the tag
Description	String	R/W	Get/ Set the description of the tag

ID	Integer	R	Unique Object ID
Name	String	R	Get object name
Order	Integer	R	Returns Branch order
TagGroup			
ID	Integer	R	Unique Object ID
Name	String	R	Get object name
TEDTechnology			
AvailableYear	Integer	R	Returns year technology was/ is available
CapacityData	Boolean	R	True if tech has capacity data
ContainsData	Boolean	R	True if tech records contains quantitative data
CostData	Boolean	R	True if tech records include cost data
EfficiencyData	Boolean	R	True if tech records include efficiency data
EmissionsData	Boolean	R	True if tech records include emissions data
FullName	String	R	Full Path Name for specified object
ID	Integer	R	Unique Object ID
InputFuel	Object	R	Gets input fuel of technology
Lifetime	Integer	R	Get lifetime of tech in years
Name	String	R	Get object name
OutputFuel	Object	R	Gets Output fuel of technology
ParentID	Integer	R	Unique Object ID
TimeSlice			
Abbreviation	String	R	Get Object abbreviation
BeginDate	String	R/W	Starting date for days in timeslice
BeginDateDay	Integer	R/W	The day of the month timeslice begins
BeginDateMonth	Integer	R/W	The month the timeslice begins
BeginHour	Integer	R/W	The start time of the day for hours in timeslice
CumulativeHours	Floating Point	R	Cumulative Hours in this and all earlier timeslices
DispatchPeriod	Integer	R/W	Get/ Set dispatch period of the timeslice
EndDate	String	R/W	The ending date for days in the timeslice
EndDateDay	Integer	R/W	The day of the month timeslice bends

EndDateMonth	Integer	R/W	The month the timeslice ends
EndHour	Integer	R/W	The end time of the day for hours in timeslice
Friday	Boolean	R	Check if Fridays included in timeslice
Hours	Floating Point	R/W	Get/ Set length of timeslice in hours
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
Monday	Boolean	R	Check if Mondays included in timeslice
Name	String	R	Get object name
Notes	String	R/W	Get/ Set object notes
Order	Integer	R	Returns Branch order
Saturday	Boolean	R	Check if Saturdays included in timeslice
Sunday	Boolean	R	Check if Sundays included in timeslice
Thursday	Boolean	R	Check if Thursdays included in timeslice
Tuesday	Boolean	R	Check if Tuesdays included in timeslice
User1	Floating Point	R/W	One of three floating point variables for use by modeller
User2	Floating Point	R/W	One of three floating point variables for use by modeller
User3	Floating Point	R/W	One of three floating point variables for use by modeller
WEAPTimeStepID	Integer	R/W	ID of WEAP timestep to which LEAP is mapped
Wednesday	Boolean	R	Check if Wednesdays included in timeslice
Unit			
Abbreviation	String	R	Get Object abbreviation
ConversionFactor	String	R	Get string showing object conversion factor
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
Name	String	R	Get object name
UnitClass	String	R	Get string indicating unit class e.g. power, mass, volume …
UserVariable			

BranchType	Integer	R	Get branch type
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
Name	String	R	Get object name
Scale	Integer	R/W	Get/ Set scaling factor for user variable
UnitStr	String	R/W	Get/ Set unit used to measure user variable
Variable	Object	R	Get specified variable object
Branch	Object	R	Gets the branch where variable is located
BranchID	Integer	R	Get unique branch ID
BranchName	String	R	Gets name of branch where variable is located
BranchVariableName	String	R	Get combined branch/variable name
DataUnit	Object	R/W	Get/ Set unit associated with data expression
DataUnitID	Integer	R/W	Get/ Set unit ID associated with data expression
DataUnitText	String	R	Get string containing scale and units of data value
DefaultResultUnit	Object	R	Get default unit for results returned by ResultValue prop
Expression	Variant	R/W	Get/ Set data expression for variable
ExpressionRS	Variant	R/W	Get/ Set data expression for current variable for specified region/scenario
ID	Integer	R	Unique Object ID
InheritedExpression	Boolean	R	True if variable expression is inherited
IsData	Boolean	R	True if Variable is a data variable, false if result variable
Name	String	R	Get object name
Scale	Integer	R/W	Get/ Set scaling factor for user variable
Value	Floating Point	R	Get Value of data OR result in specified year for active scenario & region
ValueR	Floating Point	R	Get value of data OR result in spec. region & year for active scenario
ValueRS	Floating Point	R	Get value of data OR result in specified region, scenario & year

Version			
Comment	String	R/W	Get/ Set comment on version
Date	Date	R	Get date-time of version
FileName	String	R	Get full filename, inc. path, of version
Name	String	R	Get object name
Revert	Method	NA	Revert area by specified filename
View			
Active	Boolean	R/W	Check if Object IS active in area
Index	Integer	R	Returns index number of object
Name	String	R	Get object name
YearlyShape			
ID	Integer	R	Unique Object ID
Index	Integer	R	Returns index number of object
Name	String	R	Get object name
Notes	String	R/W	Get/ Set object notes
Order	Integer	R	Returns Branch order
ProfileType	Integer	R/W	Set yearly shape e.g. peak load shape.
ProfileTypeDescription	String	R	Get text description of type of yearly shape
User1	Floating Point	R/W	One of three floating point variables for use by modeller
User2	Floating Point	R/W	One of three floating point variables for use by modeller
User3	Floating Point	R/W	One of three floating point variables for use by modeller
Value	Floating Point	R	Get Value of data OR result in specified year for active scenario & region

Appendix E – LEAP utilised in development of INDC and COP 21

Countries using LEAP for INDC analysis
Armenia
Albania
Antigua & Barbuda
Azerbaijan
Bahamas
Bangladesh
Bosnia and Herzegovina
Botswana
Cambodia
Chile
Ecuador
Federated States of Micronesia
Ghana
Haiti
Iraq
Israel
Jamaica
Lebanon
Liberia
Mauritania
Mongolia
Montenegro
Morocco
Mozambique
Myanmar
Niger
Nigeria
Palau
Palestine
Philippines
Serbia
Uganda
Yemen
Zambia
Zimbabwe

Appendix F – ASET model topology script

```
dim Sector
dim SubSector
dim Detail1
dim Detail2
dim Detail3
dim Detail4
dim TraTech
ActiveArea = "LEAPTransport"
'Print the relevant area data before continuing'

PRINT "You are currently working within the Scenario: '"& ActiveScenario.Name & "'"
'create the initial main sectors for the model'
set Sector = AddCategory("Transport",1,"","No Data")
'Add Initial Subsector Data For model structure'
set SubSector = AddCategory("Private Transport",BRANCH("Demand\Transport").BranchID," ","No Data")
'Add First Folder Level Detail for Demand Sectors'
Set Detail1 =  AddCategory("Road Private Cars",BRANCH("Demand\Transport\Private Transport").BranchID,"
","No Data")
'Add Subsectoral Detail Level 2'
Set Detail2 =  AddCategory("Petrol",BRANCH("Demand\Transport\Private Transport\Road Private
Cars").BranchID,"Million","Vehicle-km")
Set Detail2 =  AddCategory("Diesel",BRANCH("Demand\Transport\Private Transport\Road Private
Cars").BranchID,"Million","Vehicle-km")
Set Detail2 =  AddCategory("Electric",BRANCH("Demand\Transport\Private Transport\Road Private
Cars").BranchID,"Million","Vehicle-km")
Set Detail2 =  AddCategory("Petrol Ethanol",BRANCH("Demand\Transport\Private Transport\Road Private
Cars").BranchID,"Million","Vehicle-km")
Set Detail2 =  AddCategory("CNG",BRANCH("Demand\Transport\Private Transport\Road Private
Cars").BranchID,"Million","Vehicle-km")
'Add Detail Level 4'
Set Detail4 = AddCategory("A. 900 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("B. 901_1200 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("C. 1201_1500 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("D. 1501_1700 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("E. 1701_1900",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("F. 1901_2100",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("G. 2100 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("A. 900 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Diesel").BranchID,"Percent","Share")
Set Detail4 = AddCategory("B. 901_1200 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Diesel").BranchID,"Percent","Share")
```

```
Set Detail4 = AddCategory("C. 1201_1500 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Diesel").BranchID,"Percent","Share")
Set Detail4 = AddCategory("D. 1501_1700 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Diesel").BranchID,"Percent","Share")
Set Detail4 = AddCategory("E. 1701_1900",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Diesel").BranchID,"Percent","Share")
Set Detail4 = AddCategory("F. 1901_2100",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Diesel").BranchID,"Percent","Share")
Set Detail4 = AddCategory("G. 2100 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Diesel").BranchID,"Percent","Share")
Set Detail4 = AddCategory("A. 900 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol Ethanol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("B. 901_1200 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol Ethanol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("C. 1201_1500 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol Ethanol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("D. 1501_1700 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol Ethanol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("E. 1701_1900",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol Ethanol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("F. 1901_2100",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol Ethanol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("G. 2100 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\Petrol Ethanol").BranchID,"Percent","Share")
Set Detail4 = AddCategory("A. 900 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\CNG").BranchID,"Percent","Share")
Set Detail4 = AddCategory("B. 901_1200 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\CNG").BranchID,"Percent","Share")
Set Detail4 = AddCategory("C. 1201_1500 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\CNG").BranchID,"Percent","Share")
Set Detail4 = AddCategory("D. 1501_1700 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\CNG").BranchID,"Percent","Share")
Set Detail4 = AddCategory("E. 1701_1900",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\CNG").BranchID,"Percent","Share")
Set Detail4 = AddCategory("F. 1901_2100",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\CNG").BranchID,"Percent","Share")
Set Detail4 = AddCategory("G. 2100 CC",BRANCH("Demand\Transport\Private Transport\Road Private
Cars\CNG").BranchID,"Percent","Share")
'Add Technology Script'
Set TRATech  =AddTechnology("A. 900 CC_Age_0",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_1",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_2",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_3",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_4",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_5",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_6",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
```

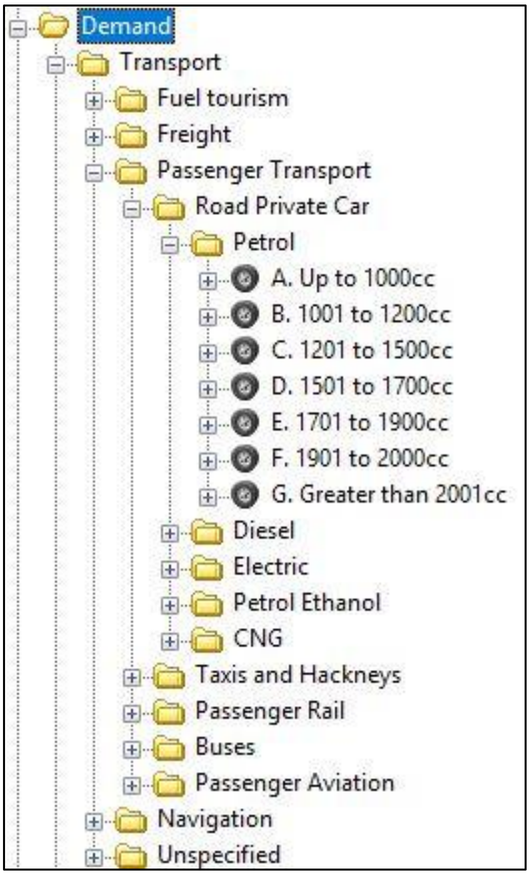
```
Set TRATech  =AddTechnology("A. 900 CC_Age_7",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_8",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_9",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_10",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_11",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_12",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_13",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_14",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_15",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_16",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_17",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_18",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_19",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_20",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_21",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_22",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_23",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_24",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("A. 900 CC_Age_25",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\A. 900 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_0",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_1",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_2",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_3",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_4",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_5",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_6",BRANCH("Demand\Transport\Private Transport\Road
Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
```

```
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_7",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_8",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_9",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_10",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_11",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_12",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_13",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_14",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_15",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_16",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_17",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_18",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_19",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_20",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_21",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_22",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_23",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_24",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("B. 901_1200 CC_Age_25",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\B. 901_1200 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_0",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_1",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_2",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_3",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_4",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_5",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_6",BRANCH("Demand\Transport\Private Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
```

```
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_7",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_8",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_9",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_10",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_11",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_12",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_13",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_14",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_15",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_16",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_17",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_18",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_19",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_20",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_21",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_22",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_23",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_24",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("C. 1201_1500 CC_Age_25",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\C. 1201_1500 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("D. 1501_1700 CC_Age_0",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\D. 1501_1700 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("D. 1501_1700 CC_Age_1",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\D. 1501_1700 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("D. 1501_1700 CC_Age_2",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\D. 1501_1700 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("D. 1501_1700 CC_Age_3",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\D. 1501_1700 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("D. 1501_1700 CC_Age_4",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\D. 1501_1700 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("D. 1501_1700 CC_Age_5",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\D. 1501_1700 CC").BranchID,"Percent","Share","Gasoline","PJ")
Set TRATech  =AddTechnology("D. 1501_1700 CC_Age_6",BRANCH("Demand\Transport\Private
Transport\Road Private Cars\Petrol\D. 1501_1700 CC").BranchID,"Percent","Share","Gasoline","PJ")
```

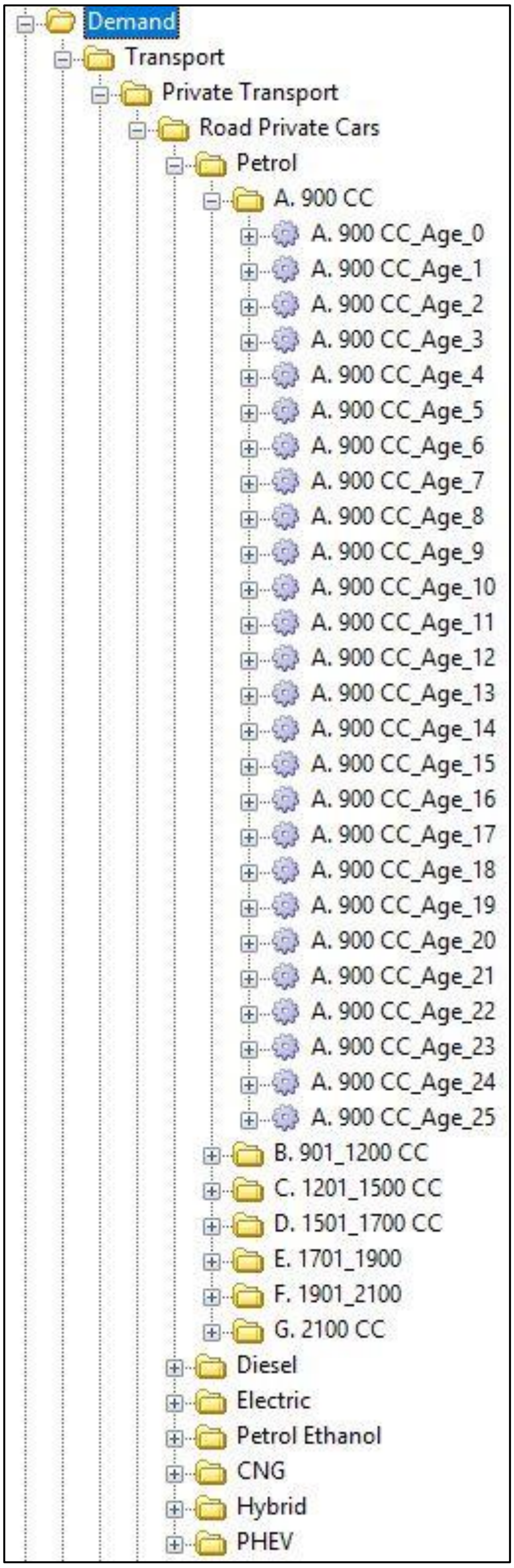
```
print "Script Complete"
```

Appendix G – LEAP UI and ASET model topology comparison



- Demand
  - Transport
    - Fuel tourism
    - Freight
    - Passenger Transport
      - Road Private Car
        - Petrol
          - A. Up to 1000cc
          - B. 1001 to 1200cc
          - C. 1201 to 1500cc
          - D. 1501 to 1700cc
          - E. 1701 to 1900cc
          - F. 1901 to 2000cc
          - G. Greater than 2001cc
        - Diesel
        - Electric
        - Petrol Ethanol
        - CNG
      - Taxis and Hackneys
      - Passenger Rail
      - Buses
      - Passenger Aviation
    - Navigation
    - Unspecified

Figure 0-2 Model A stock turnover LEAP tree structure



- Demand
  - Transport
    - Private Transport
      - Road Private Cars
        - Petrol
          - A. 900 CC
            - A. 900 CC_Age_0
            - A. 900 CC_Age_1
            - A. 900 CC_Age_2
            - A. 900 CC_Age_3
            - A. 900 CC_Age_4
            - A. 900 CC_Age_5
            - A. 900 CC_Age_6
            - A. 900 CC_Age_7
            - A. 900 CC_Age_8
            - A. 900 CC_Age_9
            - A. 900 CC_Age_10
            - A. 900 CC_Age_11
            - A. 900 CC_Age_12
            - A. 900 CC_Age_13
            - A. 900 CC_Age_14
            - A. 900 CC_Age_15
            - A. 900 CC_Age_16
            - A. 900 CC_Age_17
            - A. 900 CC_Age_18
            - A. 900 CC_Age_19
            - A. 900 CC_Age_20
            - A. 900 CC_Age_21
            - A. 900 CC_Age_22
            - A. 900 CC_Age_23
            - A. 900 CC_Age_24
            - A. 900 CC_Age_25
          - B. 901_1200 CC
          - C. 1201_1500 CC
          - D. 1501_1700 CC
          - E. 1701_1900
          - F. 1901_2100
          - G. 2100 CC
        - Diesel
        - Electric
        - Petrol Ethanol
        - CNG
        - Hybrid
        - PHEV

Figure 0-3 Model B - LEAP ASET Transport Tree Structure