Advancing Irish energy system modelling to inform residential policy

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I, Jason Mc Guire, certify that this thesis is my own work and has not been submitted for another degree at University College Cork or elsewhere.

Jason Mc Guire

Acknowledgements

I want to acknowledge the guidance and time my supervisors gave me, my colleagues' support and the anonymous referees' constructive suggestions. I also thank all participants who engaged in enlightening discussions and creative brainstorming sessions that enriched this thesis. I would like to express my gratitude to the Danish Energy Agency for their support of collaborative research efforts.

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On a personal note, I am grateful for all the influences that have shaped my journey. My family instilled in me the lasting values and purpose I carry; my friends from Killala, who underscored the vitality of teamwork and fulfilment; and my colleagues in Australia, who expanded my horizons.

Throughout crafting this thesis, my gratitude extends to Zola for the refreshing walks in the park and coffee for fuelling my perseverance. A heartfelt appreciation goes to Maggie for her unwavering support and guidance in this journey, turning a torrent of obstacles into manageable stepping stones. I look forward to sharing our family adventures with you, Maggie and Isla in our next chapter.

> *We mortgage the health of our planet for the currency of convenience, forgetting that the true cost is not measured in today's prices but in tomorrow's inheritance.*

Executive Summary

Anthropogenic greenhouse gas emissions are rising, and a lack of action towards climate policy has sparked a renewed determination to act. Energy Systems Optimisation Models (ESOMs) help guide energy policymaking to meet climate goals. This thesis uses a newly developed ESOM, TIMES Ireland Model (TIM), to explore Ireland's decarbonisation pathways. TIM incorporates empirical internal temperature variations in buildings. Building Energy Rating (BER) assessments in Ireland, based on Energy Performance Certificates (EPC), measure a building's expected energy consumption. However, it has been observed that standard BER assessments tend to overestimate residential energy consumption in Ireland by as much as 23%. When empirical internal temperatures are used in place of BER temperature assumptions, 6% less thermal retrofits are required to achieve the cost-optimal decarbonisation pathway, but energy savings are 114% less in this case. The new methodology better reflects energy consumption without overestimating the effect of thermal retrofits and provides more accurate climate policy insights.

The Danish Energy Agency supported this thesis by exploring the feasibility of district heating (DH) in Ireland. Ireland is a country with low DH deployment, but it has significant surplus heat. Using scenarios that considered different connection rates and maximum annual growth, this thesis consistently showed that DH saturates the heat market before 2050 in all scenarios. If DH is excluded, the average sectoral marginal CO_2 emission price over the model's time horizon is €729 t/$\mathrm{CO_2}$. However, when DH is permitted, this cost reduces by 13% to 25%, depending on the connection rate and maximum growth constraint.

A policy-focused aspect of this thesis explored Ireland's current *fabric-first* policy approach to understand if it is cost-effective. Alternative decarbonisation pathways allow for variations in heat pump subsidy thresholds connected to a dwelling's Heat Loss Indicator (HLI). The thesis also accounted for *sub-optimal* heat pumps, which do not achieve peak performance due to high HLIs. The findings suggest that the current *fabric-first* approach is stringent, requiring a BER rating of B2 or equivalent energy consumption, which is not cost-effective. Significant savings can be made, especially post-2030. For example, post-2030, the *fabric-first* average sectoral marginal CO_2 emission price is €675 t/$\mathrm{CO_2}$. Simply by allowing *sub-optimal* heat pump installation, this reduces to €312 t/$\mathrm{CO_2}$. Adjusting the HLI threshold to 2.3 W/K/$\mathrm{m^2}$ could further reduce this cost to €273 t/$\mathrm{CO_2}$.

This research offers a detailed exploration of the Irish residential sector, emphasising

the complex interactions among different energy sectors and advocating for a more coherent energy planning approach. For policymakers, it is essential to better understand residential energy consumption, embrace district heating through spatial energy system planning, and reevaluate the *fabric-first* approach. By doing so, Ireland could effectively achieve its climate goals more cost-effectively.

Units and Abbreviations

4GDH Fourth Generation District Heating

ArDEM-SQL Archetype Dwelling Energy Model - Structured Query Language

BER Building Energy Rating

CAP Climate Action Plan

CHP Combined Heat and Power

CO_2 Carbon Dioxide

CSO Central Statistics Office

DEAP Dwelling Energy Assessment Procedure

DH District Heating

DT Default Temperature

EPBD Energy Performance of Buildings Directive

EPC Energy Performance Certificate

ESOM Energy System Optimisation Model

EU European Union

GHG Greenhouse Gas

GIS Geographic Information Systems

HLI Heat Loss Indicator

IPCC Intergovernmental Panel on Climate Change

IrDEA Irish District Energy Association

LEAP Long Range Energy Alternatives Planning

NDC Nationally Determined Contribution

NZEB Nearly Zero-Energy Buildings

O&M Operational and Maintenance

RES-H&C Renewable Energy Source for Heating & Cooling

RES Reference Energy System

SEAI Sustainable Energy Authority of Ireland

TABULA Typology Approach for Building Stock Energy Assessment

TA Temperature Adjusted

TIM TIMES Ireland Model

TIMES The Integrated MARKAL-EFOM System model

PJ Petajoule

TWh Terawatt hour

Chapter 1

Introduction

1.1 Background

1.1.1 A Global Context

The impact of Carbon Dioxide (CO_2), the predominant Greenhouse Gas (GHG) [1], on global temperatures has long been a topic of scientific investigation. Fourier and Tyndall recognised the atmosphere's ability to trap heat radiation [2, 3]. Arrhenius proposed a substantial temperature increase in response to doubled CO_2 concentrations [4]. In 1938, Callendar confirmed Arrhenius's research [4] by establishing a correlation between increasing CO_2 levels and observed global temperatures, demonstrating that this phenomenon was not confined to laboratories [5].

The scientific consensus on human-induced climate change is now solidified [6, 7]. Experts agree that decarbonising energy supplies, altering behaviours, and adopting sustainable consumption patterns are all essential to reducing CO_2 emissions and mitigating their adverse environmental impacts [1]. Past civilisations' lessons highlight the need to prioritise long-term planetary well-being over short-term economic gains [8]. To collectively combat climate change, the Paris Agreement was established with its primary objectives of limiting the mean global temperature increase to 2°C above pre-industrial levels and reaching net-zero GHG emissions in the second half of the century [9]. However, by 2022, the global temperature rise has already reached 1.1°C [1, 10]. Some research suggests that even if all nations meet their individual National Determined Contributions (NDCs) under the Paris Agreement, it will not be enough to meet the agreement's objectives [11].

The global community is at a pivotal juncture in navigating the complexities of climate change in the 21st century. Climate change is a monumental challenge of our era, intricately linked to energy decisions. Nations worldwide face the dual challenge of meeting increasing energy demands fuelled by population growth, economic expansion, and rising aspirations while mitigating the environmental repercussions of their energy choices. The built environment, including residential and service sectors, is responsible for almost 30% of the world's total energy consumption. Space and water heating consume nearly half of the global energy used in buildings, and in 2022, almost two-thirds of the heating energy used in buildings still comes from fossil fuels [12]. Because of this, the built environment contributes to 26% of global energy-related GHG emissions [12].

1.1.2 Energy System Modelling

As the global energy landscape continues to evolve, it is crucial to establish cost-effective policies to facilitate the transition towards sustainable energy. Energy system models can enhance policy-making by providing long-term scenarios for a nation's entire energy system [13]. These models examine scenarios based on assumptions about future economic activities, demographic changes, and global energy prices [14]. Various models can address different research questions associated with energy systems [15]. Models are often classified based on their analytic approach as top-down, which uses an economic approach and aggregated data, or bottom-up, which is an engineering approach that focuses on technological details [16]. Hybrid modelling combines the strengths of bottom-up and top-down modelling approaches [15]. Energy system models can also be classified by methodologies, such as simulation, optimisation, or equilibrium models [17].

In energy planning, energy system models have been crucial for enhancing energy security [18] and, more recently, decarbonisation [19]. The findings of energy system models quantify environmental, economic, and resource factors, which are excellent tools for national and regional policy development discussions. Energy system models can account for long-term technological innovation and regulatory compliance and thus significantly reduce risks in developing a given pathway. Furthermore, energy systems transitions require significant investment and resources. The dynamics between different parts of the system are challenging to capture [20], making energy systems costly [21] and complex [22]. The transition of these systems is inherently slow, given the extensive planning and construction they require [23]. These models provide an evidence-based strategic framework for planning future energy systems, allowing for a more efficient and effective approach. With global temperatures rising, the need to address climate change is more urgent than ever, making the role of energy system models even more critical.

Although energy system models are helpful, they are simplified representations of reality and rely on statistical averages, past trends, and other assumptions [14]. Other challenges include the complexity of the models, varying scientific standards, interdisciplinary modelling [24], and effective communication of the model's findings are also crucial [25]. Recent research has tackled some of these challenges. There has been significant improvement in scientific standards whereby open-source frameworks and models are becoming more common, and this can improve transparency and stakeholder engagement [26–28]. As computational capacity grows, energy modelling complexity increases, with more multi-regional models with high temporal resolution [29, 30]. While this may help to provide more detailed insights, it can also reduce transparency due to increased complexity and require greater computational power. In recent years, energy system modelling has been advancing to address the uncertainty in the field [14, 24].

However, there are still significant gaps in modelling behavioural and transition dynamics [14, 31], and this thesis will present a methodology to address the identified gaps. For instance, in Europe, national EPC databases are frequently used for energy system research [32–36]. Despite their comprehensive details, substantial discrepancies have been identified between expected EPC and actual energy consumption due to unaccounted variations within dwellings and the use of default values [37–40]. Although the EPC databases were not initially intended for energy system modelling, they have become an essential input data source due to their highly detailed information. The Building Energy Rating (BER) is Ireland's equivalent of the EPC. It utilises an asset rating model that follows a standardised methodology for all dwellings to calculate expected energy consumption and assign a BER label within specific ranges designed to suit Ireland's housing stock. EPC databases often require calibration with empirical data and national energy balances to develop more robust decarbonisation pathways [33, 34, 38].

All modelling comprises two essential components - the model and the modeller. The structure of a model is crucial in determining how well an imperfect model can represent complex realities [41]. At the same time, the modeller's understanding and communication skills are necessary to ensure that the model's assumptions, limitations and insights are accurately conveyed and interpreted. Sterman's argument that a model's quality is not only based on its technical specifications but also the expertise of the modeller [41] when he states:

> *The most critical assumptions of a model are not in the equations, but what is not in them; not in the documentation, but unstated; not in the variables on the computer screen, but in the blank spaces around them.*

The interplay of these elements ultimately determines a model's relevance in decision-making. In the context of this thesis, my participation in university modules on environmental policy, economics, and science communication was a critical foundational step alongside the prior competition in my master's thesis, which involved using a simplified version of the TIMES model. Engagements in workshops, training sessions, and conferences significantly enhanced my knowledge of modelling frameworks. These activities also gave me diverse perspectives from Irish stakeholders and insights into cutting-edge international energy research.

1.1.3 Case Study: Ireland

Ireland presents an interesting case study to explore sustainable energy pathways. Following extensive deforestation and a population peak in the 18th century, Irish households were constrained by the availability of affordable indigenous fuel sources. In response, peat, a low-quality fossil fuel, became the primary heating source. As the nation progressed and the economy expanded, a growing dependence on imported fossil fuels emerged, but the legacy of peat harvesting persisted [42]. An overview of Ireland's 2018 GHG emissions is presented in Fig. 1.1. Agricultural non-energy GHG emissions contributed significantly to Ireland's national GHG emissions in 2018. However, this thesis solely examines the energy sector, which was responsible for 59% of total GHG emissions in 2018, with the residential sector accounting for 14.2% of the total GHG emissions [43]. Considering only energy-related GHG emissions from heat, electricity, and transport, the contribution of the residential sector rises to 24%. This thesis will focus on residential heating decarbonisation, as 80% of residential energy consumption is used for space and water heating.

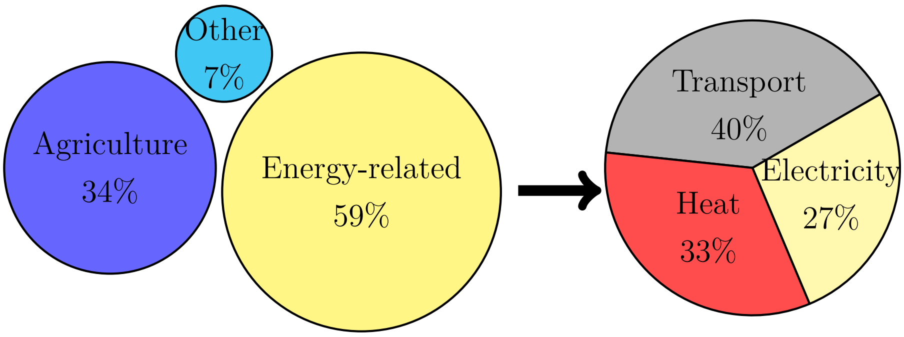


Figure 1.1: Ireland 2018 GHG Share [44]

Ireland has made significant progress in energy security and decarbonisation by relying on onshore wind electrification without tapping into the abundant offshore wind resources [45]. However, the country faces several challenges, such as fossil fuel dependency, settlement patterns, dwelling sizes, and thermal efficiency, that have impeded progress [46]. The residential sector in Ireland is challenging to decarbonise due to a high number of thermally inefficient dwellings still reliant on fossil fuels [47] and experiencing high energy poverty [48]. Even when households secure funding to transition to low-carbon electric heat pumps, they face some of the highest household electricity pre-tax costs among the EU-27 [49]. This explains why the *fabric-first* approach is favoured in Ireland and why the country's heat sector ranks at the bottom for renewable heat in Europe [50].

As of 2021, Ireland has Europe's third-highest GHG emissions per capita, trailing only Iceland and Luxembourg. The latter two represent only 0.15% of Europe's population [51]. Over the period from 1990 to 2021, Ireland's annual GHG emission per capita decrease rate was 0.7% on average, whereas the emissions for the rest of Europe decreased by 1.3%. The ambitious Climate Action and Low Carbon Development (Amendment) Act 2021 was introduced to set legally binding sectoral and national emission targets to guide the Irish government to reduce GHG emissions by 51% in 2030 compared to 2018 levels and achieve net-zero by 2050 [52]. However, the Environmental Protection Agency projections suggest that Ireland will only achieve a 29% reduction in GHG emissions by 2030 compared to the targeted 51% reduction [53]. The current housing crisis compounds the challenge of meeting climate targets, a pressing short-term political concern requiring significant construction labour. Ireland has a stringent *fabric-first* approach compared to other European countries [54], and this approach is labour-intensive [55], competing for labour in construction, which already has a housing crisis. Exploring options could harmonise addressing the housing crisis and decarbonisation goals.

1.2 Thesis in Brief

Fig.1.2 illustrates a visual overview of the chapters in this thesis. The blue segments represent chapters where I was the leading author and show which research questions they address, outlined in Section 2.5, while the grey segment represents the introduction and conclusion. The orange segment highlights the Carbon Budgets Discussion Paper [56], a non-journal paper that marked my initial lead author experience, contributing to my academic understanding and the overall thesis.

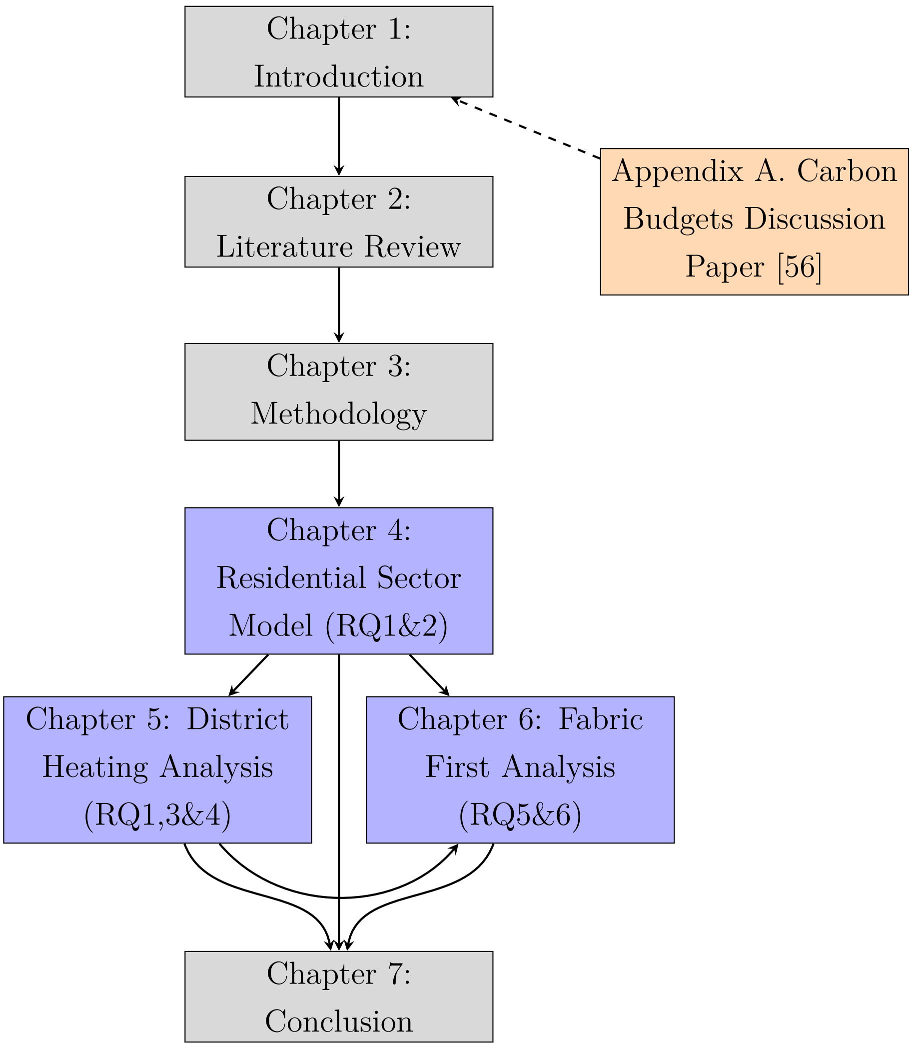


Figure 1.2: Thesis overview

Below is a summary of each chapter:

- **Chapter 1:** of the thesis provides an introduction to the research. This introduction prepares the reader for the topics presented in the following chapters. It explains the background and context, highlighting the significance of the research within the broader field. The chapter also outlines the research objectives and presents them as a series of research questions.

- **Chapter 2:** provides an overview of the factors influencing the energy landscape in Ireland, including an analysis of the policies, the legislative frameworks, and the international agreements that shape energy policy decisions. The chapter also examines Ireland's energy system context, covering infrastructure, supply sources, and consumption patterns. The chapter delves into energy system modelling studies, analysing academic literature and industry reports to identify gaps, limitations, and emerging trends.
- **Chapter 3:** Chapter 3 outlines the methodology used in the thesis. The chapter details the data collection methods, enumerating the data sources, the criteria for their selection, and the techniques used for data gathering. This chapter also describes the statistical analysis procedures.
- **Chapter 4:** involves creating the new TIMES Ireland Model (TIM) within the wider Energy Policy Modelling Group with my leading participation in developing the residential sector. The residential sector was constructed for a single region, utilising highly detailed technological data from the open-source EPC database. A thorough literature review highlighted significant energy performance disparities, particularly among dwellings of different energy ratings based on expected EPC energy consumption versus empirical energy consumption. Consequently, the model addresses this gap by incorporating empirical data, calibrating EPC data using CSO data, and aligning residential energy consumption with the national energy balance.
- **Chapter 5:** builds upon the foundation laid in Chapter 4 and explores district heating in Ireland. This research was conducted in collaboration with the Danish Energy Agency, world-leading DH and modelling experts. I spent two months developing the TIM in Copenhagen during the research phase. DH in Ireland has recently gained attention due to its substantial potential, driven by surplus heat sources and energy poverty. TIM was designed to encompass supply and demand considerations for 26 regions, with additional demand categorisations accounting for heating demand density and city municipalities. The analysis extends to residential dwellings and service sectors, highlighting the role of the DH connection rate in determining the system's capacity and the marginal distribution cost.
- **Chapter 6:** continues to build upon the research in Chapters 4 and 5, focusing

on critical residential policy strategies. This chapter includes a literature review, incorporating the latest data to assess heat pump performance in dwellings with varying Heat Loss Indicators (HLIs). The scenarios evaluate the potential of sub-optimal heat pumps installed in dwellings with higher heat loss that do not meet optimal heat pump performance standards. The existing *fabric-first* approach is directly compared to alternative strategies, offering valuable insights into their impact on thermal retrofits, residential fuel mix, and broader intersectoral dynamics.

- **Chapter 7:** summarises the key findings of this thesis. The conclusions are drawn from the consolidated insights in Chapters 4 through 6, creating a cohesive synthesis of the research outcomes and key policy insights. Moreover, this chapter addresses research questions and investigates prospective directions for future research to enhance ongoing energy system modelling.
- **Appendix A:** presents a discussion paper I led on carbon budgets for the Irish government before its implementation. The document explores various approaches, including climate science carbon budgets linked to Paris Agreement temperature goals and climate policy carbon budgets, which are set by other nations with short-term carbon budgets that do not necessarily align. It also delves into creating decarbonisation pathways tailored to Ireland, discussing the link between net-zero, decarbonisation rates and global temperatures.

1.3 Role of Collaborators

This thesis is the result of my academic journey in energy system modelling. As the leading researcher and writer, I developed the foundational concepts, conducted core research, and wrote the thesis. My colleagues, however, provided invaluable support throughout the process. Specifically, my PhD supervision team contributed critical feedback on Chapters 1, 2, 3, and 7. The role of collaborations in each peer-reviewed chapter and the discussion paper I led is specific to that research and is summarised below.

Chapter 4 constitutes a published peer-reviewed journal paper that utilises the TIM v1.0 features [57]. As for all my lead author papers, I developed the research methodology, drafted the initial manuscript, executed the model runs, and created the figures and results. Dr. Olexandr Balyk provided invaluable modelling assistance, Dr. Tomás Mac Uidhir offered guidance on internal temperature adjustments and the Irish residential sector modelling. Ankita

Guar, Dr. Fionn Rogan, and Prof. Hannah Daly reviewed the manuscript and provided feedback on the modelling and results. Additionally, the anonymous referees contributed to this paper, enhancing its quality before publication.

Chapter 5 comprises a journal paper currently under review. The inspiration for exploring DH stemmed from a collaborative effort between SEAI and MaREI, where Matthew Clancy, Donna Gartland, and I began investigating DH modelling in Ireland. The opportunity to develop TIM to include DH was facilitated by a research visit to the Danish Energy Agency in Copenhagen. Dr. Olexandr Balyk and Dr. Stefan Petrović shared their modelling expertise, further enhancing the research. Dr. Stefan Petrović, Andrew Smith, Dr. Fionn Rogan, and Prof. Hannah Daly gave feedback during the manuscript drafting procedure and provided feedback on the modelling and results. I engaged in insightful discussions with Susana Paardekooper, Michele Rosa, David Connolly, and the Integrated Environment Solution (IES) virtual network development team, contributing to the ideas and knowledge in the manuscript.

Chapter 6 constitutes a journal paper currently under review. Dr. Olexandr Balyk and Dr. Stefan Petrović, possessing prior expertise in heat pump modelling within the TIMES framework, provided valuable modelling insights and offered feedback on the manuscript. Additional insights into heat pump technology were acquired through the invaluable input of Dr. Paul Moran, who contributed to the manuscript review. Prof. Brian Ó Gallachóir and Prof. Hannah Daly provided feedback and valuable suggestions for enhancing the paper.

Appendix A is a discussion paper submitted to the Department of Environment, Climate and Communications. Dr. Fionn Rogan, Prof. Hannah Daly, Dr. James Glynn, Dr. Olexandr Balyk, and Prof. Brian Ó Gallachóir provided an iterative review of the discussion paper, suggestions on data and figures.

1.4 Thesis Outputs

Journal Papers

Mc Guire, J., Rogan, F., Balyk, O., Mac Uidhir, T., Gaur, A., & Daly, H. (2023). Developing decarbonisation pathways in changing TIMES for Irish homes. Energy Strategy Reviews, 47, 101086. https://doi.org/10.1016/j.esr.2023.101086

Mc Guire, J., Petrovic, S., Daly, H., and Rogan, F., Smith, A., & Balyk, Olexandr (2024). Is District Heating a Cost-Effective Solution to Decarbonise Irish Buildings? Energy, 296, 131110. https://doi.org/10.1016/j.energy.2024.131110

Mc Guire, J., Balyk, O., Petrovic, S., Moran, P., O Gallachóir, B., & Daly, H., Advancing Cost-Optimal Residential Decarbonisation Pathways: An Examination of Heat Pumps and Thermal Efficiency (*Submitted to Energy and Building on 15th November 2023, and review submitted 17th April 2024.*)

Balyk, O., Glynn, J., Aryanpur, V., Gaur, A., **Mc Guire, J.,** Smith, A., Yue, X., & Daly, H. (2022). TIM: modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1.0). Geoscientific Model Development, 15(12), 4991-5019. https://doi.org/10.5194/gmd-15-4991-2022

Gaur, A., **Mc Guire, J.,** O'Riordan, V., and Curtis, J., & Daly, H.(2024). Dispersed Settlement Patterns Can Hinder the Net-Zero Transition: Evidence from Ireland. Energy Strategy Reviews, 51, 101296. https://doi.org/10.1016/j.esr.2024.101296.

Conference & Workshop Presentations

Mc Guire, J., Rogan, F., O Gallachóir, B. & Daly H., 'Sensitivity of Ireland's potential carbon budget pathways with varying social discount rates in an energy system optimisation model' Presented on 3rd July 2020, at IEA-ETSAP Summer Workshop 2020, Online event.

Mc Guire, J., Rogan, F., O Gallachóir, B. & Daly H., 'Sensitivity of net-zero greenhouse gas emission pathways on social discount rate assumptions in an energy system optimisation model', Presented on 21st October 2020 at ENVIRON 2020 Conference, Online event.

Mc Guire, J., Rogan, F., O Gallachóir, B. & Daly H., 'Sensitivity of Ireland's potential carbon budget pathways with varying social discount rates in an energy system optimisation model', Presented on 29th October 2020 at DSAI Annual Conference 2020, Online event.

Mc Guire, J., 'How do changes to future technology and fuel developments affect the optimal residential heating decarbonisation pathway?' Presented on 29th November 2021, at IEA-ETSAP Winter Workshop 2021, Oslo, Norway.

Mc Guire, J., 'Is the building fabric first approach a no-regrets policy or a costly delay?' Presented on 17th May 2022, at IBPSA 2022 Conference, Galway, Ireland.

Mc Guire, J., ‘Developing decarbonisation pathways in changing TIMES for Irish homes’, Presented on 25th May 2022, at IEW 2022 Conference, Freiburg, Germany.

Daly, H.,**Mc Guire, J.,** ‘Is district heating a cost-effective way to heat Irish buildings?’, Presented on 30th May 2023, at 11th MaREI Climate & Energy Research Seminar, Dublin, Ireland.

Posters

Mc Guire, J., ‘Exploring deep decarbonisation pathway uncertainties in switching Irish households from gas boilers to electrical heat pumps’ , Presented on 25th November 2020, at MaREI Symposium 2020, Online event.

Mc Guire, J., ‘Exploring deep decarbonisation pathway uncertainties in switching Irish households from gas boilers’, Presented on 4th December 2020, at IAMC 2020 Conference, Online event.

Mc Guire, J.,, Rogan, F., Balyk, O., O Gallachóir, B. & Daly H., ‘How do changes to future technology and fuel developments affect the optimal residential heating decarbonisation pathway?’, Presented on 2nd December 2021, at IAMC 2021 Conference, Online event.

Discussion Paper

McGuire, J., Rogan, F., Daly, H., Glynn, J., Balyk, O. and Ó Gallachóir, B. (2020) The role of carbon budgets in translating the Paris Agreement into national climate policy, Discussion paper, MaREI Centre, University College Cork.

Chapter 2

Literature Review

The literature review chapter plays a critical role in setting the basis of this thesis and applies to all peer-reviewed chapters. Section 2.1 analyses the case study, Ireland and why it presents a unique and interesting case study for this thesis. 2.2 presents an overview of Energy Systems Optimisation Models (ESOMs), which focuses on the residential sector. Following this, Section 2.3 delves deeper into ESOMs, with a particular emphasis on district heating, thereby enriching the context for Chapter 5. Section 2.4 focuses on heat pumps, establishing the context necessary for Chapter 6.

2.1 Residential Sector in Ireland

Under the 2006 Intergovernmental Panel on Climate Change guidelines, Ireland's residential sector accounted for 14.2% of GHG emissions in 2018 [43], focused solely on energy-related GHG emissions from heat, electricity, and transport, the residential sector directly accounts for 24% of GHG emissions. The residential sector, where space and water heating accounts for 80% of energy consumption [58], is directly responsible for 47% of heat and 30% of electricity GHG emissions.

Irish dwellings emit 60% more direct CO_2 emissions than the EU average [58]; this is primarily due to these four variables:

1. **Fossil fuels:** The residential sector relied on fossil fuels for more than 90% of thermal energy in 2018. As a result, Ireland has the lowest renewable heat among EU member states, at only 6.3% [50]. Ireland's dependence on residential fossil fuels is underpinned by home heating oil, which represents the largest share of fuel use at 37% [58], all of which is imported [59].

2. **Settlement patterns:** The rural settlement patterns are illustrated by the

fact that only 5.8% of the Irish population lived in apartments in 2018, the lowest in the EU-27 and well below the 25.3% average [60].

3. **Dwellings size:** In the last 20 years, the average size of new Irish dwellings increased by 18% compared to a 7.8% increase in Europe [61]. Hence 71.4% of the Irish population are considered to live in dwellings too large, and the average EU-27 rate is 33% [62].

4. **Thermal efficiency:** In the 1990s, Ireland's housing stock was identified as among the least energy efficient in Europe [63]. Since then, the average thermal efficiency of existing dwellings [47] and new dwellings [64] has improved. However, as Fig. 2.1 illustrates, there is a strong correlation between the year of construction and the EPC rating. The lower share of energy efficient EPC ratings in older dwellings highlights that older dwellings are still thermally inefficient despite ongoing retrofit progress. The Central Statistics Office (CSO) states that 85% of the dwellings were built pre-2005.

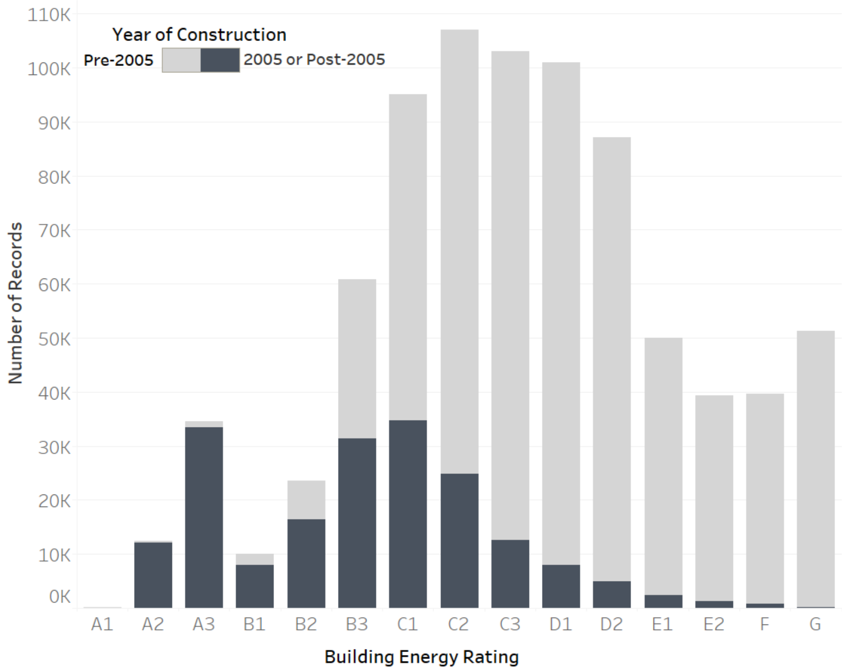


Figure 2.1: Number of records in the EPC database and the corresponding BER label (see Table 3.1 for the EPC range of BER labels). The dual colouring highlights the correlation between the year of construction and the EPC rating.

Under the Climate Action and Low Carbon Development (Amendment) Act 2021, the Irish government adopted national targets to reduce GHG emissions by 51% in 2030, compared to 2018. The Act also proposes a long-term target to achieve a climate-neutral economy or *"net-zero"* by 2050 [52]. These targets account for all emissions, both the emission trading system (ETS) and non-ETS emissions, and set out to develop legally binding sectoral five-year carbon budgets to aid the progress of the aforementioned long-term targets.

The EU's first nationally determined contribution (NDC), which had a 40% GHG emission reduction target (first NDC), has been succeeded by a new target of at least a 55% GHG emission reduction target (updated NDC) by 2030 compared to 1990 levels. Ireland's Climate Action Plan 2019 (CAP2019) [65] complies with the EU's first NDC. Climate Action Plan 2024 (CAP2024) [66] is more ambitious than CAP2019, reflecting the EU's updated NDC target and the Climate Action and Low Carbon Development (Amendment) Act 2021. Like other EU members, Ireland must also consider renewable energy targets for transport (RES-T), heat (RES-H), and electricity (RES-E) under the renewable directive (EU) 2018/2001, and energy efficiency targets under (EU) 2018/2002 when planning decarbonisation pathways.

Ireland uses both the *carrot* (subsidy) and *stick* (tax) approach to direct private investment towards low-carbon or renewable energy. A €15/ tCO_2 carbon tax was introduced in 2009 to reduce investment in fossil fuels, and the carbon tax is set to rise to €100/ tCO_2 in 2030. In parallel, solar feed-in tariffs and home energy grants are available to incentivise residential decarbonisation.

CAP2024 sets a clear path to achieve the 2030 climate targets [52]. The residential sector targets include 500,000 retrofits to a B2 EPC rating and 680,000 heat pumps, while the planning policy aims to develop smaller residential dwellings in higher-density areas. The improved thermal retrofit and heat pump grants still require significant upfront household investment, which may hinder the energy transition, considering that up to 28% of Irish households in 2016 were in energy poverty [58]. Ireland's national development plans have also recognised the need to develop a policy framework for district heating and support for expanding biomethane and anaerobic digestion heating systems.

2.2 Energy Systems Optimisation Modelling and the Residential Sector

The cost-optimal decarbonisation pathway for the residential sector depends on many factors. The cost and availability of low-carbon heating alternatives are among the most critical determinants of future residential energy transition pathways that depend on technological advances, housing stock composition, and policy support.

ESOM frameworks allow for a rich representation of these variables, including the current and future efficiency, cost, and availability of technologies and fuels. While also representing the heterogeneity of housing stock and exogenously accounting for macroeconomic variables such as economic and population growth and discount rates. ESOMs produce the least-cost energy system pathways while satisfying energy needs in end-use sectors and accounting for energy supply and demand dynamics. Consequently, ESOMs play a crucial role in understanding and providing insight into various challenges related to energy decarbonisation.

Since the oil crisis of the 1970s, ESOMs have been used to provide security and affordability insights and have since been developed to provide climate mitigation insights. However, historically, many ESOMs lack transparency regarding input data, methodology, results, and frameworks. In 2012, DeCarolis [67] found that only one-quarter of the ESOM frameworks had publicly accessible source code and data, while in 2018, Morrison [68] observed an increasing trend of transparency within the ESOMs. Previous studies have highlighted the importance of ESOM transparency for scientific standards [24] and traceability in policy decision-making [69].

There is a growing tendency for ESOMs to focus on the thermal efficiency of building fabric [70, 71], electrification [72], and sectoral coupling [73–75] when exploring the residential sector. However, the steady turnover of heating technology in the residential sector presents challenges for ambitious short-term residential decarbonisation. Thermal retrofitting of existing buildings provides an opportunity to quickly reduce demand and emissions without needing new heating technologies. The building regulations improvement requires a new dwelling to be a nearly zero energy building (NZEB). The NZEB requirements have little impact on short-term residential decarbonisation; however, it is critical in long-term residential decarbonisation.

According to a recent national literature review [28], previous energy system optimisation studies did not account for internal dwelling temperatures. The methodology applied in this thesis better reflects the expected EPC energy consumption by accounting for the internal space temperature more accurately and allowing for temperature variance, using Ireland as a case study. This thesis found that Ireland's expected EPC residential energy is overestimated by 23%. This overestimation is the gap between the expected and actual energy consumption, which is referred to as the energy performance gap in this thesis. Furthermore, the internal temperature assumptions, which address the energy performance gap, assume, based on empirical data, that thermally efficient dwellings are warmer than thermally inefficient dwellings. Therefore, the rebound effect is accounted for, which is the extent of energy savings that dwellings take back in the form of higher internal temperatures.

ESOMs have greatly enhanced comprehension of energy dynamics in residential areas. Several popular model frameworks, including Balmorel [76], OSeMOSYS [77], MESSAGE [78], TEMOA [79] and TIMES [80], have been developed, while newly developed frameworks such as DIETER [81] and RESCOM [82] are also utilised. Studies have emphasised the importance of accurate and flexible demand-side modelling [14, 83, 84], and highlighted the potential of ESOMs in guiding early-stage design decisions for energy efficiency [82]. ESOMs are also used to explore the balance between carbon tax and welfare [85] and climate impact considerations in local residential energy planning [86]. As residential energy evolves to include technologies such as photovoltaics and heat pumps [21, 87, 88], research has emphasised the impact of the residential sector on energy system cost optimisation, highlighting the importance of indigenous low-carbon energy and energy-efficient solutions during times of economic and energy crisis [89].

The TIMES (The Integrated MARKAL-EFOM System) framework, the ESOM used in this research, commands significant recognition for several reasons. It is an integral component of the Energy Technology Systems Analysis Programme (ETSAP), which was founded in 1976 under the International Energy Agency (IEA) [90]. The model boasts a rich developmental history and has been adopted across nearly 70 countries [29, 30], making it a reliable choice for techno-economic energy systems analysis. The TIMES framework is an advanced hybrid optimisation tool that uses a combination of bottom-up and top-down methodologies. It is written in a linear programming optimiser matrix called General Algebraic Modeling System (GAMS), and its source code is open source [1] [91]. The framework is adapted to analyse energy-environment systems with versatility in spatial, temporal, and sectoral resolution [80]. The TIMES model adopts a comprehensive approach that considers technology specifics and macroeconomic factors. It provides a range of modelling options by integrating market dynamics and foresight assumptions. By balancing prices and quantities, the TIMES model ensures that suppliers meet consumer demand while maximising economic surplus. This equilibrium approach allows TIMES to minimise overall energy system cost or net present value. The model considers investments, discount rates, costs, and revenues to determine the cost-optimal fuel and technology mix necessary to meet climate targets. As a result, the TIMES framework furnishes a robust framework that significantly enhances the planning of energy systems, a critical imperative given the

[1] https://github.com/etsap-TIMES/TIMES_model

substantial investments demanded by large-scale transformations in the energy sector.

Exogenous technical, physical, and regulatory constraints can be applied, and technologies have specified fuel types, efficiency, lifetime, availability, environmental characteristics, and various costs. The various cost categories include:

1. **Investment costs:** represents an investment in capacity, e.g., new boiler capital costs.
2. **Variable costs:** are associated with the activity of a process, e.g. fuel costs.
3. **Operational and Maintenance (O&M) costs:** cover maintaining existing capacity.

In TIMES, the problem formulation consists of three types of entities, the objective function (Eq. 2.1), the decision variables (Eq.2.2), and exogenous constraints (end of section 4.2). The decision variables represent the choices made by the model, the exogenous constraints are defined by the modellers to reflect reality better, and the objective function of TIMES is to use the available choices within the applied exogenous constraints to find the optimal or least-cost pathway. The prices and quantities are in equilibrium so that suppliers produce exactly the quantities demanded by consumers, and therefore the total economic surplus is maximised [80]. Therefore, the TIMES objective is to minimise the discounted total cost of the system by solving for the following:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \cdot ANNCOST(r, y) \tag{2.1}$$

Where NPV is the net present value of the total cost in the model, $ANNCOST(r, y)$ is the total annual cost in region r and year y; $d_{r,y}$ is the discount rate, which determines the present value of future cash; $REFYR$ is the reference year for discounting; YEARS is the set of years for which there are costs, and R is the set of all regions in the model. TIMES will solve Eq.2.1 given bottom-up techno-economic data, top-down macroeconomic demands, and user constraints for a specified scenario.

To solve for the objective function (Eq.2.1) the model must first solve for the decision variables (Eq.2.2). In TIMES, as in other linear optimisation models, the supply curve of energy services is determined entirely endogenously within the model [80], as shown in Eq. 2.2.

$$Min€\ \forall_s \sum_k VAR\_ACT_{k,s}(y) \geq DM_s(y) \tag{2.2}$$

Where $Min€$ is the total discounted cost to be minimised for all energy services (s). The discounted costs in Eq.2.2 are then aggregated into a single total cost, which constitutes the objective function in Eq.2.1. VAR_ACT are the activity levels of the end-use technology (k) for the energy service in year, y. DM_s is the exogenous demand per energy service in year, y. The supply-demand equilibrium is driven by the exogenous specification of price-inelastic demand functions, $DM_s(y)$ in Eq.2.2. Whereas, the price and quantity of traded commodities are determined endogenously [80] as shown on the left side of Eq.2.2.

TIMES accounts for direct or first-order effects, that is, the most apparent effects; for example, replacing oil boilers with low-carbon electrical heating will decarbonise the residential sector. While also considering the indirect or second-order effects of replacing oil boilers with low-carbon electrical heating, for example, the required power generation investments. TIMES considers further downstream or third-order effects, which are less obvious and could be separated by time, such as the dynamics between the deployment of electric vehicles and future low-carbon electric heating in the cost-optimal decarbonisation pathway.

Most studies addressing the decarbonisation of the residential sector in Ireland use bottom-up residential simulation models rather than optimisation approaches. Simulation models are similar to ESOMs in that they have a rich representation of existing and future technological variables. Nonetheless, a significant difference is that these simulation models only intend to envisage the performance of a system under a given set of conditions. In contrast, optimisation models encompass energy dynamics in the search for optimal system design [92]. Simulation and optimisation models are developed to answer different research questions; however, they can be used in parallel to strengthen climate policy insights [93].

Bottom-up residential simulation models have been extensively used to explore Ireland's residential energy. In the first comprehensive analysis of the Irish residential sector, Clinch and Healy examined fuel poverty [94], excess winter mortality [95], occupancy behaviour [96], social benefit and cost [97], and energy efficiency [96–98]. Since then, many studies have used residential simulation models to provide insight into energy policy [32, 47, 99]. This thesis accounts for data and methodology insights from previous Irish simulation model research [38, 100], which is described further in section 4.2.

ESOMs have previously been used to optimise Ireland's energy system [72, 101]. No Irish ESOM studies exclusively explore the residential sector; however, some studies focused on the residential sector with greater granularity [102, 103].

2.3 The role of district heating in decarbonisation

Many social, economic and environmental variables are to be considered in DH deployment, as highlighted in Table 2.1. This thesis uses a techno-economic model, partially accounting for the economic and environmental variables outlined.

Table 2.1: Advantages and disadvantages of District Heating

	Advantages	**Disadvantages**
Social	• DH provides affordable heating, leading to reduced energy poverty [104]. • Employment creation in building and maintaining infrastructure [23] • A central authority maintains the system and provides redundancy. Building owners are not responsible for maintaining operation [105, 106]	• A high reliance on local dynamics requiring a high level of regional planning [107–109]. • Majority of consumer procurement required; with low citizen engagement [110], obligatory DH connections ensure buy-in and competitiveness [111].
Economic	• Regional heat zone strategies bolster energy security through sector coupling and enhancing energy efficiency [112–114]. • DH is low risk; having been successfully deployed in many EU regions [115, 116]. • High energy efficiency through economies of scale and surplus heat from renewable energy sources, which might not be feasible for individual units [104, 117].	• DH is not feasible in areas of low heat density demand or low DH connection rates [117] • High investment costs [117, 118] • The thermal retrofitting of buildings lessens the demand for heating, which can have drawbacks for DH feasibility [119] • The natural monopoly of DH grid operators needs to be addressed [120].
Environmental	• DH plays a crucial role in promoting sustainability by enabling the utilisation of surplus heat that would otherwise go to waste [121] • Reduced air pollution, especially when replacing coal and biomass [122, 123]	• Embodied energy and carbon in grid infrastructure resources like insulation and metal [119, 124] • Fossil fuels sourced DH results in little environmental benefit [120, 123]

Connolly et al. [104] developed Heat Roadmap Europe, which is a data-intensive decision support tool for energy system models to explore DH and renewable heat potentials for the EU-27. Heat Roadmap Europe uses Geographic Information System (GIS) mapping to layer multiple data sets to reflect local conditions, thus creating a heat atlas. The heat atlas was analysed using EnergyPLAN, a deterministic energy system model [125]. The study highlighted Europe's surplus heat exceeds the heat demand of all buildings while acknowledging the geographical and temperature constraints. The analysis found a triad solution of thermal retrofitting, DH, and individual heat pumps [104].

In Ireland, heating all buildings represented 24% of national GHG emissions in 2019 [126]. This percentage has been on a consistent upward trend for several years [127]. Ireland has the lowest share of renewable energy in heating among all EU member states, at 6.3% in 2020 [50]. Of this, 80% is sourced from biomass, mainly to meet industrial demands [128]. In 2019, the Climate Action Plan (CAP), an annually updated report that describes the necessary policies and measures to meet climate targets, set an objective to deliver two large DH systems by 2030 [65], which are expected to be completed by 2025 [129]. In 2021, a new climate law amplified decarbonisation ambition and established legally binding five-year Carbon Budgets (CBs) consistent with a 51% reduction in GHG emissions by 2030, compared to 2018 levels [52]. Reflecting this, CAP 2024 established a DH generation target of 2.7 TWh by 2030 [66], almost twice the goal of 2019. However, to reach this target, Ireland needs to implement DH more quickly than any other European country [130–132].

The idea of utilising surplus heat from data centres as a key component in establishing DH networks in Ireland is gaining momentum. However, its role in cost optimisation still needs to be explored. Despite comprising less than 1% of Europe's population, Ireland is a crucial and unique player in the continent's digital economy and houses 30% of its data [133]. As a result, the percentage of electricity consumed by data centres is increasing rapidly, reaching 18% of total consumption in 2022, twice the figure of 2019 [134]. Moreover, the substantial increase in demand poses challenges to ensuring electricity security of supply [135], potentially impeding decarbonisation efforts [136, 137]. This thesis explores the potential of using surplus heat within the median growth pathway for data centres [138].

Previous European research indicates that regions with high heat density demand but low deployment of DH may be better suited to implement DH than areas where DH is already widely deployed [117]. However, low DH deployment regions come with their own set of challenges, including the absence of a legislative and regulatory framework [131, 139], lack of municipal support [120], and a suitably skilled workforce [129]. Despite some of the risks of DH in low deployment areas, there are rewards in developing affordable, low-carbon heating. For instance, For instance, DH could partially solve Ireland's escalating energy poverty problem, defined as a household that spends more than 10% of its net income on energy [48]. The convergence of the politics of energy poverty and ambitious legally-binding climate targets requires a political response to develop affordable low-carbon heating. DH is well-suited to meet this role.

Recent studies explicitly examining the economic potential of DH in Ireland found that more than half of all the space and water heating for residential and service buildings can be supplied by DH [127, 140, 141], see Table 2.2. Irish studies have found that surplus heat capacity holds significant potential despite variations in findings.

Table 2.2: The potential share of heat in the residential and services sector which district heating networks can serve in 2050, and the share of surplus heat supply within those district heating networks

Author	**Published**	**DH potential**	**Surplus heat**
SEAI [142]	2022	54%	38%
REI [140]	2021	56%	57%
IrDEA [141]	2019	57%	67%
AECOM [143]	2015	1.5%	1%

The AECOM 2015 study [143] suggested that DH could supply 1.5% of Ireland's building heat demand. However, using the same methodology, the SEAI 2022 study [142] revised this estimate to 54% due to reassessing DH's economic viability and expanded surplus heat use. The Renewable Energy Ireland report [140] and the Irish District Energy Association's (IrDEA) Irish Heat Atlas [141] indicate substantial potential for DH in achieving renewable heat and decarbonisation targets. Similarly, research by Thellufsen et al. [103] and analysis of Dublin [112] support these findings. These studies suggest that Ireland presents a favourable landscape for adopting DH.

2.4 The Fabric-First Approach

Ireland's current residential decarbonisation strategy takes a *fabric-first* approach. This approach prioritises the thermal efficiency of the building envelope to reduce heat loss, including building fabric measures such as increasing insulation, reducing thermal bridging, and improving air tightness. Before availing of a heat pump subsidy, Irish households must have high thermal efficiency, characterised by minimal heat loss through their building's fabric envelope and ventilation. Adopting the *fabric-first* methodology requires a comprehensive overview of its advantages and disadvantages to enhance policy strategies. These considerations should include people, planet, and policy perspectives [144]; for an overview of these factors, please refer to Table 2.3. The effectiveness of the *fabric-first* approach hinges on factors such as financial and carbon payback, market conditions, embodied carbon, material and labour costs, and cumulative energy savings, all of which are affected by the depth or target level of thermal efficiency [145]. The behavioural dynamics of the rebound effect and non-monetary benefits further complicate the *fabric-first* approach. The rebound effect occurs when energy savings from reduced heat loss are offset by occupants choosing higher internal temperatures.

Table 2.3: Advantages and disadvantages of the *fabric-first* approach compared to the energy system cost-optimal pathway from the people, planet, and profit perspectives

Perspective	**Aspect**	**Detail**
People (Household)	Advantages	• Improved EPC and increased property value [146] • Long-term energy savings [147] • Improved thermal comfort [37] • Multiple low-temperature heating technologies are suitable [148]
	Disadvantages	• Higher initial costs with the rebound effect cause payback uncertainty [149, 150] • Considerable initial disruption [31, 151] • Non-occupier owners have few advantages [146]
Profit (Installer)	Advantages	• Follows heat pump best practice guidance [152, 153] • Thermal retrofit innovation [154]
	Disadvantages	• Enhanced standards in designing, installing, and commissioning heating systems are necessary [152, 153].
Planet (Policy)	Advantages	• Minimised energy loss through the building envelope, resulting in lower emissions [147] • Long-term investment as the building's fabric is typically upgraded less frequently than building services [155] • Reduced peak electricity demands [156, 157] • Increased local employment [55]
	Disadvantages	• Increased total decarbonisation costs [158] • Moisture challenges post-retrofit [159] • Adds a barrier to the rapid energy transition [160] • After adopting a low-carbon heat supply, fabric measures do not yield further emission reductions [127] • Increased use of resources and embodied carbon [161] • Energy savings diminish with time [162]

The *fabric-first* approach to building design has many benefits but possesses significant challenges. On the positive side, it can improve EPC ratings, property value, and long-term energy savings [146, 147]. However, it can also lead to higher initial costs, requiring enhanced design and installation standards [149, 150, 152, 153], while competing for construction labour during a housing crisis [55]. Some studies suggest that the *fabric-first* approach may inadvertently increase decarbonisation costs, create barriers, and result in elevated resource use [158, 160, 161]. Some research emphasises the significance of the lock-in effect, which refers to missed insulation opportunities during construction [147]. Other research highlights the diminishing efficacy of thermal retrofits [162]. This thesis will focus on the techno-economic aspects of the *fabric-first* approach and explore how heat pump performance due to building heat loss affects optimal Irish decarbonisation pathways.

Reducing heat loss is crucial to adopting low-carbon heating in the EU strategy [163, 164]. However, Ireland's *fabric-first* approach mandates stricter building fabric standards for heat pump installation than several other European countries [54]. For example, a study conducted by SEAI suggests that the most cost-effective roof U-value for Ireland is 0.13 W/m^2K [165]. In contrast, other studies have indicated that minor improvements in fabric efficiency can be cost-effective [166–168]. The UK policy only requires the installation of loft and cavity wall insulation for heat pump subsidies without imposing a minimum thermal efficiency standard [169], making it a more lenient *fabric-first* approach. Luxembourg and Austria prioritise the functional dynamics of heat pumps over fabric prerequisites. Most European countries do not have a fabric standard prerequisite for heat pump subsidies, making it a more lenient approach to insulation prerequisites than Ireland [170]. Ireland, France and the Netherlands are the only countries in the EU that support minimum fabric standards, with the latter two providing subsidies for fabric upgrades paired with heat pump installations without defining a baseline for fabric standards [171]. In summary, with the diverse European policy landscape, Ireland is distinguished by its notably strict thermal efficiency requirements [54, 169].

To address financial challenges, the Irish government has increased subsidies for heat pumps. However, the Heat Loss Indicator (HLI) presents a significant obstacle to homeowners looking to take advantage of these subsidies. The HLI assesses the fabric and ventilation conditions of a dwelling to determine the total heat loss per unit of floor area. The introduction of the HLI criterion, aimed at protecting households from rising energy bills, is particularly significant in Ireland, where people are already affected by high electricity prices [49] and energy poverty [48]. As the energy transition progresses, current HLI standards could act as a barrier to heat pump installation, hindering decarbonisation progress. This thesis aims to investigate decarbonisation pathways that support the installation of heat pumps in dwellings with a higher HLI (i.e., lower thermal efficiency) than the current policy allows.

Previous research has explored heat pumps' economic, regulatory, and infrastructural aspects [172]. Heat pumps operate differently from traditional fossil fuel boilers, and ambient temperature significantly affects their efficiency. Utilising the Danish TIMES model, Petrovic and Karlsson [87] explored the effects of ambient temperature variations on the performance of air-source heat pumps. Their analysis indicated an increase in heat output by 9.5% when a static Coefficient of Performance (COP) was used, as opposed to using a COP value adjusted for ambient temperature fluctuations [87]. Other research highlights the cost-effectiveness of thermal storage, especially in hourly energy system models [83], by prioritising heat pump operation during hours when electricity production costs are low, resulting in a reduced need for peak and reserve capacity investments, optimising both investments and operations. Thermal storage can be classified into categories, including active thermal energy storage, such as thermal storage tanks for space heating and hot water, and passive thermal storage, where building mass or interiors store energy [173].

Although high-precision studies on heat pumps [174, 175] provide valuable insight, energy system models often overlook these finer operational details [57, 176]. While energy system models have analysed the role of heat pumps in decarbonisation pathways, previous studies have mainly focused on temporal resolution [177], demand-side responses [178], energy security [179], and load shifting [156, 157]. In heat pump performance analysis, accounting for heat loss in dwellings could reduce the energy performance gap in energy system models.

2.5 Aims

The literature review has identified research gaps in residential heating modelling, which has been foundational in developing the research questions for this thesis. Despite emerging evidence of its potential, there is a lack of research on DH in Ireland, highlighting a significant opportunity. Additionally, previous studies have not adequately addressed the impact of empirical internal temperature and heat pump performance thresholds on cost-optimal pathways. Addressing these gaps has led to the development of specific research questions to provide a deeper insight into the optimal strategies for residential decarbonisation in Ireland.

This section addresses the energy transition challenges faced by the residential sector in Ireland by examining three critical aspects of the residential heating system that could improve the country's decarbonisation pathways: thermal retrofitting, heat pumps, and district heating [46, 180, 181]. In the past, DH was not considered a viable option in Ireland [143], but recent studies have shown significant potential [141, 142]. DH has emerged as a reliable low-carbon heating option that effectively harnesses surplus heat from diverse sources, such as industry and data centres. The percentage of electricity consumed by data centres in Ireland has surged, accounting for 18% of total consumption in 2022, a number that is twice as high as that of 2019 [134], which is a higher percentage than the rest of Europe [133]. However, there is an opportunity to repurpose this waste surplus heat from data centres to provide affordable heating to buildings. Furthermore, heat pumps which leverage ambient energy to provide heating or cooling solutions and, if combined with low-carbon electricity, optimising their deployment could significantly decarbonise Ireland's built environment. This thesis explores how current heat pump threshold subsidies affect Ireland's optimal decarbonisation pathways. It also investigates the significance of residential internal temperatures and their influence on understanding residential energy and policy insights, such as thermal retrofits.

This thesis advances Ireland's current energy policy modelling practices by integrating the most up-to-date technoeconomic and macroeconomic data while establishing a replicable methodology that can be utilised in other regions. The insights gained from this research strengthen the models to provide evidence-based policies in Ireland. Furthermore, the methodologies developed here can be tailored for various energy modelling applications. The Research Questions (RQs) outlined below serve as a roadmap for this thesis:

- **RQ1.** How do changes to future technology development affect how Ireland should set cost-optimal GHG targets in the residential sector?
- **RQ2.** How does using empirical internal temperature data, adjusted for energy-efficient dwellings, influence the optimal decarbonisation pathway compared to relying on EPC database defaults?
- **RQ3.** What role can district heating play in Ireland's fuel mix to achieve cost-optimal heat decarbonisation?
- **RQ4.** At what connection rate does district heating become cost-effective?
- **RQ5.** Does Ireland's existing *fabric-first* approach align with the cost-optimal pathway for achieving residential decarbonisation?

- **RQ6.** How does the Heat Loss Indicator threshold for optimal heat pump performance affect optimal residential decarbonisation pathways?

Chapter 3

Methodology

This chapter introduces the foundational methodology used across all studies in this thesis. In Chapter 4, a simplified version of this methodology is applied, specifically tailored to the grouping of energy archetypes. Chapter 5 extends the model by integrating district heating considerations while accounting for the energy archetypes. Lastly, Chapter 6 builds upon the framework established in Chapter 5 by incorporating heat pump thresholds, further refining the model. Each study within this thesis utilises the foundational methodology from this chapter but extends the methodology to address the research question being explored. These methodological developments are further explained in their respective chapters.

It is imperative to acknowledge the fundamental role that GHG accounting methodologies play in energy system modelling. These methodologies significantly impact the parameters and insights derived from such models. Therefore, it is crucial to comprehend their influence before delving into the methodologies presented in this thesis. Two main methods for accounting for GHG emissions are territorial or production-based and consumption-based emissions. The Intergovernmental Panel on Climate Change (IPCC) GHG guidelines use the territorial emissions which account for GHG produced within a nation's borders [182]. Consumption-based emissions consider the global interconnectedness of emission sources and account for emissions based on where they are consumed, regardless of where they are produced [183, 184]. This thesis only considers territorial emissions as climate policy insights based on IPCC GHG accounting. In this thesis, Ireland is presented as a case study, and its consumption-based GHG emissions are 74% higher than its territorial emissions [185]. It is essential to recognise that imports contribute to emissions, but they are outside the scope of this thesis, which uses the IPCC GHG accounting methodology.

As part of this thesis, the TIMES Ireland Model (TIM) residential sector was developed using the TIMES framework [57]. The schematic in Fig. 3.1 shows the main TIM sectors, representing the demand-side modules and how they link with the supply-side modules to create an overview of the national energy system. A new methodology was developed to address the energy performance gap between expected EPC and actual energy consumption. The rich EPC data source is calibrated against additional national data sources [37, 127, 141, 186] to better reflect national energy and account for internal temperature variations based on empirical data, which is explained further in this chapter. This methodology addresses a significant energy performance gap in state-of-the-art ESOMs.

This thesis takes a significant step towards understanding the potential cost-optimal pathways for DH in a low-deployment nation. Until now, DH has been overlooked in Ireland [143], but the research presented in this thesis has developed TIM to include DH, allowing an exploration of the impact of DH on the built environment and other energy sectors [180]. To better represent DH supply, demand, and costs, the robust Heat Roadmap Europe methodology [187] is used, and the influence of DH connection rates on costs and capacity is explored in Chapter 5, utilising input data from Ireland's Heat Atlas [141], which is based on European data. This work offers valuable policy insights by including and representing DH in an energy system model for countries with low DH deployment [104, 108, 122].

Integrating thermal retrofits and heat pumps into energy system models can be complex. Ireland's *fabric-first* approach prioritises building insulation as Heat Loss Indicators (HLIs) to determine eligibility for heat pump subsidies. To accurately reflect HLI values, data is sourced from Ireland's EPC database [188] and used to inform decarbonisation strategies [181]. Previous energy system models have examined heat pump performance concerning ambient temperature [87] and thermal storage [83]. However, this thesis aims to fill a gap in knowledge by examining the effect of a dwelling's HLI on heat pump performance in Chapter 6, which is especially crucial in Ireland, where many buildings are thermally inefficient. This thesis addresses the gap in understanding the impact of a dwelling's HLI on heat pump performance in Chapter 6.

3.1 TIMES Ireland Model (TIM)

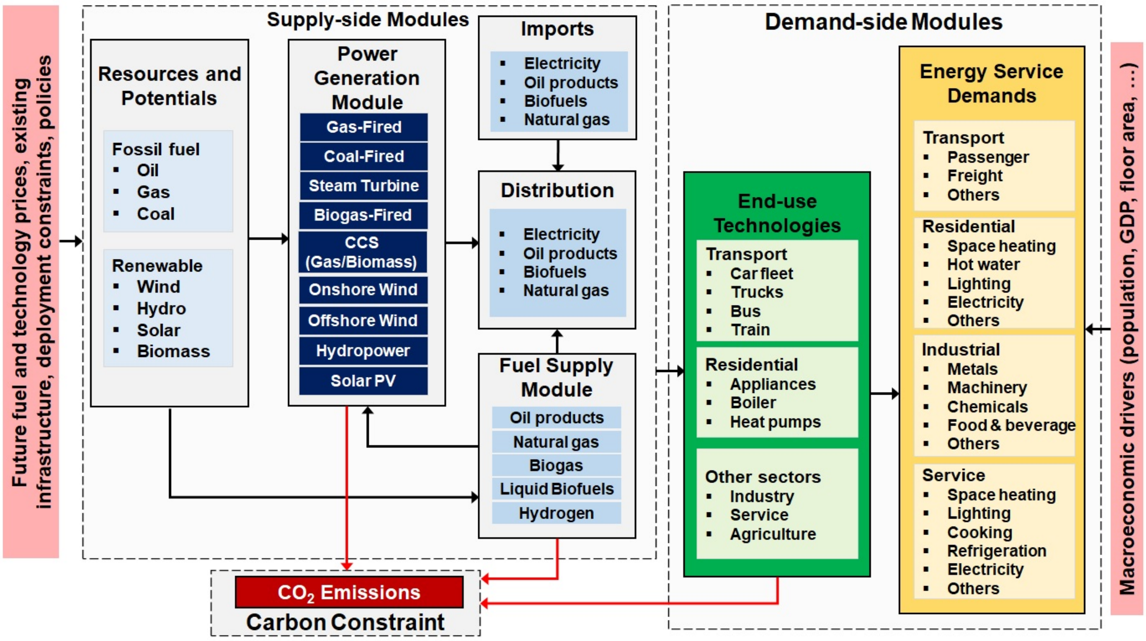


Figure 3.1: The simplified reference energy system in the TIMES Ireland Model illustrating where the residential sector fits into the model [57]

Previous versions of the Irish TIMES model have provided invaluable insights into Irish climate policy over the past decade, including updating input data [189–192]. However, the model was not open-source, and the model structure was not exclusively developed for Ireland, resulting in reduced flexibility. The need for a transparent, flexible, and robust national model is a critical driver in developing TIM.

TIM is designed with regional flexibility, and a region refers to a geographical region; TIM can solve either one single national region or a 26 multi-regional model where each region represents a municipal area known as a county. TIM also has flexible temporal resolution options, from hourly to annually. For the results in this paper, a national region with 40 time-slices is used. The time-slices are divided by season, weekday and weekend, and five different daily periods (Midnight-7 am, 7 am-9 am, 9 am-5 pm, 5 pm-7 pm & 7 pm-Midnight). The discount rate, $d_{r,y}$ in Eq. 2.1, is set to 4% for all regions and years in TIM. The discount rate is based on Ireland's public spending code and plays an essential role in the model's objective function. The TIM base year, to which all future values are discounted, is at the beginning of the model time horizon and contains a single year of calibrated values that are in equilibrium, i.e., supply equals demand. The base year selected in TIM is 2018, which aligns with the reference year for the new Irish climate targets [66, 193].

Each sector of the energy system was developed concurrently and periodically consolidated using a git-centred model development process[1], allowing model developers to analyse the entire model while sectoral development progressed. The transparency of TIM [194] improved the engagement in the development process, whereby external energy experts and other stakeholders contributed using web-based dashboards[2]. The current results used in this chapter can also be analysed via web-based results[3], or downloaded [195].

The transparency checklist created by Cao [27] was used to visualise the transparency of TIM, which is shown in Table B.6. Although TIM does not comply with the entire checklist, the model fulfils 14 criteria and partially fulfils four criteria, only failing one criterion, the robustness analyses. TIM failed in the robustness analysis because it was not compared with another Irish ESOM. All other Irish ESOMs are outdated because of the use of obsolete technology data and national climate targets. The partially satisfied criteria of: identification of uncertain factors, uncertainty consideration, model validation, and sensitivity analyses all require further development. The ongoing TIM development will fully satisfy more criteria from the transparency checklist.

3.2 TIM: Residential Sector

The residential sector in TIM was developed to reflect recent developments in national climate policy, particularly ongoing national retrofit and electrification strategies. TIM has two energy services illustrated in Fig. 3.2 - Non-building and building archetypes. Essentially, the six non-building archetype energy services lack granularity and cannot be accurately assigned to a type of building. The base year consumption data for the non-building archetype energy services were sourced from a national report [58] and results [196] from an EU model [197]. Cooking is the only non-building archetype energy service that uses fuel other than electricity; alternative fuel sources are gas and LPG.

[1]https://github.com/MaREI-EPMG/times-ireland-model
[2]https://tim-review1.netlify.app
[3]https://tim-carbon-budgets-2021.netlify.app

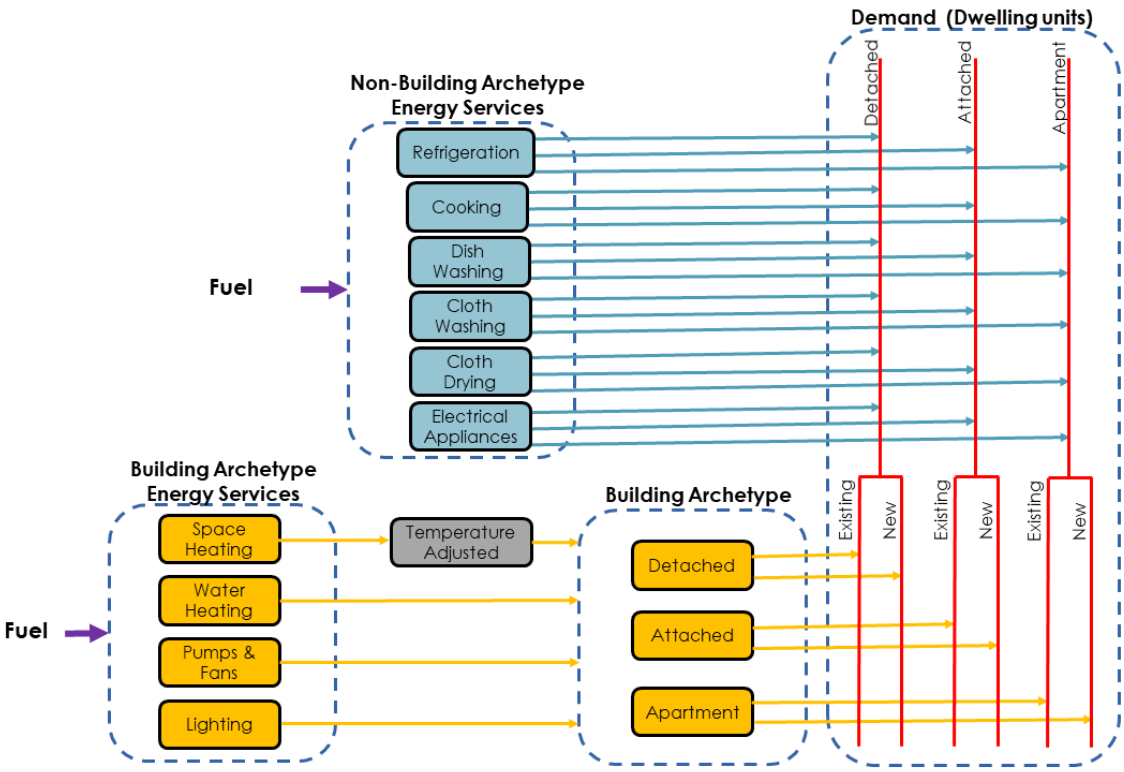


Figure 3.2: Residential reference energy system in Times Ireland Model, flowing from left to right are the fuels, energy services, and demands.

The building archetype energy services data is sourced from the EPC database[4]. To reduce the computational requirement of the initial version of the model described in Chapter 4, the existing dwelling energy demand is calculated from the weighted average of the nine groups of EPC ratings shown in Table 3.1. Where the new dwelling energy demand aligns with the energy demand of A-rated EPC dwelling for each building archetype. The development of the model shows the energy archetypes used in chapters 5 and 6.

[4]https://ndber.seai.ie/BERResearchTool/ber/search.aspx

Table 3.1: BER labels in EPC database and ranges used in the TIMES Ireland Model

Label		Energy
EPC	TIM	$kWh/m^2/yr$
A1 A2 A3	A	≤ 75
B1	B1	76-100
B2	B2	101-125
B3	B3	126-150
C1 C2 C3	C	151-225
D1 D2	D	226-300
E1 E2	E	301-380
F	F	381-450
G	G	>450

The heterogeneity of the dwelling stock is captured in the initial Chapter 4 TIM version in by the 1,188 different archetypes (three buildings, 11 space heating fuels, 12 water heating fuels, and three cooking fuels) that exist in the base year of the model. Solar energy is excluded as a space heating fuel; however, all other combinations exist in the base year. The internal space temperature adjustments, detailed in section 4.2, reduces the energy performance gap by compensating for the overestimation of space energy consumption in the Dwelling Energy Assessment Procedure (DEAP) asset rating tool. The demand for building and non-building archetype energy services is ultimately determined by the number of residential dwellings, as illustrated in Fig. 3.2.

The first methodology step involves filtering and extracting EPC data. The filtered EPC database overview shown in Fig.6.1 is based on previous research [38, 46, 100]. The filters used are detailed in Table 3.2.

This thesis focuses on three types of buildings - apartments, attached, and detached - each of which falls into one of nine distinct BER categories. The dwelling archetypes are derived from a previous study [46], which uses two Irish datasets to represent three different types of buildings. Apartments refer to any dwelling that has a shared entrance. Attached refers to any dwelling connected to another dwelling but has its private entrance, such as semi-detached, terrace, basement dwellings and maisonettes. A detached dwelling is not connected to another dwelling.

Table 3.2: Filters applied to the Irish EPC database

Filter Name	Data Removed	Reason
Ground Floor Area	$< 30m^2$ & $> 1000m^2$	Considered erroneous
Provisional Records	All	Higher Inaccuracies
Thermal Bridging Factor	$\leq 0.15W/m^2K$	Outlier
Declared Loss Factor	$> 20kWh/day$	Considered erroneous
Living Area Percent	$< 5\%$ & $> 90\%$	Outlier
Secondary Heat System Supply Fraction	$> 21\%$	Outlier
Heat System Efficiency Adjustment Factor	< 0.7	Considered erroneous
Main Space System Efficiency	$\leq 19\%$	Considered erroneous
Water System Efficiency Adjustment Factor	< 0.7	Considered erroneous
Main Water System Efficiency	$\leq 19\%$ & $> 320\%$	Considered erroneous

An overview of the data handling processes applied is illustrated in Fig. 3.3, and is described in this section.

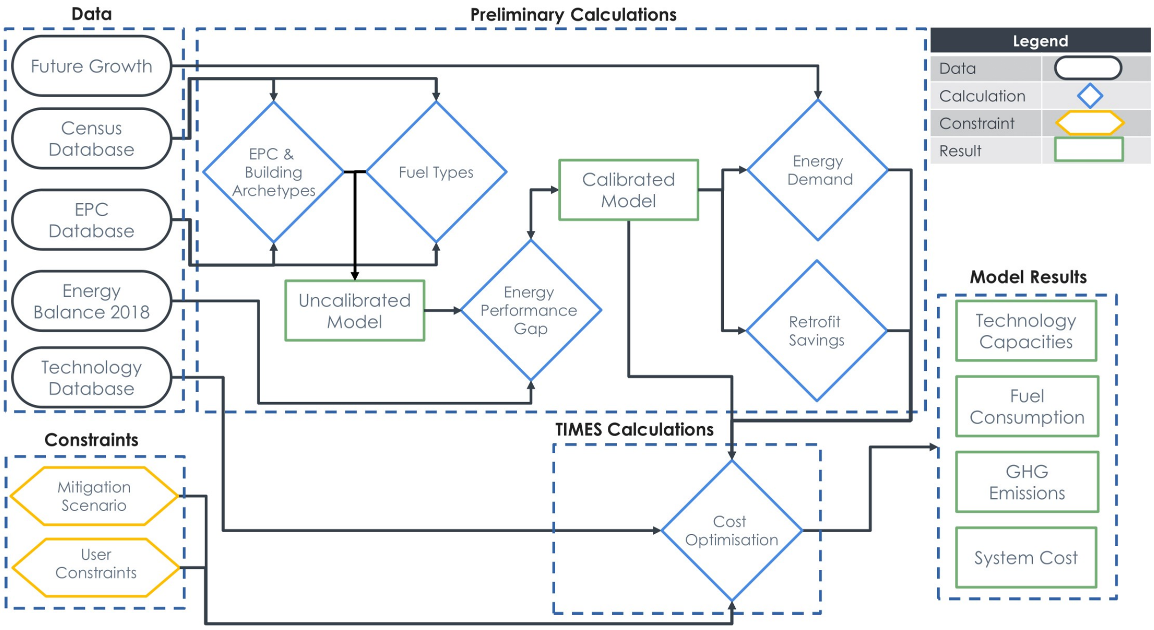


Figure 3.3: Simplified methodology process flow chart for the residential sector in TIMES Ireland Model

The Irish EPC database, which complies with the Energy Performance of Buildings Directive (EU) 2018/844 (EPBD), contains the expected EPC energy consumption for heating, lighting, and pumps & fans. These building archetype energy services accounted for 85% of residential energy in 2018. Each EPC rating in Ireland has 15 possible Building Energy Rating (BER) labels; these labels are specific to Ireland, and the BER labels are referred to as EPC ratings in this study. The aggregation of 15 to nine EPC ranges in TIM is presented in Table 3.1. The purpose of keeping the narrow ranges of B1, B2, and B3 is due to the current emphasis of the retrofitting policy on upgrading homes to a B2 EPC standard. The nine energy archetypes described here are not found in the initial results of the model. Instead, a weighted average calculation is used to group all existing dwellings.

Over 53% of Irish households are recorded in the growing EPC database, which is used in Chapter 4; this share has continually grown throughout each study. Each EPC record shows more than 200 energy-related variables corresponding to more than 180 million data points in Chapter 4. Therefore, to remove erroneous data, a data filtering process is necessary; the filters applied in this thesis originate from a previous study [38] and are outlined in Table 3.2. The filters remove 10% of all EPC records. Data processing and filtering are carried out in Tableau[5], and the publicly available EPC database can be downloaded and imported into the Tableau workbook [198], which provides reproducible processing and filtering for transparent export to TIM. Therefore, the open-source Tableau workbook created can filter and handle an updated EPC database. It is acknowledged that the default values in the EPC database skew the distribution of certain variables [32], but this is not addressed in this paper.

DEAP is an asset rating tool used to benchmark energy consumption per dwelling area, thus not accounting for any technical or social variables. The DEAP space heating calculation framework is based on IS EN 13790 [199], where each dwelling has two thermal zones, a living area and a non-living area. DEAP assumes all dwellings heat the living area (living room, sitting room, and possibly kitchen) to 21°C and the non-living areas (bedroom, bathroom, hallways) to 18°C. DEAP uses one calculation to account for these two thermal zones by obtaining the average internal temperature based on the fraction of the living area. Additionally, DEAP assumes each dwelling heats for 56 hours/week from October to May inclusively, and the average ambient temperature during the heating season is 7.6°C. The internal temperatures assigned by DEAP, referred to as the default temperature in this thesis, result in a significant error whereby space heating is overestimated by 23%. This is consistent with previous research on Irish dwellings, which found a 7.5% change in energy consumption for every 1°C internal temperature shift [38].

The empirical energy consumption data from Coyne and Denny's study [37] reveal variability in energy use across 10,000 gas-heated urban dwellings in Ireland, categorised by BER labels. This thesis compares the primary energy consumption reported by Coyne and Denny [37] with the energy consumption used in this analysis, benchmarked against the expected EPC energy consumption in Table 3.3. Modifications to the energy consumption in this thesis are based solely on one

[5] https://www.tableau.com/

variable: internal temperature. The assumptions regarding internal temperature lead to variance in energy consumption and are used to calibrate the model shown in Figure 3.3, which are outlined in Table 3.4. Due to the limited sample size, this thesis omits the full range of energy consumption data found in [37] , thus addressing concerns about potential uncertainty.

Table 3.3: The percentage change of energy variance compared to the expected EPC rating is shown for the empirical data [37] and applied in TIMES Ireland Model.

EPC Rating	Empirical data	TIM
A & B	+44%	+15%
F & G	-56%	-39%

The Archetype Dwelling Energy Model - SQL (ArDEM-SQL) [100] is a simulation model used for pre-processing data in this study. ArDEM-SQL imports Ireland's EPC database into Microsoft SQL language and re-calculates the expected energy consumption by adjusting internal temperatures. Different internal temperature assumptions were applied using ArDEM-SQL, and the temperatures selected in this thesis better reflect the actual temperature [37] and match the top-down 2018 SEAI Energy Balance[6]. The chosen temperatures are outlined in Table 3.4. There is still uncertainty associated with the precision and variance of internal temperatures within building archetypes and fuel due to a lack of data. The reductive internal temperature assumption is the only assumption applied to cover the heterogeneity of the occupancy behaviour. Therefore, further work is required to obtain more reflective temperature assumptions.

Table 3.4: The internal temperature assumptions applied in this study.

EPC Rating	Living Area	Non-Living Area
A	23°C	20°C
B	21°C	18°C
C	18°C	15°C
D	18°C	15°C
E	18°C	15°C
F	18°C	15°C
G	18°C	13°C

The three building archetypes used in TIM are derived from the CSO [200] and the EPC database; this overview is shown in Fig. 3.4. Similar building types in each database are grouped; each group is distinct and matches a group in the corresponding

[6]https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/energy-data/

database. The *"Mobile or Temporary Structure"* and *"Not Stated"* CSO categories are grouped together; however, with no similar parallel group, they form the non-stated building archetypes (nsa) in Eq.3.1. It was possible to separate attached into semi-detached and terraced in the CSO database and match them with groupings in the EPC database. However, on examination, there was no evidence that semi-detached and terraced dwellings are distinctly different in terms of fuel, building fabric, and energy demand.

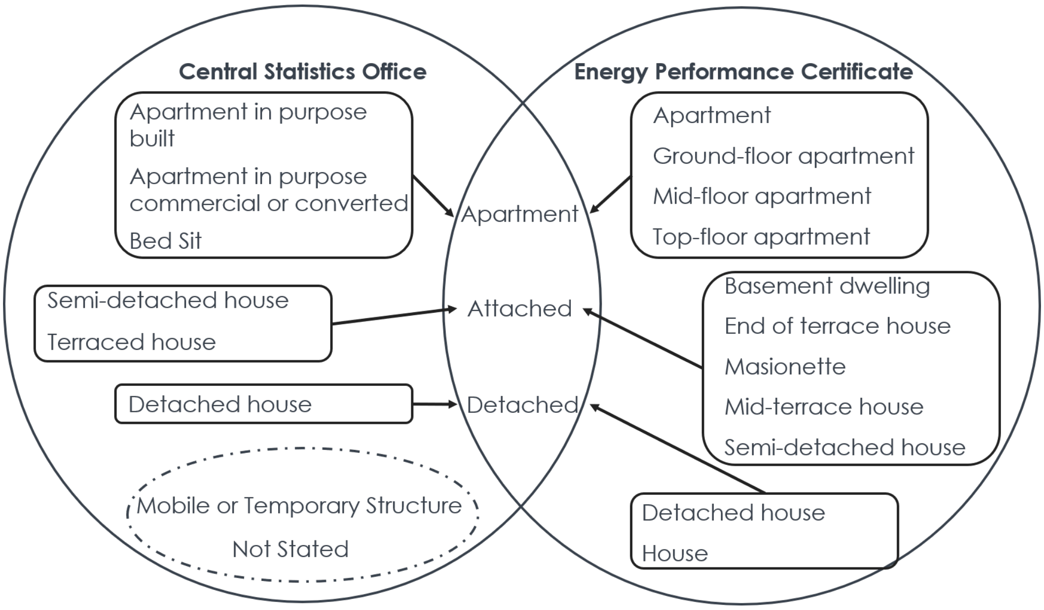


Figure 3.4: Illustration of the methodology used to select building archetypes in the TIMES Ireland Model. The three building archetypes shown in the circle intersection are used.

The 2016 CSO Census database [200] is used with the EPC database to calculate the base year dwelling stock. The CSO dataset, E1005, represents private households in permanent housing and provides a split of eight building archetypes for each of the 26 counties in Ireland. Once the EPC and CSO database tables have been filled in to include dwellings per building archetype and per county. The next step is to scale up the EPC database to calculate the residential dwelling stock; this was done by finding the ratio of building archetypes per county between the EPC database and the CSO data, as shown in Eq.3.1.

$$R_{a,c} = \frac{CSO_{a,c}}{EPC_{a,c}} + \frac{CSO_{nsa,c}}{CSO_c} \tag{3.1}$$

$R_{a,c}$ is the ratio per building archetype (a) and per county (c), which is a region in TIM. $CSO_{a,c}$ represents the number of building archetypes per county in the CSO database, $EPC_{a,c}$ is the number of building archetypes per county in the EPC database. $CSO_{nsa,c}$ represents the non-stated building archetypes (nsa) per county in the CSO database. Which is divided by CSO_c, the total number of dwellings per county in the CSO database, allowing for the non-stated building archetypes per county to be assigned a building archetype based on the share of known building archetypes of that county.

The next step is multiplying the number of EPCs per building archetype and county by the relevant ratio, as shown in Eq. 3.2.

$$TIM_{a,c} = EPC_{a,c} \cdot R_{a,c} \tag{3.2}$$

$TIM_{a,c}$ represents the final data on the dwelling stock per building archetype, and per county. The initial release of TIM, described in this paper, does not use dwellings per county/region; instead, a national total number per building archetype is used, as per Eq. 3.3. The calculations applied here allow for higher spatial analysis in future model versions.

$$TIM_a = \sum_{c=1}^{26} TIM_{a,c} \tag{3.3}$$

TIM_a is calculated by summing the total number of building archetypes per county. Once the final dwelling stock is complete, the next step is to assign an EPC rating to all dwellings. This was done in Eq. 3.4 by comparing nine different age ranges of dwellings for each of the three building archetypes between the EPC and the CSO database.

$$TIM_{e,a} = CSO_{y,a} \cdot \frac{EPC_{e,y,a}}{EPC_{y,a}} \cdot \frac{CSO + CSO_{nsa}}{CSO} \tag{3.4}$$

Where $TIM_{e,a}$ is the total number of dwellings in TIM per EPC rating (e) and per building archetype. $CSO_{y,a}$ is the number of dwellings by year of construction (y) and building archetype in the CSO database; note that there is no EPC rating in the CSO database. $EPC_{e,y,a}$ is the number of dwellings per EPC rating, per year of construction, and per building archetype from the EPC database and dividing this value by $EPC_{y,a}$ results in a probability that a dwelling built in a given age range falls within an EPC range. The final part of the equation $\frac{CSO+CSO_{nsa}}{CSO}$ compensates for the non-stated building archetypes in the CSO data, where CSO is the total number of dwellings in the CSO dataset and CSO_{nsa} is the total number of non-stated building archetypes. The EPC probabilities' results are summarised for each building archetype in Table B.2,B.3 & B.4, while Table 3.5 shows the values for $TIM_{e,a}$.

Table 3.5: The number of dwellings per EPC rating and building archetype in the base year of TIMES Ireland Model

EPC Rating	Apartment	Attached	Detached
A	9,419	15,472	20,379
B1	7,459	9,538	9,434
B2	14,042	17,545	20,091
B3	19,924	49,769	53,466
C	58,905	282,152	251,319
D	43,739	187,627	166,668
E	25,768	101,419	81,397
F	12,331	50,124	43,241
G	15,211	52,707	78,436
Total	**206,799**	**766,352**	**724,430**

Investment and O&M costs are applied to the residential sector. However, variable or fuel costs are not applied. Instead, variable costs are applied in the supply sector, where cost data are sourced from the latest World Energy Outlook report [12]. Both the SEAI Energy Balance and EPC databases have 18 different fuels. The fuels are aggregated into 13 in TIM, as shown in Table 3.6. Fuels are grouped in a way that simplifies the model and exposes fuel decarbonisation insights. For example, the solid multi-fuel from the EPC database represents an open fire fuelled by coal, peat, or wood. After examining the SEAI Energy Balance and EPC database, the fuel share was set at 19.4%, 74.4% and 6.2%, respectively; these percentages are non-adjustable, as the share of these fuels will not provide any significant insight into residential decarbonisation. However, disaggregating the ambient heat used by heat pumps could potentially provide insights; therefore, *"Space ambient heat"*, which is the ambient heat used by heat pumps for space heating, and *"Water ambient heat"*, which is the ambient heat used by heat pumps for water heating, are separate fuel sources in TIM.

The costs of space and water heating technology and the associated technical data are obtained from EU TIMES [71] and an EU report [201]. The report has spatial cost data from which the north EU region (Denmark) was mainly used; this data

Table 3.6: The SEAI Energy Balance and EPC database were analyzed to select 13 different fuels in TIM, which are shown in the right column.

SEAI Energy Balance	**EPC Database**	**TIM**
Bituminous Coal	House Coal	Coal
Anthracite + Manufactured Ovoids	Anthracite	
Lignite / Brown Coal	Manufactured Smokeless	
Sod Peat	Sod Peat	Peat
Briquettes	Peat Briquettes	
Kerosene	Heating Oil	Kerosene
Gasoil / Diesel		
Petroleum Coke		
Natural Gas	Mains Gas	Natural Gas
Biomass	Wood Chips	Biomass
	Wood Logs	
	Wood Pellets (bulk)	
	Wood Pellets (in bags)	
Solar Thermal		Solar
Solar Photovoltaic		
Ambient Heat		Space Ambient Heat
		Water Ambient Heat
Electricity	Electricity	Electricity
Heat	Unknown	Heat
LPG	Bottled LPG	LPG
	Bulk LPG	
Biodiesel	Biodiesel	Biodiesel
Bioethanol	Bioethanol	Ethanol
	Solid Multi-Fuel	Coal
		Peat
		Wood

are sourced from the continuously updated and expanding Danish Energy Agency's technology data for individual heat production dataset[7]. Where data from the north EU region were missing, data from the central EU region (Germany) was used.

The technological data for refrigerators, washing machines, dryers, and dishwashers are sourced from Topten EU [202] and SEAI [58]. Topten EU has an extensive database covering a variety of electrical appliances in the European market, the data includes cost and efficiency, and Topten EU reports have appliance sales and market shares [203]. The Topten EU database is also used to obtain cooking data, which is then cross-checked with Eurostat [204] and SEAI [58]. Additionally, Eurostat [204] and SEAI [58] are used to source the *"Electrical Appliances"* category, which covers any appliance that uses electricity that is not classified separately, e.g., television, multimedia, and outdoor appliances.

TIM has two thermal retrofit options per building archetype, which is consistent with other Irish retrofit studies [205, 206]. In TIM, a shallow retrofit is defined as when the

[7]https://ens.dk/en/our-services/projections-and-models/technology-data

final energy is reduced by $\leq 35\%$, a deep retrofit reduces the final energy by $> 35\%$, and a reduction of $> 75\%$ is considered infeasible. Table B.1 shows the final energy savings of the thermal retrofits for each EPC rating. The scenarios in the results with and without internal temperature assumptions consider the expected energy savings with the rebound effect partially included and the rebound effect excluded, respectively. In this study, all post-retrofit EPC ratings are fixed to a B2 EPC rating, the prerequisite for installing electric heat pumps. Specific work performed during the thermal retrofit upgrade is not taken into account; rather, a holistic approach is chosen, whereby the average cost that takes a dwelling from a pre-retrofit to a post-retrofit EPC rating is taken. Ali et al. [207] thermal retrofitting cost data is used exclusively for 80% of the thermal retrofit options in TIM. The remaining 20% of thermal retrofit options use an average of Ali et al. [207] and the Typology Approach for Building Stock Energy Assessment (TABULA) [208] cost data. Despite Ali et al. [207] using cost data from Ireland's two largest thermal retrofitting databases [209, 210], TABULA cost was added to minimise cost uncertainty.

Equations 3.5 and 3.7 are used to find the average cost of a retrofit per retrofit depth and per building archetype.

$$\overline{€}Retrofit_{rf,a} = Average((Ali_{rf-rt} \cdot AF), TABULA_{rf-rt,a}) \tag{3.5}$$

Where $\overline{€}Retrofit_{rf,a}$ is the average capital cost of retrofitting from a given pre-retrofit EPC rating or rating from (rf) to a post-retrofit B2 EPC rating for each building archetype. $TABULA_{rf-rt,a}$ is the average retrofit cost [208] from the pre-retrofit EPC rating to the post-retrofit B2 EPC rating for each building archetype. Similarly, Ali_{rf-rt} represents retrofit costs [207]; however, building archetypes are excluded, so a building Archetype Factor (AF) was calculated as per Eq. 3.6. The AF calculation applies a factor based on the average floor area per building archetype. The EPC database accounts for more than half of the dwelling stock and accounts for the floor area; however, assumptions are applied for the remaining dwellings that result in an assumed average floor area of 98 m^2. The average floor area of the building archetype is calculated to be 80 m^2, 95 m^2, and 118 m^2 for an apartment, attached, and detached dwelling, respectively. Larger dwellings benefit from a cheaper retrofit per floor area. The following equation from Tribe [211] is used to calculate the value of AF for each building archetype:

$$AF = (\frac{A_2}{A_1})^{0.6} \tag{3.6}$$

Where A_2 is the assumed average area of the apartment, attached, or detached dwelling, and A_1 is the assumed area of all dwellings (98 m^2). The AF value for apartments, attached, and detached dwellings are 0.9, 1 and 1.1, respectively. This value is used in Eq. 3.5. As different EPC ratings have been aggregated in the initial model version, the next step is to calculate a weighted cost per type of retrofit for each building archetype:

$$TIM€Retrofit_{a,d} = \sum_{rf \in d} \overline{€}Retrofit_{rf,a} \cdot \frac{TIM_{rf,a}}{TIM_{r-Arated,a}} \tag{3.7}$$

In Eq. 3.7, a weighting factor $\frac{TIM_{rf,a}}{TIM_{r-Arated,a}}$ is used, where $TIM_{r-Arated,a}$ is the number of non-A EPC rated (r-Arated) dwellings per building archetype. It is assumed that the A-rated EPC dwellings cannot be retrofitted further. $TIM_{rf,a}$ is the number of dwellings per building archetype and a given pre-retrofit EPC rating that aligns $\overline{€}Retrofit_{rf,a}$ which is detailed in Eq. 3.5. The number of average capital costs from the pre-retrofit EPC rating for each depth of retrofit is not specific to the building archetype. There are six average capital costs (rf values) for shallow retrofits and five for deep retrofits. The average weighted cost per retrofit depth and building archetype, $TIM€Retrofit_{a,d}$ is summarised in Table 3.7 together with the expected savings from the DEAP Default Temperatures (DT) and the Temperature Adjusted (TA) values described in this study, $AS(\%)_{a,d}$ calculated in Eq.3.9.

Table 3.7: Thermal retrofit cost per depth and building archetype are shown alongside the expected energy savings for internal Temperature Adjusted (TA) and DEAP internal Default Temperature (DT).

	Attached			Detached			Apartment		
Retrofit	Cost	Savings		Cost	Savings		Cost	Savings	
		TA	DT		TA	DT		TA	DT
Shallow	€9.61k	20%	35%	€14.3k	20%	35%	€11.2k	22%	37%
Deep	€20.56k	44%	57%	€22.26k	42%	57%	€15.98k	37%	51%

The methodology applied to calculate the expected savings, shown in Table 3.7, of thermal retrofitting is now examined. Annual heating costs per building archetype and per EPC rating are sourced from SEAI's indicative energy running costs. The internal temperature adjustments in Table 3.4 are incorporated to calculate the annual running costs presented in Table 3.8. Table 3.4 assumes that the C-rated dwellings have an internal temperature in the range of 15-18°C and B-rated dwellings are in the range of 18-21 °C, this results in the B3-rated dwellings being more expensive to operate than the C-rated dwellings. Although this is not a rational assumption, it calibrates the residential energy used in TIM to match the 2018 SEAI Energy Balance. This assumption is reductive, as in reality, many behavioural variables affect energy performance, which are not considered in a techno-economic model and, therefore, are outside the scope of this paper. The running cost in Table 3.8 accounts for different dwelling sizes of the building archetypes but does not account for different sizes between EPC ratings.

Table 3.8: Shows the indicative annual heating fuel cost per EPC rating and building archetype for internal Temperature Adjusted (TA) and DEAP internal Default Temperature (DT).

	Attached		Detached		Apartment	
EPC	TA	DT	TA	DT	TA	DT
A	€591	€430	€944	€700	€367	€257
B1	€745	€745	€1,200	€1,200	€440	€440
B2	€950	€950	€1,500	€1,500	€570	€570
B3	€1,150	€1,150	€1,900	€1,900	€700	€700
C	€1,022	€1,600	€1,671	€2,567	€603	€967
D	€1,567	€2,350	€2,567	€3,800	€900	€1,400
E	€2,115	€3,100	€3,439	€5,000	€1,253	€1,900
F	€2,740	€3,950	€4,403	€6,300	€1,626	€2,400
G	€2,702	€4,950	€4,398	€7,900	€1,687	€3,000

Table 3.8 outlines the effect of the temperature adjustment at the household level, enabling us to inspect if the adjustments are realistic. As TIM only inputs the savings per retrofit depth and per building archetype, some calculations must be performed in Table 3.8 to calculate the annual percentage savings of running costs from thermal retrofits, as shown in Eq. 3.8 and 3.9.

$$\overline{AS}(\%)_{rf,a} = 1 - \left(\frac{\overline{(€_{rt,a}/year)}}{(€_{rf,a}/year)}\right) \tag{3.8}$$

Where $\overline{AS}(\%)_{rf,a}$ is the average annual percentage savings of running costs per building archetype and pre-retrofit EPC rating. The average post-retrofit EPC rating annual running costs are defined by $\overline{€}_{rt,a}/year$ and the annual running costs of the pre-retrofit EPC rating are captured by $\overline{€}_{rf,a}/year$. The next step is using Eq. 3.9 to find the weighted average annual percentage savings of running costs for each type of retrofit and for each building archetype.

$$AS(\%)_{a,d} = \sum_{rf \in d} \overline{AS}(\%)_{rf,a} \cdot \frac{TIM_{rf,a}}{TIM_{r-Arated,a}} \tag{3.9}$$

The same weighting factor $\frac{TIM_{rf,a}}{TIM_{r-Arated,a}}$ used in Eq. 3.7 is multiplied by the associated pre-retrofit EPC in $\overline{AS}(\%)_{rf,a}$ from Eq. 3.8 to find the $AS(\%)_{a,d}$ which is the weighted annual percentage savings of running costs per building archetype and per retrofit depth presented in Table 3.7.

The next step in the methodology is to calculate the base year's final energy consumption by fuel, building archetype and energy service, as described in Eq. 3.12, using components from Eq. 3.10 & 3.11.

$$TIM_{a,f,s} = (\frac{EPC_{a,f,s}}{EPC_{a,s}}) \cdot TIM_a \tag{3.10}$$

TIM_a is calculated in Eq. 3.2, $TIM_{a,f,s}$ represents the number of dwellings or heating systems in TIM by building archetype, fuel type (f) and energy service (s); it is assumed that all dwellings have a heating system. $EPC_{a,f,s}$ is the number of dwellings by building archetype, fuel and energy service from the EPC database, and $EPC_{a,s}$ is the number of dwellings per building archetype and per energy service from the EPC database. The second equation that forms a component in Eq.3.12 is:

$$CF_{a,f,s} = (\frac{TIM_{a,f,s}}{EPC_{a,f,s}}) \cdot TempA_a \cdot CaliF_{f,s} \tag{3.11}$$

$CF_{a,f,s}$ represents the correction factor applied in TIM for each building archetype, each fuel, and each energy service. $TIM_{a,f,s}$ was calculated in Eq. 3.10, $\frac{TIM_{a,f,s}}{EPC_{a,f,s}}$ represents the ratio of the number of dwellings in the EPC database to TIM. $TempA_a$ is the temperature adjustment factor, which is only applicable for space heating in scenarios where the internal temperature is adjusted, this value is found using ArDEM-SQL and applying the internal assumptions in Table 3.4. The calibration factor, $CaliF_{f,s}$, is adjusted to match the fuel usage in the model exactly with the 2018 SEAI Energy Balance to ensure that the model is in equilibrium. The previous two equations lead to Eq. 3.12:

$$TIME_{a,f,s} = CF_{a,f,s} \cdot Average(BER\eta_{a,f,s}) \cdot EPCFE_{a,f,s} \tag{3.12}$$

$CF_{a,f,s}$ is from Eq. 3.11, $Average(BER\eta_{a,f,s})$ is the average technology efficiency per building archetype, fuel, and energy service assigned by the EPC assessors in the EPC database. The assessors define the space heating system efficiency, which converts final energy into useful energy, and this model assumes that the water efficiency is the same as most heating systems are wet. The last component in the calculation is $EPCFE_{a,f,s}$; this is the total final energy of the energy service per building archetype and per fuel in the EPC database. $TIME_{a,f,s}$ is the result, which represents the total final energy per building archetype, fuel, and energy service in TIM. The base year values, for $TIME_{a,f,s}$ in terajoules for both space and water heating, are shown in Table 3.9.

Table 3.9: The residential final energy in terajoules for space and water heating for building archetype, and fuel in TIM base year (2018), this value corresponds to $TIME_{a,f,s}$ in Eq.3.12

	Space Heating (TJ)			Water Heating (TJ)		
Fuel	Apartment	Attached	Detached	Apartment	Attached	Detached
Coal	165	5053	4441	7	411	193
Peat	63	1980	5354	7	386	412
LPG	84	328	1296	42	150	316
Kerosene	278	7949	28538	72	3065	8289
Natural Gas	1233	11253	5089	734	4688	1626
Solar	0	0	0	28	266	266
Wood	12	252	865	4	44	103
Space Ambient	163	105	120	0	0	0
Water Ambient	0	0	0	309	147	88
Ethanol	0	0	0	0.04	0.02	0.07
Biodiesel	0.02	0.02	0	0.05	0.08	0.07
Electricity	726	1093	1597	718	571	479
Heat	38	44	150	10	2	1

The demand for energy services in the residential sector is driven by the total dwelling stock for non-building archetype energy services, while apartment, attached, and detached dwelling stock drive the demand for building archetype energy services, as represented in Fig. 3.2. The projections for dwelling stock up to 2040 are taken from housing growth estimates [212], and beyond 2040 the growth rate is extrapolated. However, building type data is limited; for this reason, a simple linear regression, as shown in Eq. 3.13 is used to calculate the share of the building archetype in a given year (bas). This is represented graphically in Fig. 3.5. The apartment growth rate is higher than that of detached and attached dwellings, and the obsolescence rate of existing dwellings is 0.35%.

$$
\begin{aligned}
Apt(\%) &= 7.5 \ln(bas) - 56.97 \\
Att(\%) &= -2.53 \ln(bas) + 19.68 \\
Det(\%) &= -4.93 \ln(bas) + 37.91
\end{aligned}
\tag{3.13}
$$

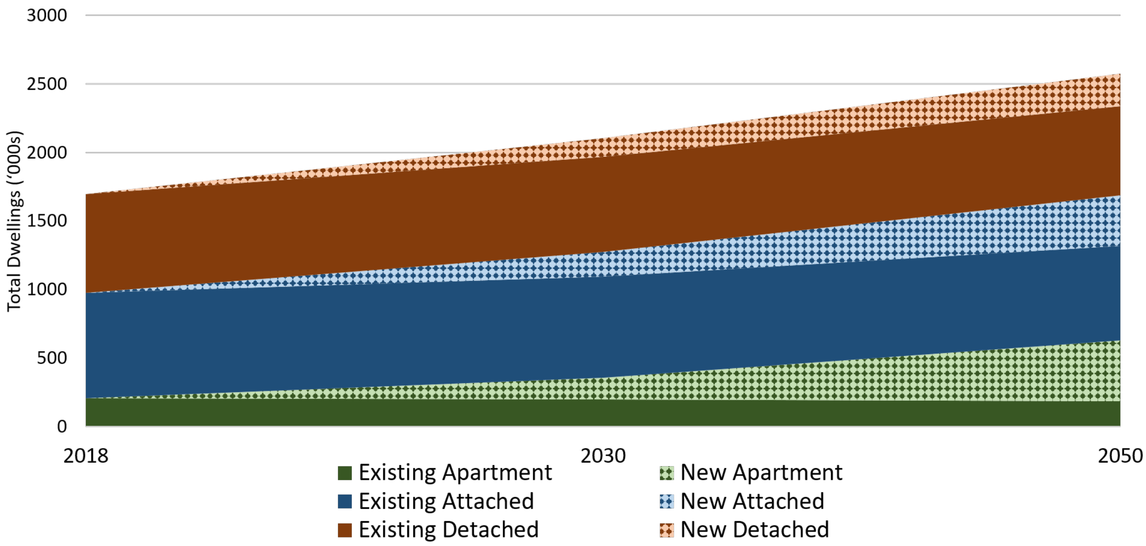


Figure 3.5: Dwelling growth per building archetype is derived from Bergin and Garcia-Rodriguez [212] up to 2040, beyond 2040 the growth rate is extrapolated, and the obsolescence rate for existing dwellings is 0.35%

Chapter 4

Developing decarbonisation pathways in changing TIMES for Irish homes

4.1 Introduction

Decarbonising and improving the energy efficiency of dwellings is a priority for climate and energy policy. However, integrated energy systems modelling, commonly used to inform decarbonisation pathways, typically does not capture the heterogeneity of the dwelling stock, particularly internal dwelling temperatures, a key determinant of the cost of switching to low-carbon heating and upgrading building fabric. Addressing this gap, this chapter presents a new model of the residential sector within an ESOM, developed using an EPC database and measured energy consumption data, allowing for the heterogeneous depiction of the housing stock.

The analysis is carried out for Ireland, which has committed to ambitious legally binding climate targets. The Irish residential sector, which represented 22% of energy-related CO_2 emissions in 2020, is characterised by poor thermal efficiency and high reliance on fossil fuels. The TIM is developed within a framework demonstrating cost-optimal pathways for energy supply, transformation, and demand sectors. The model is open-source, and the methodology outlined in this thesis is replicable for any country with an EPC database. The methodology applied in this thesis improves the representation of residential energy by accounting for internal space temperature more accurately and allowing for temperature variance, reducing the energy performance gap. The model complies with scientific reproducibility standards and has contributed to the development of national carbon budgets [193]. The model will provide policy insights and continued support for national energy decarbonisation.

The results presented are indicative of the type of insights that such modelling can provide and demonstrate that to meet climate targets, a rapid reduction in residential fossil fuel heating is necessary. The results show that deeper decarbonisation pathways require more thermal retrofits and electrical heat pumps, increasing the total cost of the energy system. The results explore the effect of internal temperatures, highlighting the importance of using empirical data for accounting for the rebound effect. Exemplifying the value of an integrated system modelling approach, deeper decarbonisation pathways place further costs on the electrical system.

The unique Irish residential sector provides an interesting case study. The new Irish climate targets mean the previous Irish models are outdated based on superseded climate targets. A transparent ESOM aligned with current climate policy is needed to explore optimal decarbonisation pathways and provide insights on *how Ireland should set cost-optimal GHG targets in the residential sector?* While also considering energy transition dynamics between and within sectors. The chapter addresses another critical research question: *how does using empirical internal temperature data, adjusted for energy-efficient dwellings, influence the optimal decarbonisation pathway compared to relying on EPC database defaults?*

The layout of the rest of this chapter is as follows; section 4.2 explains the methodology used to develop the residential sector, the data handling process is described, the calculations are presented, and the assumptions and constraints are highlighted. Section 4.3 outlines the scenarios used and displays residential and energy system results from the model. Section 4.4 discusses the newly developed model's results, strengths, and limitations. Section 4.5 draws some conclusions and discusses possible future work.

4.2 Methodology

The methodology applied in this study is described in detail in Chapter 3. The methodology here describes the initial version of TIM, which is in Chapters 5 and 6. The energy services demands in this chapter depend on whether a dwelling is existing or new. TIM uses the standard approach of defining the average performance of several building archetypes [20], and the average energy service demand of each building archetype is shown in Table 4.1.

Space heating, water heating, pumps & fans, and lighting energy services for existing

Table 4.1: Energy services demand for new and existing building archetypes in the TIMES Ireland Model

Energy Service	Apartments ($kWh/house/yr$)		Attached ($kWh/house/yr$)		Detached ($kWh/house/yr$)	
	Existing	New	Existing	New	Existing	New
Space Heating	3,853	1,106	7,852	2,561	14,405	6,070
Water Heating	3,408	1,384	3,011	1,481	3,805	1,571
Lighting	179	156	254	229	418	392
Pumps & Fans	55	177	106	208	131	307
Space Cooling	0	54	0	60	0	66

dwellings are calculated from the average calibrated demand. Since all new dwellings are required to be A-rated, the energy service demand for new dwellings in TIM is calculated from the average calibrated demand of existing A-rated dwellings. Even though no space cooling data is available for the base year, it is a building archetype energy service, and future demand aligns with POTEnCIA's space cooling projections per household in Ireland [196].

All space and water heating technologies are building archetype specific, and some technologies provide water and space heating, while other technologies can provide only one type of heating; the list of available technologies is described in Table B.5. Thermal retrofits are included as a space heating technology, as they satisfy the residential space heating demand, even though they do not consume fuel. Although there are many technological options for heating, all other energy services have little or no choice in different technologies. Therefore, residential decarbonisation in TIM focuses on heat which accounts for 80% of energy in the base year; in section 4.5.1, non-heating energy services are listed as part of the future work of TIM.

"User Constraints" are any combination of fixed, maximum, or minimum bounds on growth or shares of technologies or fuels. The user constraints listed here apply to all scenarios, while each scenario applies certain emission constraints and internal temperature assumptions, which are outlined at the beginning of section 4.3.

1. One space and water heating system per household (stoves excluded), this user constraint is applied to represent individual heating systems.
2. Maximum 60% of existing buildings are to be retrofitted by 2030 and 95% by 2070; the maximum value is interpolated between 2030 and 2070. This user constraint exceeds the maximum available labour [213] to account for future improvements in the delivery of thermal retrofitting [154]. This constraint was applied during the model development.
3. To qualify for a heat pump grant, a dwelling considered "heat pump ready"

must have a heat loss indicator (HLI) of $\leq 2\, Watts/Kelvin/m2$. The HLI is equivalent to having a B2 EPC rating, which is a simplified assumption applied in this chapter and is explored later in more depth in this thesis. Based on the dwelling stock outlined in Table 3.5, for the installation of electric heat pumps, 85.5% of dwellings require thermal retrofitting. The thermal retrofit requirements are categorised by building archetype and thermal retrofit depth in Table 4.2. Hybrid heat pumps are not subject to this constraint as they can provide higher water temperatures without compromising performance [214]. This constraint is in place due to insufficient data on the performance of electric heat pumps in thermally inefficient dwellings.

Table 4.2: Percentage requirements for retrofitting existing building types to accommodate electric heat pump installations

Requirement	Apartment	Attached	Detached	Total
No Retrofit	24.5%	14.3%	12%	14.5%
Shallow Retrofit	28.5%	34.7%	36.8%	34.9%
Deep Retrofit	47%	51%	51.2%	50.6%

4. The maximum fuel share of cooking with natural gas and LPG is 40% and 10% respectively. The fuel share for natural gas in the base year is 32%, and LPG is 1.5%. This user constraint was applied before model development to align with the increasing market share of electrical induction hobs.

5. Maximum 10% solar input into dual fuel heating technology. This constraint was applied based on technological constraints.

6. Maximum 30% natural gas input to gas hybrid heating pumps. This constraint was applied based on of technological constraints.

7. The percentage of electrical heating systems in the EPC database that are heat pumps is 41%, 63%, and 65% for apartments, attached, and detached dwellings, respectively. However, the EPC database has a skewed representation of the dwelling stock, covering a larger share of newer buildings. Older dwellings use a higher share of electrical resistance heaters than heat pumps, compared to newer dwellings. Furthermore, the total amount of heat pumps sold in Ireland is known, so an assumption was required to constrain the maximum share of heat pumps within electrical heating systems in 2018. This maximum constraint is 30%, 35% and 30% for apartments, attached and detached, respectively.

Other constraints are applied in different sectors, which affect the residential sector and vice versa, they are not listed in this chapter.

4.2.1 Methodology Reproducibility

Although EPCs are a legal requirement in the EU, an EPC database is not. However, under the EPBD, EPC databases are necessary as a consequence of implementing an *"independent control system"*. The type of EPC data to be collected depends on each member state. Different specifications of energy-related variables are applied to different calculation methods, resulting in different EPC labels and ranges throughout the EU. In addition, there are different levels of public accessibility due to data protection regulations and other legal provisions at the member state level. For example, in eight member states, including Ireland, a public EPC register is developed to comply with EPC quality requirements; however, nine EU member states have no access to national EPC databases, while the other member states offer limited access. The combination of various data and access levels makes it difficult to compare the EPC database of each member state [36].

The methodology is based on Ireland's unique national open-source EPC and CSO databases. Adapting this methodology for other countries depends on the accessibility and content of their national EPC databases, supporting databases, and empirical internal temperature data. The building archetypes in Fig. 3.4, fuels groups in Table 3.6 and energy groups in Table 3.5 are specific to Ireland, relying on data matching from the CSO and Irish EPC databases. Other countries may have differences in data coverage, granularity, temporal consistency, integration capabilities, and the availability and accuracy of energy consumption data. By acknowledging these discrepancies and customising the methodologies to the specific data context of each country, the outlined approach can be effectively implemented in various national settings.

4.3 Results

The methodology provides the novelty in this paper; the results presented in this chapter are not comprehensive and are illustrative of the application and indicative of the results and insights such modelling can provide. The TIM results describe sectoral decarbonisation pathways for Ireland to achieve the GHG targets cost-optimally. TIM also accounts for the second and third-order effects within and between sectors, quantifies the level of investment required, and the timing of key milestones. The three scenarios are developed to quantify the overarching policy ambition and the effects of the internal temperature adjustments. The scenarios and descriptions are as follows:

1. **Previous Effort Temperature Adjusted (PETA)** scenario complies with Climate Action Plan 2019 targets up to 2030, whereby Ireland reduces non-ETS GHG emissions by 30% in 2030 compared to 2005, and post-2030 no emission targets are applied. This scenario achieves an energy system GHG emissions reduction of 34% in 2050 compared to 2018, thus not achieving net-zero in 2050. The internal temperature adjustments in Table 3.4 are applied.

2. **Current Effort Default Temperature (CEDT)** scenario complies with Climate Action and Low Carbon Development (Amendment) Act 2021, whereby energy system GHG emissions reduces by 65% in 2030 compared to 2018. Agricultural GHG emissions are required to be reduced by 25% by 2030 [66]. The 65% energy system reduction and 25% agriculture reduction equate to the overall 51% reduction target in 2030. In this scenario, net-zero is also achieved by 2050. The default internal temperature assumptions of DEAP are applied, whereby all living and non-living areas are dwellings are heated to 21°C and 18°C respectively.

3. **Current Effort Temperature Adjusted (CETA)** scenario has the same GHG emissions constraints as the CEDT scenario. The only difference is that the internal temperature adjustments in Table 3.4 are applied here.

4.3.1 Residential sector results

The combination of increased thermal efficiency through building regulations and an increase in the overall share of apartments results in a lower final energy consumption per dwelling. The internal temperature adjustment aligns with the national energy balance of 124.6 PJ in the base year. Failure to apply this adjustment results in 153.4 PJ, which is an overestimation of 23%. Therefore, the CEDT scenario and two temperature adjustment scenarios have different starting points, i.e. different quantities of final energy in the base year. A summary of the different future pathways of final energy in each scenario is illustrated in Table 4.3.

Table 4.3: The change, by percentage, in total final residential energy and final energy per dwelling in 2030 compared to 2018 is shown for each scenario.

	Scenario		
	PETA	CEDT	CETA
Total Final Energy	+9%	-29%	-13%
Final Energy / dwelling	-12.5%	-43%	-30%

The difference between PETA and CETA highlights the large incremental step in ambition in the scenarios. The difference between CEDT and CETA shows the effect of the internal temperature adjustment. A larger reduction in the total final energy is seen in CEDT because the effects of thermal retrofitting are greater in this scenario.

An expeditious change of the fuel-mix is required in the residential sector, especially to comply with 2030 targets. The divergence from fossil fuel is particularly rapid in the two current effort scenarios. The final energy difference between the two base years and the fuel-mix results of all scenarios for 2030, 2040, and 2050 are summarised in Fig. 4.1.

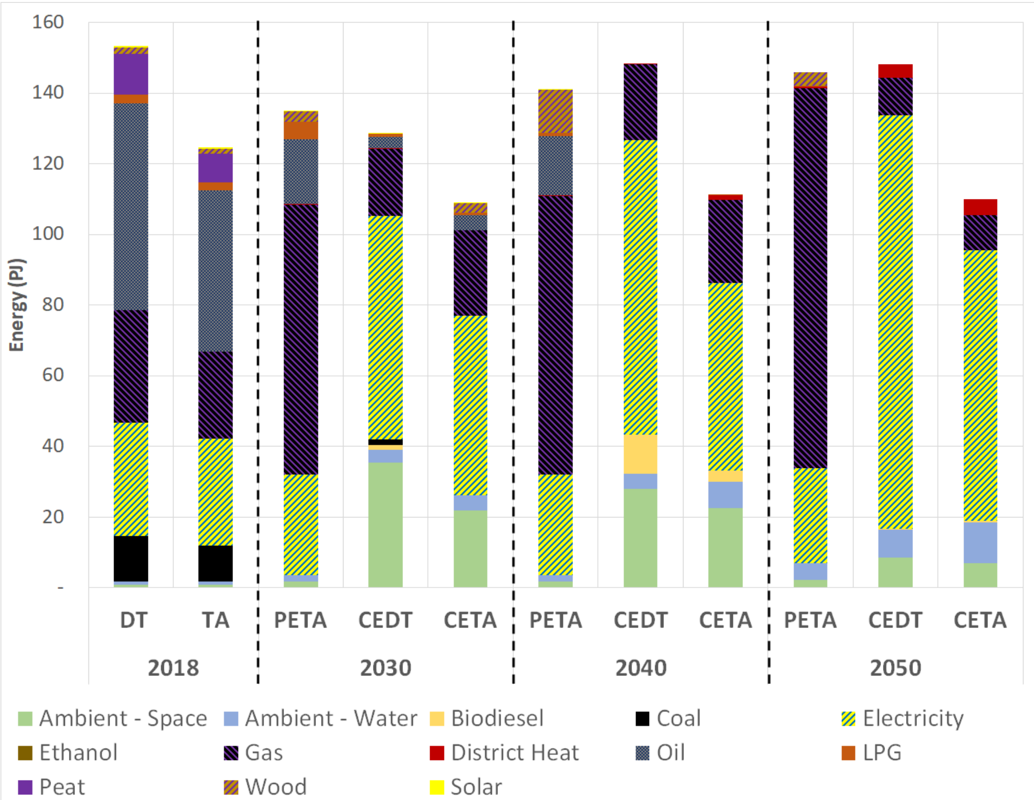


Figure 4.1: Residential final energy fuel usage is shown. The two base years using Default Temperatures (DT) and Temperature Adjusted (TA) on the left are compared against all scenarios for the selected years of 2030, 2040 and 2050.

The three scenarios show some common fuel-mix pathways; for example, oil in 2030 is reduced by between 60% and 94%. In 2018, oil represented the largest share of fuel use [58]. Therefore, the least-cost insights show that the energy transition would require significant efforts to achieve the 2030 climate targets. Furthermore, peat is completely phased out of all scenarios by 2030. The PETA scenario shows final energy increasing, with natural gas playing a pivotal role by gaining a greater share of the fuel mix, resulting in an absolute increase of 211% in 2030. The gas grid investment required to satisfy the increasing gas demand in the PETA scenario is not accounted for; this is recognised as a limitation in the model. However, the CETA and CEDT scenarios, which comply with the current climate targets, show a reduction of gas by 2% and 40% by 2030, respectively.

The 2030 electricity demand increases by 70% in the CETA scenario and 97% in the CEDT scenario. The SEAI Heat Study, which has the same 2030 and 2050 targets, found electricity demand to increase by between 45% and 62% [127]. This model shows a greater expansion of electricity compared to the SEAI Heat Study. The share of electricity and ambient energy which heat pumps consume in the residential fuel mix for CEDT and CETA scenarios is compared against the four scenarios of similar ambition in the SEAI Heat Study [127], summarised in Table 4.4.

Table 4.4: CEDT and CETA results of electricity and ambient energy in the residential fuel-mix in the years 2030 and 2050, compared to the SEAI Heat Study [127]

		2030	2050
SEAI	Electricity (%)	35-42%	45-54%
	Ambient (%)	16-26%	37-43%
TIM	Electricity (%)	47-49%	70-79%
	Ambient (%)	24-30%	11-17%

TIM finds that combined electricity and ambient consumption accounts for 71-79% of the fuel mix by 2030, compared to 51-68% [127]. The results of this model show a higher short-term growth in electricity and ambient energy in the residential fuel mix compared to the SEAI Heat Study [127]. Therefore, current effort scenarios illustrate electrical heat pumps as the cornerstone for decarbonising residential heat in the short-term; this is examined further in Fig. 4.3. However, there are differences in the short-term growth rate and the long-term pathway. The TIM results show a decrease in ambient heat post-2040 due to the power generation sector becoming net-zero in 2040. This result differs from the SEAI Heat Study, which shows a continued growth of ambient heat up to 2050 [127]. In TIM, electrical resistance heaters are an attractive technology option post-2040 due to low costs and negative electricity emissions.

As shown in Table 4.2, thermal retrofitting is a prerequisite for heat pumps in 85.5% of dwellings. Consequently, the results of this model show that thermal retrofits are a key component in the cost-optimal residential decarbonisation pathway. The optimal number of thermal retrofits per scenario and time period are shown in Fig. 4.2. The cumulative energy savings from thermal retrofitting is also illustrated by markings and quantified on the secondary axis.

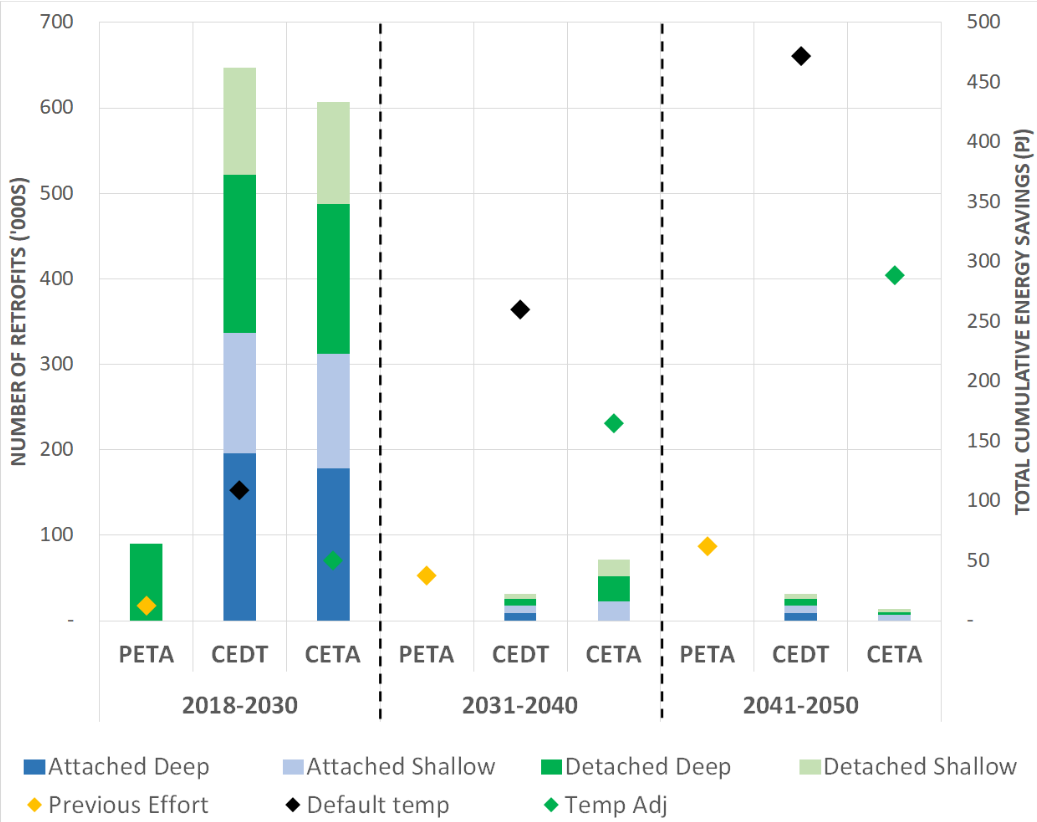


Figure 4.2: The number of retrofits in each scenario for the time periods of 2018-2030, 2031-2040, and 2041-2050 is represented by the bar chart and quantified on the primary axis. The corresponding cumulative energy savings are quantified on the secondary axis.

Although CAP2019 targeted 500,000 retrofits [65], the PETA scenario, which complies with CAP2019 GHG emission targets, found it optimal to only retrofit 90,000 up to 2030. It should be noted that all thermal retrofits in the PETA scenario are deep and in detached dwellings. There is a greater quantity and mix of thermal retrofits in the current effort scenarios. The CETA scenario shows 607,000 dwellings are retrofitted up to 2030, while the CEDT scenario has a similar mix of thermal retrofits but a higher quantity of 647,000. The CEDT scenario shows 6% more dwellings retrofitted than the CETA scenario; however, CEDT, which does not account for the rebound effect, expects to save 114% more through thermal retrofitting. A common result across the scenarios shows that no apartments are retrofitted. Apartments are the smallest building archetype and do not benefit from the economy of scale [211] and therefore are the most expensive per floor area. The apartments are also newer with thermally efficient building fabric and generally use natural gas, which is less carbon-intensive than oil. Thus, carbon abatement through individual apartment thermal retrofitting is expensive and does not feature in the results. Furthermore, the expected cumulative energy savings through thermal retrofitting in the CETA scenario up to 2030 are four times higher compared to the PETA scenario; this result highlights the incremental step in ambition. Post-2030, new thermal retrofits take a sharp decline in all scenarios illustrating the importance of early retrofitting to achieve 2030 and 2050 GHG emission targets.

As mentioned previously, thermal retrofits are a prerequisite for installing electrical heat pumps in 85.5% of existing Irish dwellings, while all new dwellings are heat pump ready. The model assumes a lifetime of 20 years for all electrical heating technologies, so it may be possible for one dwelling to get two new electrical heating installations over the next 30 years. Therefore, electrical heating technologies have a higher maximum limit than retrofits. The number and type of electric space and water heaters installed per scenario and time period are outlined in Fig. 4.3.

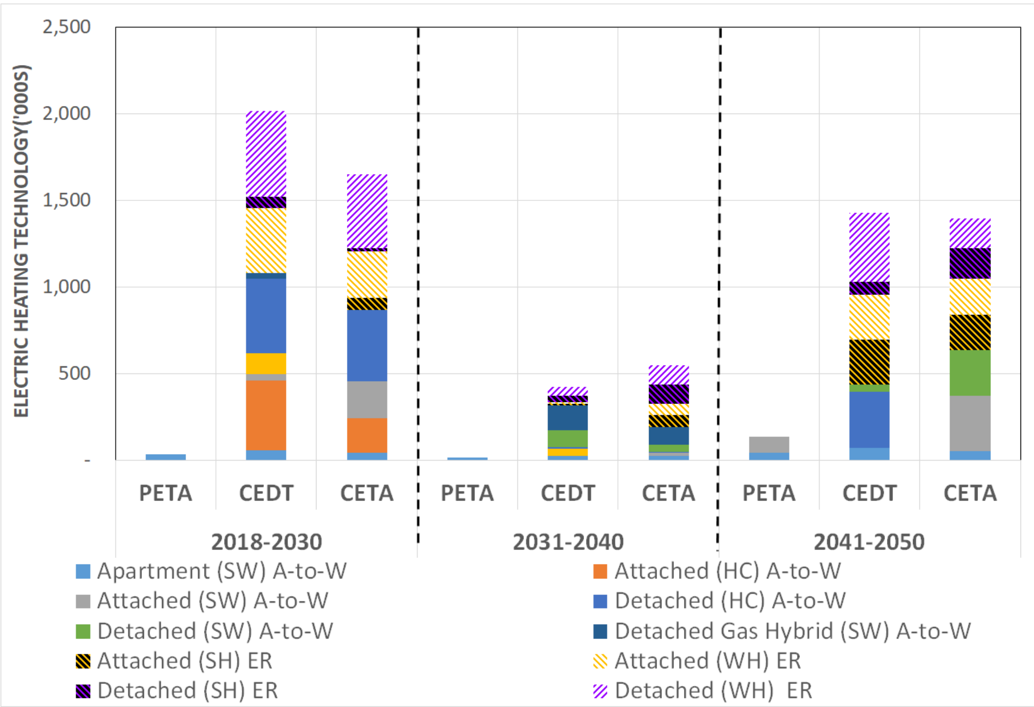


Figure 4.3: The number of new electrical heating technologies installed in each scenario and time period of 2018-2030, 2031-2040, and 2041-2050 are illustrated. The technology abbreviations are SW = Space & Water heating, HC = space Heating & Cooling, SH = Space Heating, and WH = Water Heating. The type of technologies shown are either A-to-W = Air to Water heat pumps or ER = Electric Resistance heaters

In Fig. 4.3, the optimal number of heat pumps installed between 2018 and 2030 ranges from 39,000 to 1.08 million. The current effort scenarios have a large growth of thermal retrofits and, consequently, electric heat pumps and ambient heat. In contrast, the PETA scenario shows a slow growth of electrical heat pumps, as natural gas heating dominates the heat market, as shown in Fig. 4.1. The current effort scenarios prioritise electricity for space heating from 2018 to 2030. In the CEDT scenario, heat pumps account for 54% of new electric heating technologies by 2030 and 53% in the CETA scenario. Between 2031 to 2040 there is a decrease in new electrical heating technologies and heat pumps. This is due to the power generation sector having net-zero emissions in 2040, resulting in lower to no potential emission savings of heat pumps over electrical resistance heaters. The largest number of installed electrical heaters is between 2041 and 2050; it is worth noting that electricity emissions are negative during this period.

An overview of residential direct CO_2 emissions is shown in Fig. 4.4 where annual emission snapshots for 2030, 2040 and 2050 are shown for all scenarios.

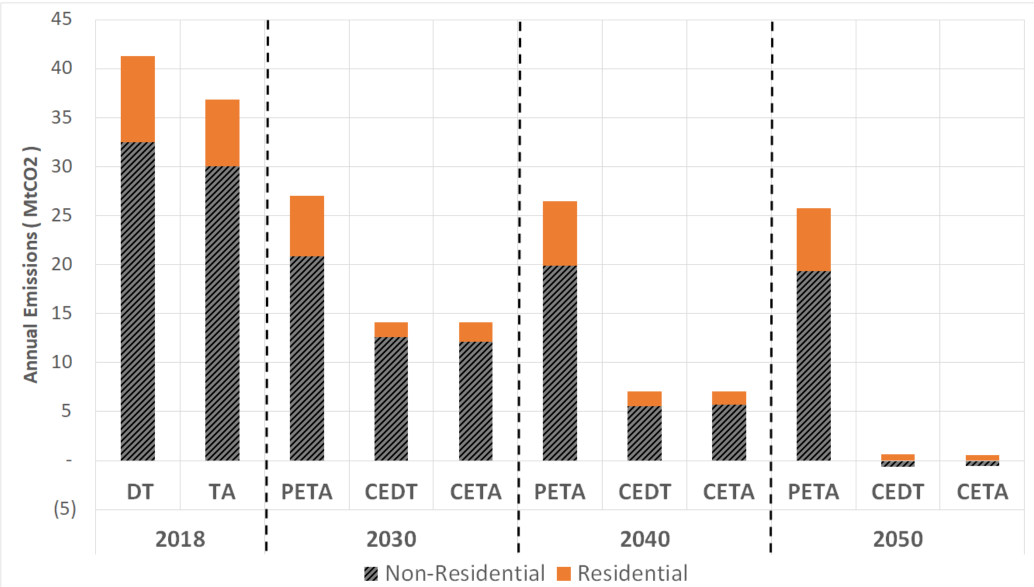


Figure 4.4: The residential & non-residential energy system annual CO_2 emissions. The base years and the PETA, CEDT & CETA scenarios for the selected years of 2030, 2040 and 2050 are illustrated.

Residential direct CO_2 emissions in the PETA scenario show an 8% CO_2 reduction in emissions by 2030. However, the adjacent CO_2 emission reduction in the power generation and transport sector in 2030 is 68% and 24%, respectively, showing that the model finds that the optimal solution is to prioritise decarbonisation of non-residential sectors when the climate targets are relaxed. In contrast, the more ambitious climate targets in the current effort scenarios reduce residential CO_2 emission by between 70% and 82%, which is greater than the reduction in power generation of 58% to 59% and the overall energy system GHG emission reduction of 65%. Under current effort scenarios, the residential sector is still a source of direct CO_2 emissions in 2050. This is offset by negative CO_2 emissions in the power sector to achieve net-zero throughout the energy system, as shown in Fig. 4.4. The PETA scenario only achieves a reduction of 5% in residential direct CO_2 emissions to comply with CAP2019 targets [65], and an overall 34% reduction in the energy system in 2050.

As mentioned previously, TIMES provides insights into the cost-optimal decarbonisation pathway. The annual residential investment and O&M cost results from TIM are illustrated in Fig. 4.5.

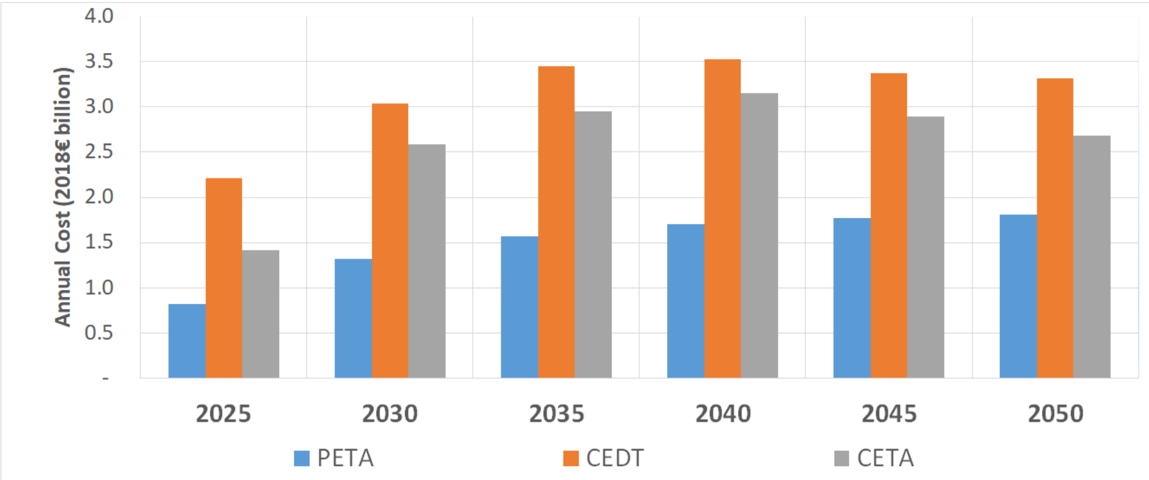


Figure 4.5: The annual residential investment and O&M costs for all scenarios, every five years from 2025 to 2050 inclusive.

The PETA scenario can find a more cost-effective solution, as fewer constraints allow for more options within the model, e.g., natural gas is chosen over heat pumps because it is cheaper and still satisfies emission constraints. Meanwhile, current effort scenarios require a large short-term expenditure increase that peaks in 2040. Furthermore, when analysing the effect of the internal temperature on the cost-optimal pathway up to 2030, it can be deduced that the internal temperature adjustment is €3.4 billion cheaper than the default temperatures, as many dwellings are colder, using less energy than expected.

4.3.2 Energy system results

The results in this section use the strength of an ESOM to capture the dynamics of the second and third-order technological effects between sectors.

Fig. 4.6 presents the final energy fuel-mix for four sectors - power generation, transport, services, and residential in the years 2030, 2040, and 2050 for all scenarios.

Figure 4.6: The final energy fuel-mix for the power generation, residential, services and transport sectors in all scenarios are shown for the selected years of 2030, 2040 and 2050.

Intersectoral connections can be observed in all scenarios with the large growth of renewable energy in the power generation sector that affects electricity uptake in the other sectors; this is especially the case in the current effort scenarios. The PETA scenario prioritises natural gas in the transport and residential sectors. Still, PETA invests in renewable energy, accounting for 69% of power generation in 2050, whereas the current effort scenarios have a more significant renewable share of 92-93%. Electricity is the cornerstone of long-term deep energy system decarbonisation, accounting for 55-57% of the fuel mix in transport, services and residential combined for the current effort scenarios in 2050. Renewable energy supports electricity by accounting for 17-19% of the fuel mix in three sectors in 2050.

As previously mentioned, the three types of costs analysed in TIM are investment, variable, and O&M costs. Fig. 4.7 illustrates all cost types for the entire energy system.

Figure 4.7: Annual energy system investment, variable and O&M costs in all scenarios

The three different types of costs across the entire energy system can provide policy insights. The current effort scenarios show spikes in 2029 to achieve the 2030 targets. The residential cost results in Fig. 4.5 show that residential investment peaks in 2040. However, the energy system investments continue to increase, showing that the energy system cost optimal pathway is to front-load residential investments, which aligns with the significant residential decarbonisation compared to other sectors, as shown in Fig. 4.4. Additionally, compared to the PETA scenario, the more expensive current effort scenarios invest more in technology and spend less on fuel (variable costs). Table 4.5 details the cumulative costs up to 2030 and 2050.

Table 4.5: The cumulative expenditure (€bn), by cost types, for all scenarios are shown up to the years 2030 and 2050.

	2030			2050		
	PETA	CEDT	CETA	PETA	CEDT	CETA
O&M	40.1	49.5	50.6	145.9	180.6	186.3
Investment	32.1	57.7	56.1	247.3	354	369.5
Variable	79.7	79.3	74.3	214	190.3	162.2
Total	**151.9**	**186.5**	**181**	**607.2**	**724.9**	**718**

By 2050, the CETA scenario requires 18% more expenditure than the PETA scenario. Analysing this further, the energy system fuel savings in the CETA scenario offset 42% of the additional investment costs. Therefore, despite the extra expenditure required due to increased climate ambition, consideration of the cost type is essential in the energy transition.

4.4 Discussion

The initial or first iteration of TIM, described in this chapter, will be continually improved with ongoing model development and studies. This section discusses the strengths and limitations of the residential sector in TIM.

4.4.1 Strengths

TIM provides insight into cost optimal technological pathways. At the same time, the iterative and transparent development of the residential sector, which aligns with current climate policy, will allow modellers to explore a range of research questions. The strength of TIM is that it can provide important insights into the costs and scale of residential decarbonisation needed to achieve climate targets, including thermal retrofits and heat pumps. The new methodology better reflects the heating consumption of each EPC rating, using an internal temperature adjustment, which is consistent with previous Irish studies that note that in cold temperatures in dwellings with poor thermal efficiency [38, 94, 95, 98]. This chapter identifies and addresses the energy performance gap between the expected EPC database and the actual energy consumption in Ireland. Furthermore, variation in internal temperature partially accounts for the rebound effect, providing an improved representation of residential energy and energy savings from heating technologies and thermal retrofits. The residential sector in TIM was designed and built concurrently with the residential sector in the Low Emissions Analysis Platform (LEAP) simulation model [215] to allow for the soft-linking of models to combine simulation and optimisation insights. The open-source Tableau workbook [198] created as part of this chapter allows for transparent reproducibility, so that updated EPC databases can be easily incorporated into updated model versions. TIM can also provide building specific insights for apartments, attached, and detached dwellings. Although the results in this chapter only explore national insights per building archetype, the applied methodology allows for extra features in future model iterations, such as the nine EPC ranges and 26 county regions, and TIM has different temporal resolution options available.

4.4.2 Limitations

Energy system models contain inherent uncertainties as a result of the mercurial behaviour of the economy. Fuel prices and macroeconomic projections are sensitive to economic shocks and key variables in determining ESOM results. Such inherent uncertainties limit the robustness of models; hence, model results are said to provide insights, not answers. However, this section covers only the limitations within the residential sector of TIM. Although the growing open-source EPC database provides high granularity data for residential modelling, caution should be exercised because the EPC database does not contain measured values. The values are estimated using the DEAP assessment rating tool. The energy performance gap addressed in this chapter applies a temperature adjustment based on a small share of urban gas heated dwellings [37]. TIM does not account for the full range of energy consumption found [37], which reduces the rebound effect and consequently increases the monetary benefits of thermal retrofitting. This chapter would benefit from a larger empirical database covering a greater range of building archetypes, fuels, EPC ratings, and regions.

Further analysis, discussion, and updating of the filters [38] would improve the representation of the dwelling stock in the model. Other studies found that European EPC databases contain assessor input errors or irregularities [35, 206, 216, 217]. Furthermore, statistically anomalous spikes in the data caused by the application of default values [32] affect the EPC database; however, this is not part of the scope of this paper. Furthermore, solar photovoltaics are expected to play a role in the energy transition, and a limitation of the EPC database is the absence of solar photovoltaic capacity.

TIMES assumes perfect foresight and rational behaviour, yet it's understood that consumer choices aren't solely driven by costs [20, 218], and no consumer or producer has complete knowledge of current and future energy prices and technological specifications. Therefore, the model will tend to produce lower total discounted costs than in reality. The results of all the scenarios in this chapter show a rapid reduction in the use of oil boilers. Unless incentivised, it may not be economically optimal for a household to replace an oil boiler; the model framework does not account for who pays the costs, public or private. Fodstad et al. [14] echos this limitation by stating, *"quantitative models (such as TIMES) provide cost-effective solutions that may not match the expectations of different stakeholders"*. Furthermore, it is necessary to improve the representation of financial and social barriers to better represent the consumer's choice.

The performance of heat pumps in thermally inefficient homes is a source of uncertainty, mainly due to the lack of reliable data. This chapter applies an exogenous constraint: electric heat pumps can only be installed in A, B1, and B2 EPC rated dwellings. However, this restriction could be relaxed pending improved empirical data.

There is a housing stock gap between the total number of dwellings in the census year (2016) and the base year of the model (2018) was initially ignored. The dwelling stock in TIM does not account for the existing dwellings built in 2017 and 2018. However, it does account for the energy consumed by them, thus overestimating the expected final energy per dwelling of 2%.

The residential sector in TIM accounts for all commercially available heating technologies; however, some technologies with low levels of technological readiness, such as hydrogen, are not yet included in the residential sector. Additionally, the model result shows apartments don't get thermal retrofits. In future iterations of TIM, including community thermal retrofit options could alter this result. Energy storage options are not factored into the residential sector in TIM. However, these are likely to play an essential role in a decarbonised energy system, for example, through decentralised batteries to store electricity for hours or days, seasonal heat storage in combination with district heating networks, and more extended duration storage solutions such as hydrogen. These solutions are the source of more considerable uncertainties – particularly for cost and availability – than the mitigation options explored in this paper. However, if deployed, they will likely result in more substantial sector coupling and utilisation of renewable energy (i.e., lower curtailment). Therefore, this topic is identified as an important area for future research.

TIM does not compensate for the predicted warmer weather [219], changes in the floor area of new dwellings, non-monetary benefits of thermal retrofitting, changes in occupancy behaviour or type of tenure (owners, tenants, etc.). Nor does TIM consider the effect of higher EPC ratings on property value, which could underestimate the role of retrofits in optimal decarbonisation.

4.5 Conclusions

The residential sector within the TIMES Ireland Model has been developed to map the rapid technological transition required by new ambitious climate policies, namely the rapid deployment of thermal retrofitting and heat pumps. The results show the increasing importance of residential decarbonisation with increasing climate targets. The new methodology described in this chapter provides more insight by better reflecting the internal temperature and the expected energy savings of thermal retrofitting and heating technologies. The methodology also provides a quality representation of the dwelling stock using the EPC database, while the heating technologies have been expanded and updated.

The results of this chapter highlight the importance of the often-overlooked precision and variance of internal temperature in the residential sector. Comparing the CEDT (default DEAP temperatures) and CETA (temperature adjusted) scenarios allows the quantification of the internal temperature effect and partially accounts for the rebound effect in the CETA scenario. Thermal retrofitting is a priority of Irish climate policy; however, it requires high investment costs and results in relatively low emission savings, especially when applying internal temperature assumptions that account for warmer temperatures in thermally efficient dwellings. The results show that the number of thermal retrofits in 2030 is 6% higher, yet the expected savings are 114% higher in the CEDT scenario compared to the CETA scenario. The number of thermal retrofits and quantity of expected savings affect both the optimal number of electrical heat pumps and the amount of ambient heat, see Fig. 4.6. This result shows the importance of accounting for internal temperature precision and variance in the residential sector to obtain more accurate climate policy insights. Thermal retrofitting alone does not play a significant role in optimal decarbonisation pathways, but when a high level of thermal efficiency is a prerequisite for installing electricity heat pumps and where climate targets are ambitious, thermal retrofitting becomes significant. Additionally, unlike other heating technologies, thermal retrofits will require further analysis as the non-monetary advantages and disadvantages of various internal temperatures, such as thermal comfort and health, remain challenging to incorporate into a cost optimisation model. While increased internal temperatures are a rebound effect of thermal retrofits, these non-monitory benefits are out of the scope of this modelling analysis but warrant further research.

The TIM results incorporate all energy sectors and indicate the optimal change in the residential fuel mix and investment costs; *TIM insights show how changes to future technology development affect how Ireland should set cost-optimal GHG targets in the residential sector.* The results highlight the dependency of the decarbonisation of residential heating on low-carbon electricity, which will enable discussions around the security of supply, the effects of fuel prices, and the feasibility of the power generation expansion rate. The phase-out of peat and large reductions in coal and oil by 2030 will require further scrutiny and discussion. These changes to the energy sector require early retirement of existing heating systems, which may not be cost-optimal for some households. Further discussion on the share of public and private cost types is needed.

Section 4.2.1 explores the broader implications of this chapter by examining the methodology reproducibility using other national EPC databases. Asset rating tools develop EPC databases to benchmark dwellings; they generally have no empirical data, and EPC databases contain enormous detail. This thesis found that Ireland's EPC database overestimates residential energy by 23%. Other EU countries find similar EPC energy performance gaps when using the EPC databases [33, 34]. Thus, filtering and data handling should be applied. However, this model accounts for the often overlooked energy performance gap and rebound effect by using empirical energy consumption data to assign internal temperatures to dwellings of various EPC ratings.

Finally, the ambitious 2030 climate target to reduce Ireland's GHG emissions by 51% in 2030, compared to 2018, shows large investments in the optimal decarbonisation pathway before 2030. However, there are long-term fuel savings beyond the large short-term investment required as the energy system uses more renewables and indigenous fuels. Overall, the more ambitious CETA scenario costs 18% more than the PETA scenario up to 2050. However, 25% less is spent on fuel while investment and O%M costs increase 50% and 27%, respectively. The type of cost will enable the discussion of maximising economic benefits, such as energy security and employment.

4.5.1 Future Research

The residential sector described in this paper, as part of the newly developed TIMES Ireland Model, provides a platform on which future model versions, features, and scenarios can be built. Additional model developments may address the following issues of relevance to policy:

1. Identify and incorporate the performance of electric heat pumps in dwellings with heat loss above the heat pump grant threshold. The results of the CETA scenario show that less than half of electrical heating technologies are electrical heat pumps. It is cost-optimal to install electric resistance heating rather than thermally retrofit and install an electric heat pump. However, the results do not account for electrical grid restrictions or short- and long-term storage options. Therefore, incorporating storage options into an electrical heat pump performance analysis in thermally efficient and inefficient dwellings is an important area of future research.

2. Further development of the EPC data filtering and default assumptions process would improve the quality of data used in TIM and other Irish energy models and could be applied to national EPC databases in other countries. Iterative contributions from external energy experts will be required to identify and develop improved filters and appropriate substitution of default values using alternative databases and measured data.

3. Improving the representation of electricity and gas networks by accounting for future infrastructure investment costs is critical for analysing the role of renewable sources and energy storage. This future research will also assist in examining the viability of electricity and gas-sourced technologies.

4. District heating is gaining more government support [66]. A high spatial resolution heat map of all available heat sources, various demands, and infrastructure costs are available online [141]. Incorporating heat map data into TIM allows for a more detailed understanding of the role of heat grids in the energy system's decarbonisation.

5. TIMES is a techno-economic model. However, residential energy consumption is highly dependent on household behaviour, which in the TIMES framework can be represented through technology-specific discount rates [151]. Additionally, improving the representation of taxes and subsidies and energy demand elasticity using empirical data would improve the behavioural realism of the model and allow for the impact of policy levers to be analysed.

6. The residential sector has been developed to focus on heat decarbonisation. Future development of the model can incorporate non-heating energy in the residential sector. The non-heating energy will account for a larger share of residential energy over time as the heating share is reduced.

Chapter 5

Is District Heating a cost-effective solution to decarbonise Irish buildings?

5.1 Introduction

Heat constitutes the most significant portion of global energy end-use [12] and plays a pivotal role in our society and economy [220]. However, the predominant use of fossil fuels for heat production contributes to 40% of global carbon dioxide (CO_2) emissions [221], causing adverse impacts on both health and the environment [222]. In the EU, the heating of space and water in buildings accounts for 28% of energy consumption, with 70% of this energy sourced from fossil fuels [223]. In response to the environmental impact of heating buildings and other related activities, the EU has implemented the European Green Deal, a legally binding initiative aimed at reducing GHG emissions by at least 55% by 2030, relative to 1990 levels [224]. European and Irish strategies for decarbonising building heat primarily focus on energy renovation, renewable energy, bioenergy, and electrification [224–227]. The electricity sector, with its well-established infrastructure, skilled workforce, and progressive policies, is often considered a leading option for decarbonisation. On the contrary, District Heating (DH) is frequently overlooked or deemed less significant due to its limited suitability in areas with low heat density demands [226], and its system-wide significance can be better managed in future decarbonisation pathways. Achieving decarbonisation of the heating sector is a major challenge, especially in Ireland, which has the lowest proportion of renewable heat in Europe. In economically pursuing ambitious and equitable climate targets, Ireland's Climate Action Plan 2023 set a goal of reaching

2.5 TWh of district heating by 2030 [227], starting from a limited existing capacity.

DH refers to a network of insulated underground pipes transporting pressurised heated water from centralised heat sources to buildings. DH systems have existed for 140 years [115, 116], evolving through four distinct generations [116]. The main distinguishing factor between these generations lies primarily in the operating temperature of the DH systems. The current fourth-generation district heating (4GDH) supplies low-temperature water to energy-efficient buildings. The heated water is sourced from surplus heat and renewable sources, facilitating the energy transition to address climate change concerns [116].

According to Fig.5.1, Renewable Energy Sources in Heating and Cooling (RES-H&C) make a contribution of 23.1% to the overall generation of heat and cooling in the EU, while DH contributes 12% [226]. The extent of RES-H&C varies between member states, ranging from 66.4% in Sweden to as low as 6.3% in Ireland, and there is a correlation between the percentage of DH use and fossil fuel consumption among EU member states.

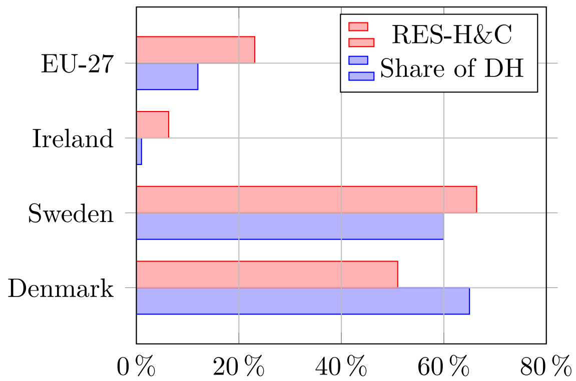


Figure 5.1: Share of RES-H&C and share of heating served by district heating per region in 2020 [50, 120, 226]

Within the EU, fossil fuels remain the primary heat source for district heating systems. The most significant portion is held by natural gas at 30.4%, followed by coal and peat, which contribute a combined 26.7% [120]. However, more sustainable options are available in smaller amounts, including industrial surplus heat at 1.7% and heat pumps at 1.2% [120]. The continued reduction in the carbon intensity of DH networks can be attributed to the greater use of renewable energy, surplus heat, and lower supply temperatures [131, 226]. Various studies have explored potential pathways for decarbonising DH systems in the EU [104, 108, 109, 228–230], Denmark [136, 231–234], and Sweden [235, 236].

One motivation behind incorporating DH into an ESOM in Ireland is the vast amount of surplus heat available that leads to high DH potential in Ireland, highlighted in recent studies [140, 141, 237]. Ireland has ambitious climate targets; however, Ireland also has a history of failing to meet climate targets. The inclusion of DH offers some redundancy to Ireland's decarbonisation pathways as the current policy approach heavily relies on electricity for building decarbonisation. While significant progress has been made in decarbonising electricity, the urgency of exploring alternative energy solutions is highlighted by Ireland's household pre-tax electricity prices, which are regularly the highest in Europe [49]. This economic barrier not only impedes households from participating in energy-efficient practices but also exacerbates the issue of energy poverty [48].

In light of these challenges, for the first time, this chapter aims to understand the role that DH could have in Ireland's energy system, particularly in achieving cost-optimal heat decarbonisation pathways. An ESOM is utilised to address the following research questions: (i) *How do future technology developments affect Ireland's strategy for setting cost-optimal GHG targets in the residential sector?* (ii) *What role can District Heating play in Ireland's fuel mix to achieve cost-optimal heat decarbonisation pathways?* and (iii) *At what level of DH connection rate does district heating become cost-effective?*

The rest of this chapter is layout is a follows, where section 5.2 presents the data sources and model utilised in this study, along with a detailed explanation of the applied methodology. Within the section 5.2, five cities are grouped into one heating demand cohort, each with its city municipality that oversees housing and planning, thus providing regional-specific insights. In the section 5.3, the findings obtained from the model are presented. Section 5.4 interprets the results, addresses the strengths and limitations of the model, and identifies future research priorities. Finally, the section 5.5 highlights insights gained throughout the study.

5.2 Methodology

This chapter presents a new methodology integrating the Heat Roadmap Europe cost methodology with a national open-source ESOM incorporating DH. The methodology utilises regional data to calculate national inputs to the model. This feature enables easy integration of regional data in future model development. This section explains the methodology in detail. The model inputs [238] and results are available for download [239] and results can be viewed from an online dashboard[1].

[1]https://epmg.netlify.app/tim-dh-study-2023/results/overview/

5.2.1 District Heating

Integrating DH into energy system modelling enhances sector coupling, promoting integration across energy sectors and unearthing synergies that boost the overall efficiency and flexibility of the energy system. TIM enhances sector coupling and encapsulates critical elements of a competitive DH system, such as local heat sources, heat density demand, and distribution costs [115]. A novel process has been developed to include DH in an ESOM with minimal or no existing DH systems. This process is founded on the robust Heat Roadmap Europe methodology. The Danish Energy Agency, which has extensive DH modelling and implementation expertise, collaborated in developing this methodology suited explicitly to the DH supply source and heating demand density within the case study, Ireland. The schematic in Fig.5.2 presents a roadmap of the methodology employed to integrate DH into TIM. Detailed explanations for each stage outlined in this roadmap are shown in the following section, while section 5.2.1.3 describes the scenarios.

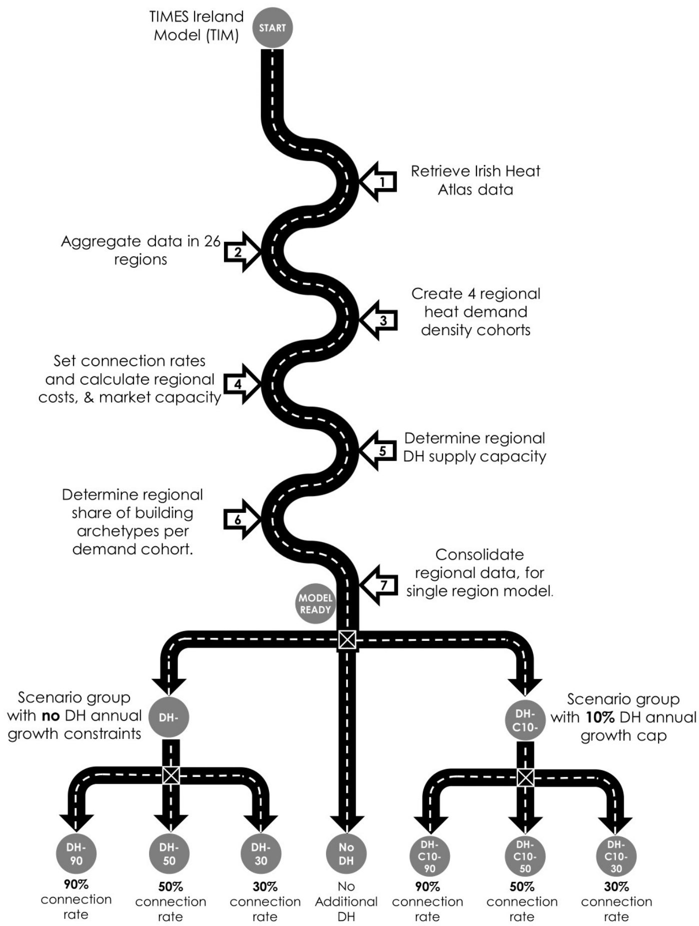


Figure 5.2: District Heating Methodology Roadmap

1. The Irish Heat Atlas [141] contains the total heating demand and both marginal

and average distribution capital costs for each potential DH zone. The Heat Atlas data extracted for this study[2] is founded on the robust Heat Roadmap methodology [187].

2. The Irish Heat Atlas identifies 622 potential DH zones [141], of which 253 in Northern Ireland are excluded from this study. The Republic of Ireland, referred to as Ireland in this paper, has 369 potential DH zones [141], which are included. Ireland has 31 municipal areas, and TIM has 26 regions; therefore, some municipal areas are grouped into a TIM region. The groups are outlined in Table 5.1, while the remaining 21 regions and municipal areas correspond directly.

Table 5.1: Aggregation of Municipal governments into regions in TIMES Ireland Model

Local Authorities	**TIM Region**
Dublin City Council Dún Laoghaire–Rathdown County Council Fingal County Council South Dublin County Council	Dublin
Cork City Council Cork County Council	Cork
Galway City Council Galway County Council	Galway
Waterford City and County Council	Waterford
Limerick City and County Council	Limerick

3. The cumulative heating demand for each region is partitioned into four cohorts, determined by governance or heat density demand. The *Cities* category comprises five cities possessing city-level governance, depicted in the right column of Table 5.1. The remaining three categories *High Density, Medium Density, and Low Density,* are distinguished based on heat density demand. The heat density demand cohorts selected specifically for this thesis distribute the 369 potential DH zones evenly into groups. This thesis examines the third-generation district heating potential (3GDH) within the *Cities, High Density and Medium Density cohorts.* Meanwhile, the *Low Density* cohort explores the feasibility of future 4GDH [108, 117]. This novel feature separately quantifies 3GDH and 4GDH. Table 5.2 elaborates on these four categories.

4. The DH connection rate refers to the maximum percentage of buildings within

[2] https://www.arcgis.com/home/item.html?id=db518c34494743f39ab8541c35eb0cb5#data

Table 5.2: TIM District Heating group details

Group	**Condition**	**Zones**	**Heat (Q_s)**
Cities	Municipality	5	15,944 TJ
High Density	$> 75\ TJ/km^2$	114	12,026 TJ
Medium Density	50 - 75 TJ/km^2	124	5,145 TJ
Low Density	$< 50\ TJ/km^2$	126	1,268 TJ

a DH zone connected to a DH system. A lower connection rate accounts for buildings with the highest heat density areas first, resulting in shorter pipe lengths per unit of heat sold. While higher connection rates lead to longer pipe lengths per unit of heat sold, they also enable more heat to be sold. Table 5.3 summarises the weighted average DH distribution costs ($\overline{C_{d,g}}$) calculated using Eq.5.3. The table also includes the respective heat demand capacities ($Q_{s,g}$) associated with three different DH connection rates of 30%, 50%, and 90%.

Table 5.3: The average DH distribution cost $\overline{C_{d,g}}$ ($€/GJ$) and quantity of heat sold $Q_{s,g}$ (PJ) per group, g.

	30%		**50%**		**90%**	
	$\overline{C_{d,g}}$	$Q_{s,g}$	$\overline{C_{d,g}}$	$Q_{s,g}$	$\overline{C_{d,g}}$	$Q_{s,g}$
City	2.37	9.6	3.04	15.9	4.88	28.7
High demand	2.54	7.2	3.23	12	5.49	21.6
Medium demand	4.35	3.1	5.68	5.1	10.15	9.3
Low demand	9.24	0.8	12.2	1.3	20.8	2.3

5. This step leverages the surplus energy available per region. Ireland has a unique advantage in this regard, as most data centres are in the area with the highest heating demand. Table 5.4 outlines the technological options for DH supply along with their capacity and costs [142, 240, 241]. The surplus heat capacity in each region is sourced from the SEAI Heat Study [142] and the Irish Heat Atlas [141]. Table C.1 summarises all DH sources, only including industrial surplus sources ($\geq$ 20 MWth) and power sources ($\geq$ 50 MWth).

Table 5.4: TIM District Heating Supply Options

Technology	**Invesment** (M€/GW)	**O&M** (M€/GW/yr)	**Efficieny** (%)	**Lifetime** years	**Capacity** PJ
Electric Boiler	70	1.07	99	20	-
Gas Boiler	60	1.95	94	25	-
Biomass Boiler	490	48.2	98	25	-
Solar	310	0.06	43	30	5
Electric ASHP	860	2	350	25	-
Electric Geothermal HP	2700	23.2	548	25	5
Gas Geothermal HP	1386	11.1	165	25	5
Surplus Industry	668	38	100	25	10.3
Surplus Power	2670	38	100	25	44.6
Surplus Data + ASHP	926	24.9	460	25	15
Centralised Storage	161	2	70	35	-
Decentralised Storage	823	2	98	30	-

6. This chapter estimates 55% residential and 45% services split for DH demand. This estimate is based on past gas usage data [242], as similar to DH, gas only serves high heating demand and future urbanisation projections [186]. Changes in dwelling types from 2018 to 2070 are considered, as presented in Fig.5.3. Due to limited data, the services sector, including commercial and public subsectors, is assumed to have a constant share distribution.

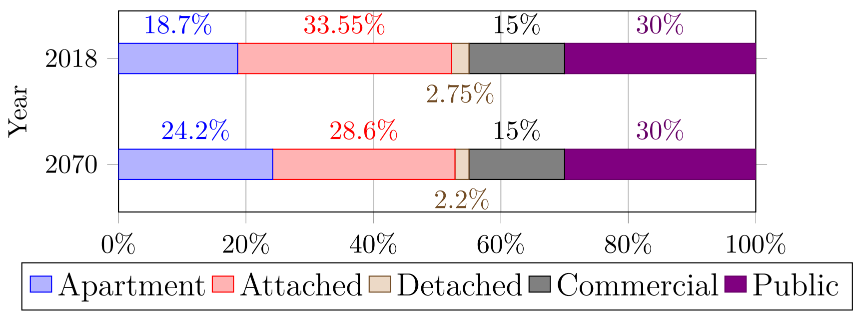


Figure 5.3: Share of district heating demand by building linearly interpolated between 2018 and 2070.

7. A single national region is used to simplify the model and reduce computation time. However, an allocation factor can be applied to divide the results into separate regions to obtain regional insights. This results in an efficient aggregated model that maintains accuracy comparable to multi-regional models [29].

The Reference Energy System (RES) in Fig.5.4 illustrates how DH is represented in TIM. It uses boxes to represent processes or technologies and vertical lines to denote commodities. Interconnections between these elements are represented by links, illustrating the commodity flow and providing a visual overview of the model's operation.

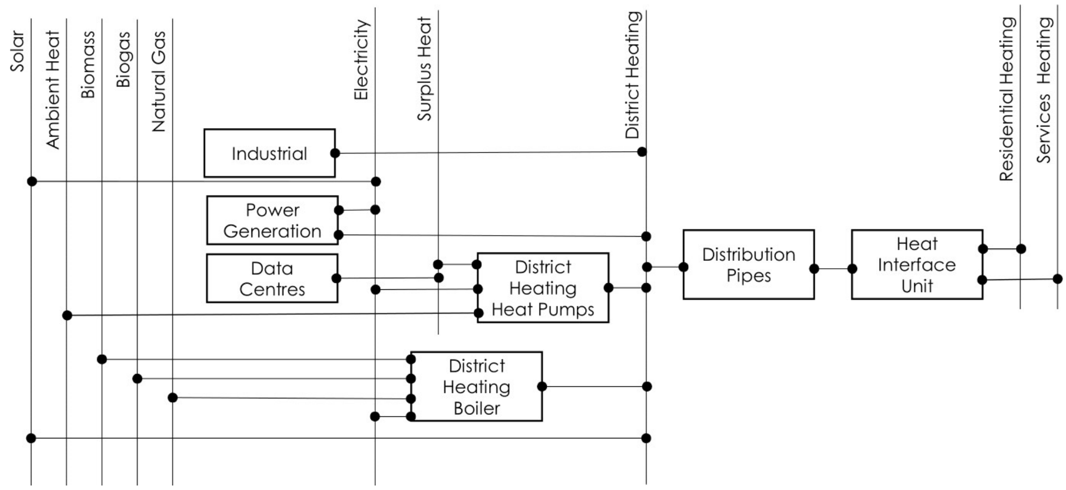


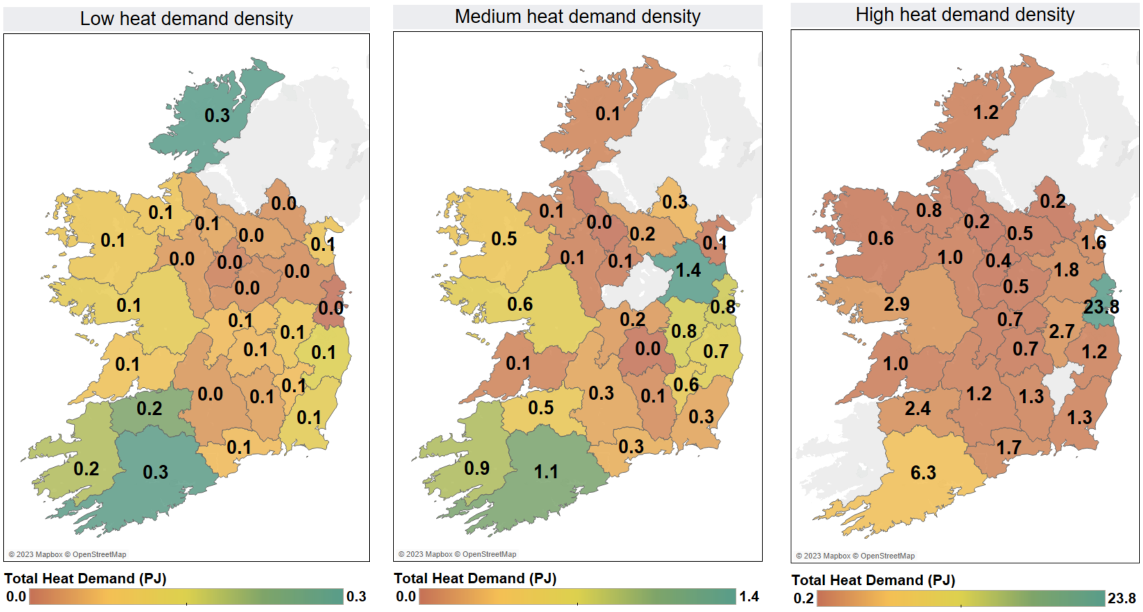
Figure 5.4: Reference Energy System for District Heating in the TIMES Ireland Model

5.2.1.1 Spatial and Temporal Data

The combined heat demand of the residential and service sectors in the EU-27 amounts to 8,070 PJ, with an average heat density of 1.9 TJ/km^2, similar to Ireland's. Heat density demands of $\leq 30TJ/km^2$ are considered unsuitable for DH [243]. Notably, 1.4% of the European land area is responsible for 78% of the building heat demand [117], underscoring the importance of spatial planning in decarbonisation strategies [108]. Despite accounting for only 1.3% of Ireland's land, Dublin accounts for over 20% of heating demand, indicating its suitability for high-detail spatial modelling [112].

At a 90% connection rate, the DH generation capacity for *Cities* is 9.5 TWh, a value four times the 2030 climate target [227]. Ireland's largest city, Dublin, would require 7.8 TWh of this DH generation - three times the 2030 climate target [227]. The concentration of data centres in Dublin [141] positions it as a pivotal location for advancing low-carbon DH solutions within the country. This scenario presents a unique opportunity for a European city to showcase how surplus heat from data centres can be effectively utilised for building heating. To guide the feasible development of DH, a 10% annual growth constraint is implemented, which is believed to be ambitious yet achievable. This belief is grounded in the observed DH growth rates in Italy and Sweden, which are 6.8% [131] and 8% [130], respectively. Under this constraint, the feasible DH generation capacity in 2030 is limited to approximately 2.9 TWh.

Following the *Cities* cohort, DH is extended in *High Density* demand cohorts. However, the model results are based on national average cost and supply and do not provide detailed regional insights. Fig.5.5 visually depicts the regional DH demand for demand cohorts, with *Cities* and *High Density* demand combined.



(a) Regional heat demand in low-density zones ($< 50\ TJ/km^2$)

(b) Regional heat demand in medium-density zones (50 - $75\ TJ/km^2$)

(c) Regional heat demand in high-density zones ($> 75\ TJ/km^2$) and Cities

Figure 5.5: Cumulative heat demand per heat density demand group and region

Examining the services and residential sectors separately is crucial due to their distinct heat energy consumption patterns. Floor area determines the heating demand in the services sector and whether it is a commercial or public building. As per the model base year (2018), the heating demand intensities of commercial and public buildings are 110.2 $kWh/m^2/yr$ and 47.6 $kWh/m^2/yr$ respectively, as depicted in Fig.C.1. The projections for service demand are based on the modified gross national income [244] obtained from the Central Statistics Office (CSO) labour force scenario and are coupled with a prediction for output per person [245].

The determination of residential heating demand in this chapter incorporates several key factors, including building archetype, EPC rating [188], assumed internal temperatures, and the number of dwellings [46]. Future projections for dwellings are derived from Guar et al. [244] and are projected along with the regional growth of dwellings [212]. The initial heating demand for the base year 2018, denoted as ${}_{2018}\theta e, r, a$, is established using Eq. 5.1. This foundational demand calculation facilitates the projection of future heating requirements across different residential building archetypes within various regions, as detailed in Eq. C.1.

$$ {}_{2018}\theta_{e,r,a} = \gamma_{r,y,a} \cdot \frac{\beta_{e,r,y,a}}{\beta_{r,y,a}} \cdot \frac{\gamma + \gamma_{r,nsa}}{\gamma_r} \tag{5.1} $$

Where ${}_{2018}\theta_{e,r,a}$ is the total number of base year dwellings in TIM per EPC rating (e), building archetype (a), and region (r). $\beta_{e,r,y,a}$ is the number of dwellings per EPC rating, region, year of construction, and building archetype from the EPC database and dividing this value by $\beta_{r,y,a}$ results in the regional probability that a dwelling built in a given period falls within an EPC range. $\frac{\gamma+\gamma_{nsa}}{\gamma}$ compensates for the non-stated building archetypes in the CSO data, where γ_r is the regional number of dwellings and $\gamma_{r,nsa}$ is the regional number of non-stated building archetypes.

Temporal resolution is also a key component, as peak energy demand significantly affects the overall cost of an energy system [246]. To capture daily and seasonal demand variations, TIM uses a 40 timeslice temporal resolution, capturing the share of energy consumption in each timeslice. However, TIM v1.0 [57] used an outdated heating profile, which does not reflect current heating in Ireland. As part of this study, the heating demand profile was updated, shown in Fig.5.6.

The following describes the data and method used to update the heating profile. Firstly, the non-daily metered gas [247] and total electricity hourly consumption data [248] are gathered. Only 20% of Ireland's residential electricity consumption is heating in the model base year [46]. Therefore, a baseload is applied to electricity but not to gas, as 97% of dwelling gas consumption is to satisfy heating demand. The calculations applied are outlined in Eq.5.2 and described below. The two hourly data sets (gas and electricity) are combined using a weighting factor to produce an innovative methodology that removes non-heating consumption to develop an enhanced heating profile.

$$ \Delta\% = W_\lambda * \frac{\sum^{2018} \lambda_\Delta}{\sum^{2018} \lambda} + W_\mu * \frac{\sum^{2018} \mu\Delta - Min(\mu_\Delta) * 0.8}{\sum^{2018} \mu} \tag{5.2} $$

$\Delta\%$ is the percentage of space heating demand from each timeslice. The weekday/weekend and synoptic timeslices of (A) Midnight-7 am, (B) 7-9 am, (C) 9 am -5 pm, (D) 5-7 pm, and (E) 7 pm - Midnight are taken into account in each season. W_λ is the weighted gas and W_μ is the weighted electricity. The base year data shows that gas consumption for residential heating is six times higher than electricity consumption, which is reflected in the weighting factor. As the electricity consumption data used is for the entire national grid, the electricity non-heating baseload is removed by subtracting $Min(Elec_{ts}) * 0.8$, from each timeslice.

The new heating profile, which better represents residential energy consumption patterns, demonstrates changes in the distribution of heating demand across different times of the day. Specifically, the average demand during A and C timeslices decreased by 62% and 30%, respectively. However, demand has increased in the B, D, and E timeslices by 85%, 451%, and 63%, respectively. This means that the morning and evening peak demands have become more prominent. The findings show that 17.2% of heating is consumed during the morning peak time, while 30.6% is consumed during the evening peak time. These two periods together account for roughly half of the total heating consumption.

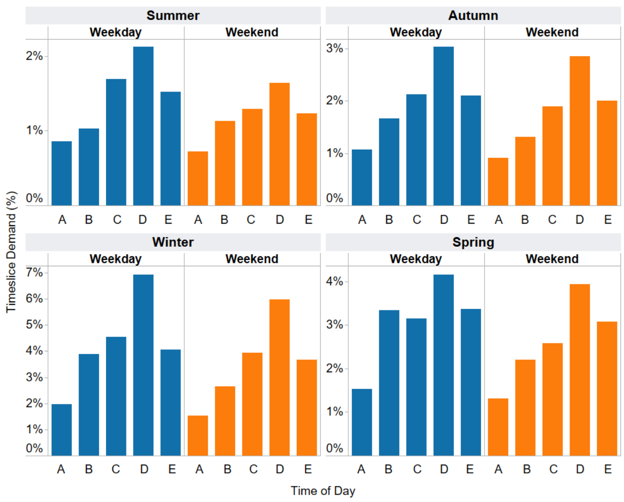


Figure 5.6: The 40 timeslice Heating Profile containing seasonal, weekend/weekday, and five synoptic timeslices of (A) Midnight-7 am, (B) 7-9 am, (C) 9 am -5 pm, (D) 5-7 pm, and (E) 7 pm - Midnight.

5.2.1.2 Techno-economic data

The techno-economic data used in this thesis is derived from the Irish Heat Atlas [141], SEAI Heat Study [126, 127, 142] and the Danish Energy Technology Catalogue [240, 241]. The Irish Heat Atlas is based on the Europe Heat Roadmap methodology

[187], encompassing four models, including the EU TIMES model [71]. The SEAI Heat Study [126, 127, 142] is conducted based on the methodology of the National Energy Framework Model [249]. This thesis incorporates consultation with key stakeholders, uses a high spatial-level analysis to quantify prospective supply areas, including surplus heat, and assesses heat density demand in Ireland. The methodology and results of the Irish Heat Atlas and SEAI Heat Study serve as the foundation for this model, which extends their work by incorporating DH into an ESOM for Ireland.

The marginal distribution costs, C_d (€$/GJ$), represent the investment cost associated with a specific connection rate and are calculated based on previous studies [115, 117, 228]. Many variables are incorporated into calculating C_d, such as population density, length of distribution pipes, average system pipe diameter, the ratio between land area, discount rate, lifespan, total network capital investment costs, annual heat quantity sold and heat demand per capita. The marginal distribution cost of each DH demand cohort is visually represented in Fig.5.7.

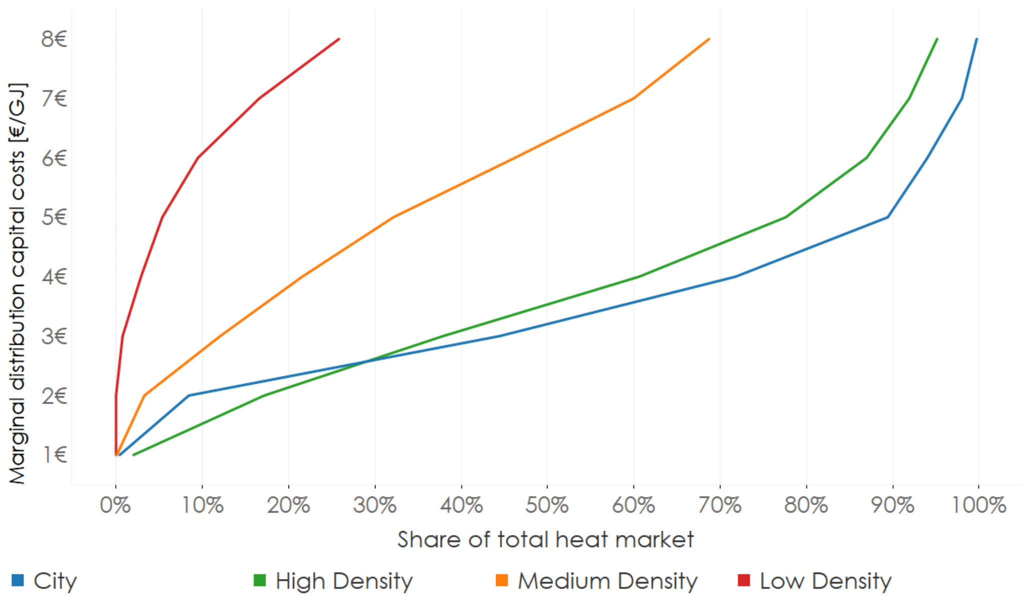


Figure 5.7: Marginal distribution capital costs, denoted as C_d, for each DH group and the associated DH connection rates or heat market shares.

In this study, the weighted average DH distribution capital cost at a national level is denoted as $\overline{C_{d,g}}$. This equation evaluates the ratio of accumulated investment costs to heat demands for each marginal distribution capital cost level, C_d. Eq.5.3 expresses the $\overline{C_{d,g}}$ calculation, where $Q_{s,r,g}$ denotes the annual heat sold in a specific region and group, while $\overline{C_{d,r,g}}$ represents the average DH distribution cost within that region and group.

$$\overline{C_{d,g}} = \frac{\sum_{r=1}^{26}(Q_{s,r,g} \cdot \overline{C_{d,r,g}})}{\sum_{r=1}^{26} Q_{s,r,g}} \tag{5.3}$$

The cost of energy supply to the DH network is another factor influencing the DH feasibility. Table 5.4 provides an overview of the available DH supply options and their associated costs. Furthermore, a sensitivity analysis is performed on the distribution costs by exploring the connection rates at 30%, 50% and 90%. The wide range of connection rates captures the cost sensitivities of DH while simplifying the model by not capturing all connection rates.

5.2.1.3 Scenarios

This thesis identifies cost-optimal decarbonisation paths aligning with Ireland's 2021 Climate Action and Low Carbon Development Bill [52]. The scenarios incorporate sectoral CO_2-equivalent emissions upper constraints or sectoral CBs to reflect these commitments, as outlined in Table 5.5. Provisionally, the third carbon budget (CB3) is defined without sectoral limits; this thesis can offer insights into potential sectoral constraints. No constraints are set between 2035 and 2050, allowing the model to determine the optimal pathway toward net-zero in 2050. Furthermore, no sectoral budgets for Land Use, Land-Use Change, and Forestry (LULUCF) are yet established.

Table 5.5: Ireland's sectoral emission ceilings, national carbon budgets and climate targets ($MtCO_2eq$) are all included in the model.

Sector	**2018**	**CB1** (2021-2025)	**CB2** (2026-2030)	**CB3** (2031-2035)	**2050**
Electricity	10	40	20	-	-
Transport	12	54	37	-	-
Residential	7	29	23	-	-
Services	2	7	5	-	-
Industry	7	30	24	-	-
Agriculture	23	106	96	-	-
LULUCF	5	-	-	-	-
Other	2	-	-	-	-
National	**68**	**295**	**200**	**151**	**0**

Table 5.6 summarises the seven scenarios developed in this study, along with their corresponding DH growth constraints and connection rates. These scenarios are also visualised in Fig.3.1, which presents a graphical representation of the study's

roadmap.

Table 5.6: Summary of District Heating scenarios and associated growth constraints and connection rates

Scenario Group	Growth Constraint	Scenarios	Connection Rate (%)
DH-	No growth limit	DH-30 DH-50 DH-90	30, 50, 90
DH-C10-	10% annual growth limit	DH-C10-30 DH-C10-50 DH-C10-90	30, 50, 90
NoDH	-	NoDH	-

This chapter explores three scenario groups: DH-, DH-C10-, and NoDH, each in compliance with national climate targets. The *DH-* group allows unrestricted DH growth. The *DH-C10-* group, however, limits DH growth to 10% annually, a rate higher than the European leaders Sweden [130], thus pushing the feasibility limits [250]. The *NoDH* group, with the same emission constraints but no new DH, acts as a baseline for comparison, highlighting the impacts of DH.

5.3 Results

This section presents a comprehensive summary of the findings, and a complete set of results is available to view on the web results platform[3] or downloaded from Zenodo [239]. The results presented here concentrate on the implications of various DH pathways, examining their impact on fuel use, emissions, and cost dynamics within the national energy system.

5.3.1 Fuel

The diversity of pathways in this chapter is highlighted by analysing three scenarios depicted in Fig.5.8. In the DH-C10-90 and DH-90 scenarios, Irish buildings' total final energy consumption is approximately 9% and 9.5% higher, respectively, compared to the NoDH scenario. This increase in energy consumption is primarily attributed to DH displacing more efficient heat pumps, as the number of thermal retrofits remains consistent across all scenarios. Additionally, electric heat pumps, which enable the utilisation of renewable ambient heat, play a significant role in all scenarios depicted in Fig. 5.8. The dependence on electricity decreases with the presence of DH, offering

[3] https://epmg.netlify.app/tim-dh-study-2023/

flexibility to address potential challenges in meeting the heat pump targets. The rapid DH growth in DH-90 and DH-C10-90 emphasises the cost-effectiveness of DH.

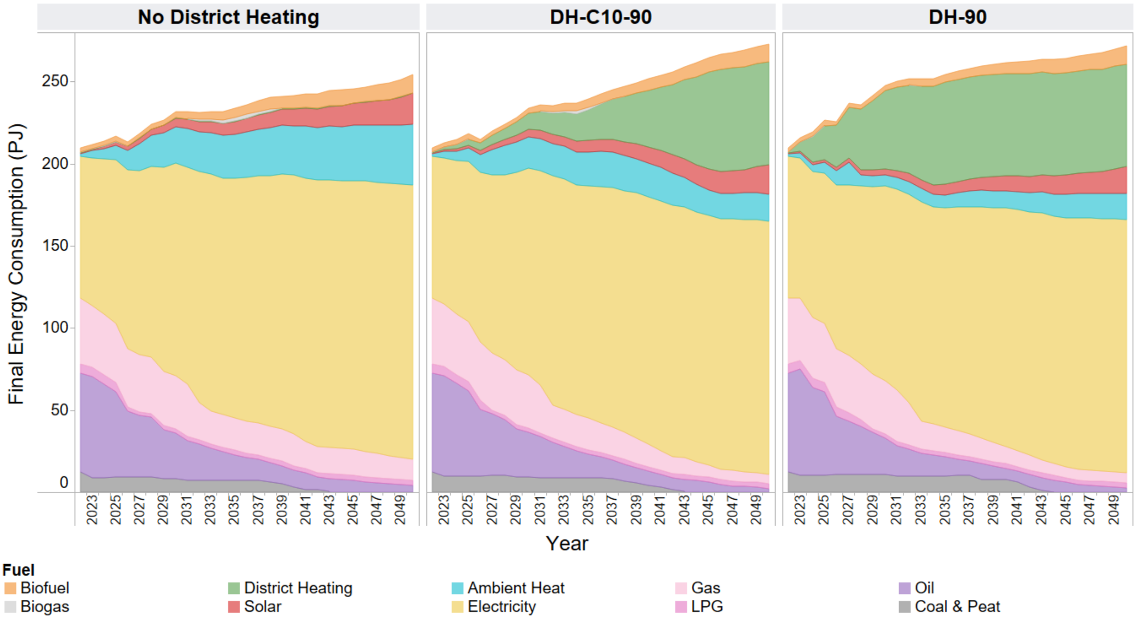


Figure 5.8: The final energy consumption in both residential and services by fuel is illustrated for three contrasting scenarios

5.3.2 Production

Fig.5.9 illustrates DH supply by source, contingent on the DH connection rates of 30%, 50%, and 90%. The model deploys DH at the maximum annual DH growth constraint in the DH-C10- scenario group, resulting in DH reaching full capacity in the heat market before 2050 in all scenarios. Specifically, the DH-C10-30, DH-C10-50, and DH-C10-90 scenarios saturate the heat market in 2036, 2041, and 2046, respectively. The DH- scenario group, devoid of any DH annual growth constraints, provides additional insights. Here, the annual growth rate averages approximately 40% until the market reaches saturation, substantially exceeding China's world-leading DH annual growth rate of 15% [105]. This highlights that this study's feasible DH deployment rates are only a quarter of the optimal deployment rate.

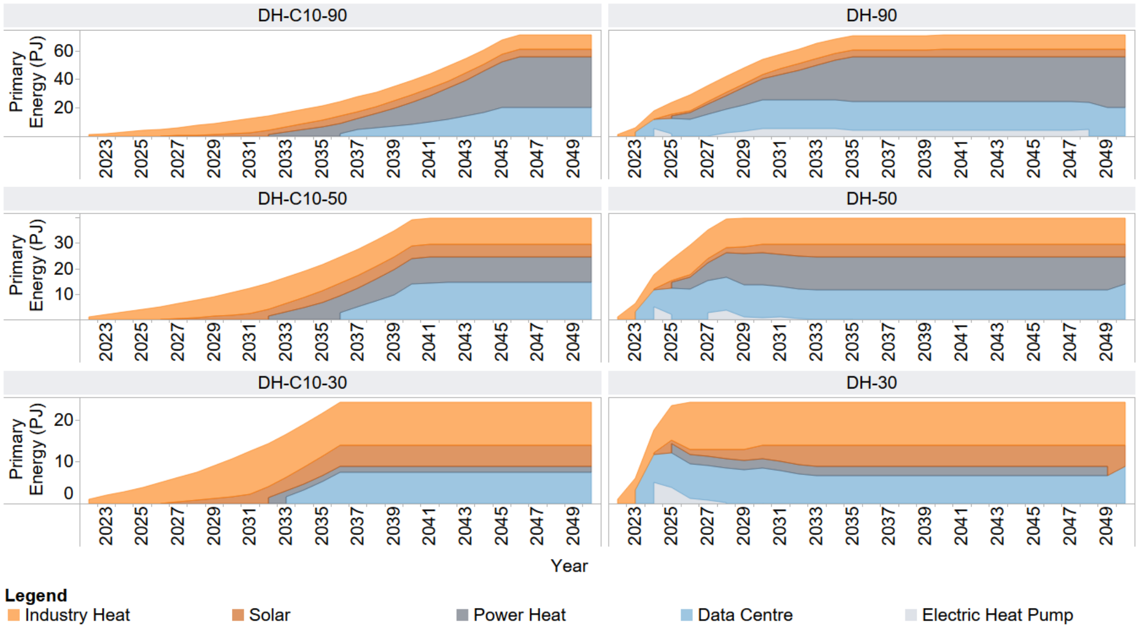


Figure 5.9: District Heating supply by source.

This thesis employs a static heat market for DH. However, it is reasonable to expect the DH market to grow in correlation with urban densification in Ireland [244]. In addition, the rapidly growing sector of data centres [134] presents an abundant source of surplus low-grade heat. While the deployment of electric heat pumps as an independent DH supply option arises solely in the DH- scenario group.

5.3.3 Emissions

The ambitious sectoral and national 2030 climate targets led to minimal divergence in sectoral emissions pre-2030 across the scenarios explored in this study. This is highlighted in Fig.5.10, where sectoral CO_2 emissions appear similar when the DH-C10-90 and NoDH scenarios are compared side by side. In 2022, Ireland emitted 45 $ktCO_2$, which must decrease to 17.5 $ktCO_2$ in 2030, a decrease of 60% in 8 years [53]. Furthermore, aviation transport is excluded from national accounting but accounts for 4.1 $ktCO_2$ of the 4.7 $ktCO_2$ in the transport sector in 2050, as shown in this study. Thus, net-zero is achieved in the energy system when aviation transport is excluded.

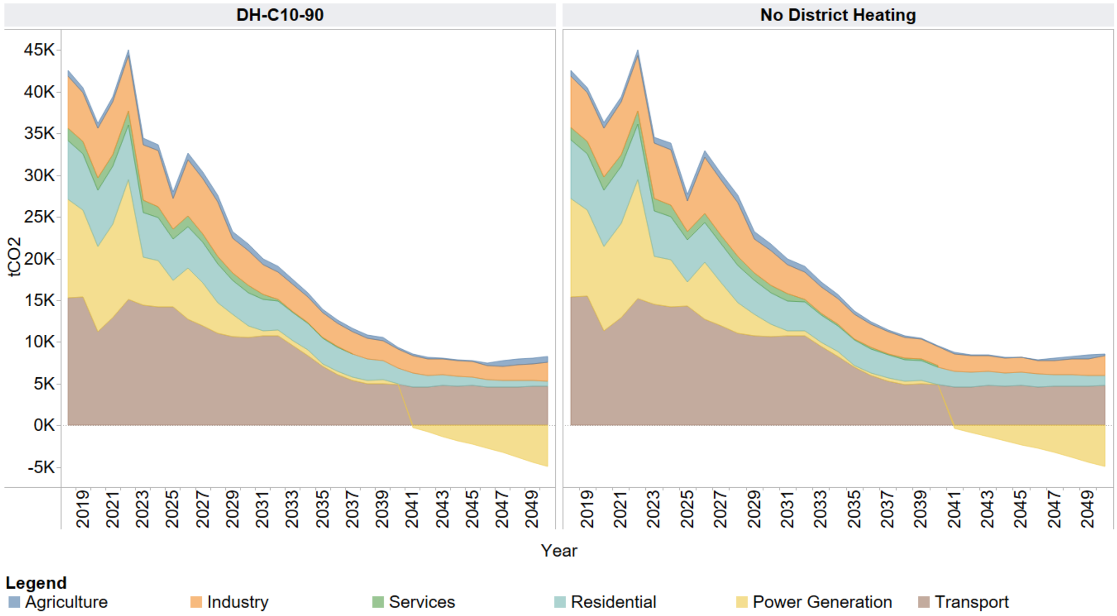


Figure 5.10: Sectoral annual emissions in the DH-C-90 and NoDH scenarios from 2018 to 2050.

Fig.5.11 analysis at a higher resolution level than Fig.5.10 to examine the sectoral CO_2 emissions differences in scenarios.

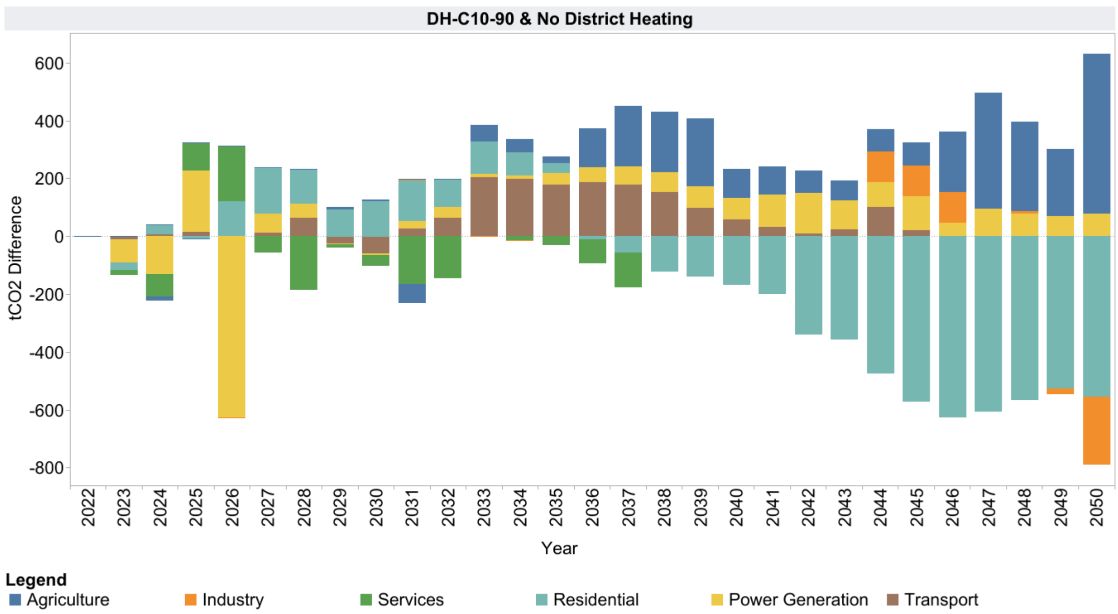


Figure 5.11: Comparison of sectoral CO_2 emissions in the DH-C10-90 and NoDH scenarios: positive values indicate higher emissions in DH-C10-90, negative values indicate lower emissions in DH-C10-90.

Fig.5.11 compares the DH-C10-90 scenario with the NoDH scenario, highlighting the effect of sector coupling through variations in sectoral emissions. A notable difference is observed in 2026, where the NoDH scenario shows 600 tCO_2 more in power generation compared to the DH-C10-90 scenario. This difference arises due to the additional 6 PJ of electricity required to meet the building's energy demand, which is primarily gas-sourced. However, until 2030, the differences in the total energy system CO_2 emissions between scenarios remain ≤ 1 %. As DH becomes more established post-2030 and the annual decarbonisation rate slows due to relaxed climate targets, distinct sectoral pathways emerge. The impact of DH on building decarbonisation is pronounced, with the residential and service sectors emitting less CO_2 in DH-C10-90 compared to the NoDH scenario. Cumulatively, the building sector emits 5.4 $ktCO_2$ less in DH-C10-90 compared to the NoDH scenario, allowing the power generation, agriculture, and transport sectors to emit more CO_2 while still meeting climate targets.

5.3.4 Cost

The chapter focuses on marginal and annualised costs. The sectoral marginal CO_2 emission price signifies the cost of mitigating the most expensive CO_2 tonne within a sector to meet carbon constraints. Utilising the mean sectoral marginal CO_2 emission price provides a comprehensive view of DH's impact, accounting for sector coupling. A common trend in mean sectoral marginal CO_2 emission prices across scenarios reflects the immediate decarbonisation ambition. This trend is notable in the current and upcoming CB phases (2021-2030). Although Ireland's projections fall short of these targets [53], this thesis assumes that all climate targets will be met. Consequently, the mean sectoral marginal CO_2 price peaks in the remaining CB1 phase, ranging from €1,537/ tCO_2 to €1,684/ tCO_2, and vary from €862/ tCO_2 to €1,000/ tCO_2 in the CB2 phase.

Table 5.7 delves into how the DH deployment rate and capacity impact the sectoral marginal CO_2 emission price across different scenarios. The mean sectoral marginal CO_2 emission price is lowest in DH-90, which has the largest DH capacity and no growth restrictions, and highest in the NoDH scenario. The considerable difference between pre-2030 and post-2030 prices in each scenario provides valuable insights. The mean sectoral marginal CO_2 emission price over the entire time horizon highlights DH's long-term impact. Excluding DH leads to a mean price of €729/ tCO_2 while allowing only 30% of the heat market to have DH results in a price of €635/ tCO_2. Although a greater DH market share yields lower prices, the marginal reduction diminishes. Overall, the DH network's capacity significantly reduces marginal CO_2

emission price over time.

Table 5.7: Mean sectoral marginal CO_2 emission price (€/ tCO_2) of all scenarios for pre-2030, post-2030, and all modelled years (2023 - 2050)

Scenario	Pre-2030	Post-2030	All
DH-90	€978/ tCO_2	€375/ tCO_2	€547/ tCO_2
DH-50	€969/ tCO_2	€425/ tCO_2	€581/ tCO_2
DH-30	€972/ tCO_2	€467/ tCO_2	€611/ tCO_2
DH-C10-90	€1,062/ tCO_2	€415/ tCO_2	€600/ tCO_2
DH-C10-50	€1,062/ tCO_2	€439/ tCO_2	€617/ tCO_2
DH-C10-30	€1,059/ tCO_2	€466/ tCO_2	€635/ tCO_2
NoDH	€1,077/ tCO_2	€590/ tCO_2	€729/ tCO_2

The annualised costs of the energy system can be classified into three categories: investment costs, variable costs, and fixed costs. Investment costs relate to establishing new technology capacity, variable costs are linked to process activities such as fuel expenses, and fixed costs are incurred to maintain existing technology capacity. Fig.5.12 demonstrates an increasing annual disparity in cost categories between the DH-C10-90 and NoDH scenarios, with the DH-C10-90 scenario displaying lower costs.

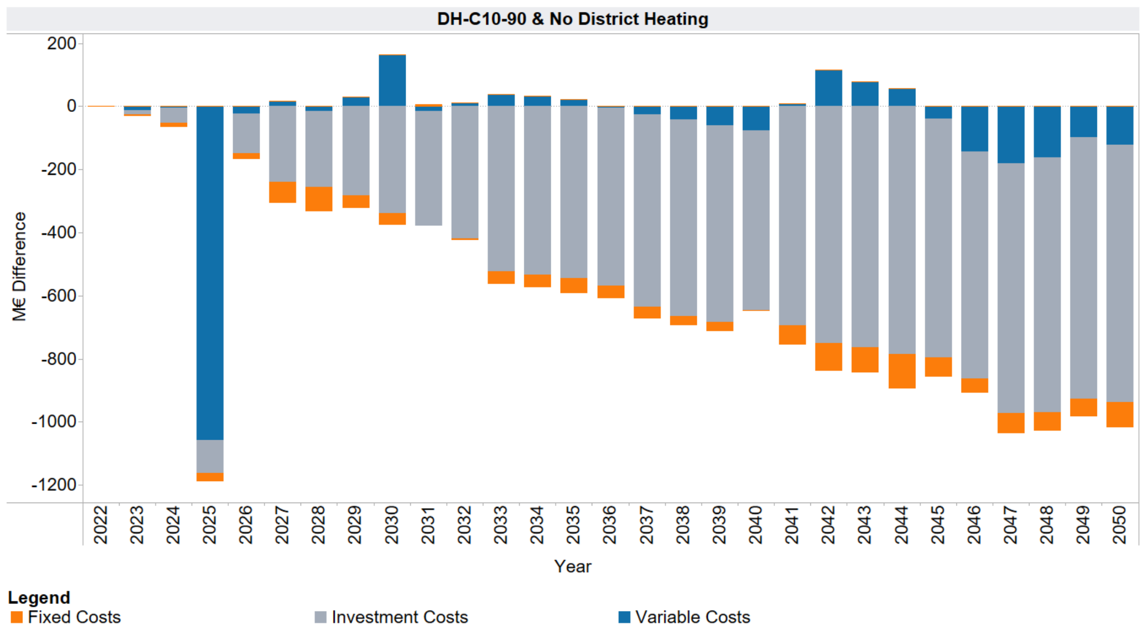


Figure 5.12: Comparison of Annualised energy system cost categories in the DH-C10-90 and NoDH scenarios: positive values indicate higher costs in DH-C10-90, and negative values indicate lower costs in DH-C10-90.

The variable cost disparity in 2025 in Fig.5.12 is due to the model's *unmitigated* CO_2 *backstop*, which assigns a €2,000/ tCO_2 cost to non-mitigable emissions, ensuring climate targets are met; this occurs primarily in the industrial sector. The DH-C10-90 scenario has cost advantages over NoDH, especially in investment costs, yielding annual savings of €820 million in 2050. Considering all cost types, the cumulative savings are projected to reach €17.2 billion by 2050.

Fig.5.13 illustrates the expenditure in the residential and services sectors under the DH-C10-90 and NoDH scenarios. Implementing DH reduces the need for more expensive heating solutions, resulting in savings of €1.4 billion in electrical technologies in the DH-C10-90 scenario before 2030. Although there is additional spending on DH and thermal retrofitting, the DH-C10-90 scenario results in cumulative savings of €1.1 billion pre-2030 and an extra €11.9 billion post-2030, compared to NoDH. This does not include building fuel, labour, or policy costs related to DH deployment but highlights significant savings.

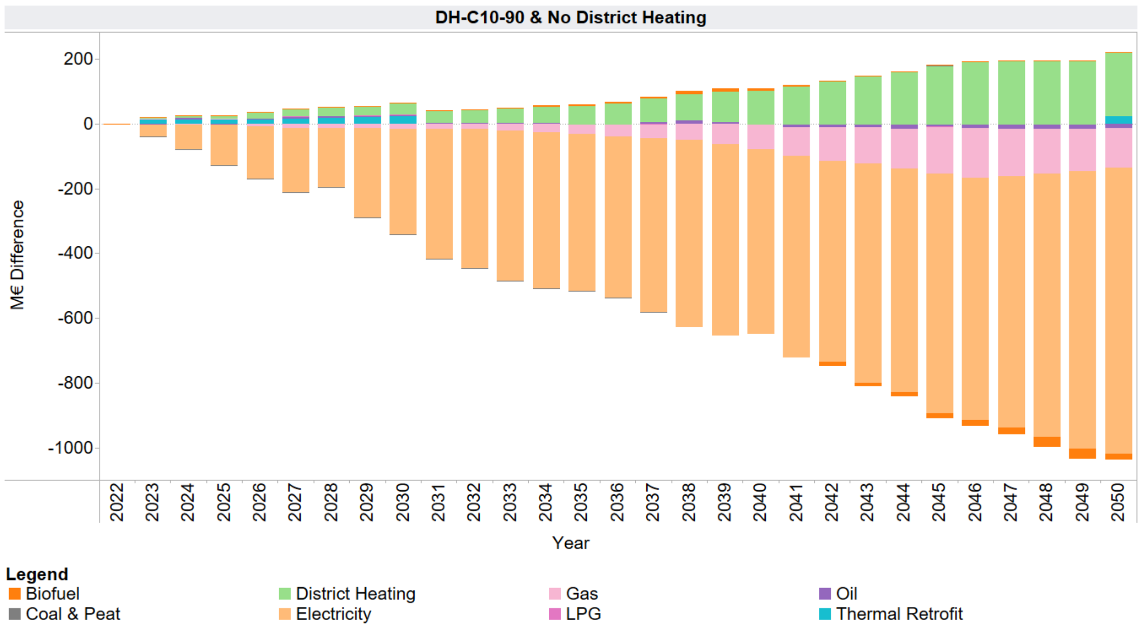


Figure 5.13: Comparison of annualised building sector investment cost by fuel in the DH-C10-90 and NoDH scenarios: positive values indicate higher DH-C10-90 costs, and negative values indicate lower DH-C10-90 costs

5.4 Discussion

Our model suggests electrification is vital to building decarbonisation in Ireland, with DH reducing costs significantly. Despite the existing Irish policy endorsing decarbonisation, it lacks spatial optimisation. With the highest DH potential, Dublin received 27% of the energy grant funds for individual dwellings. This approach compromises the optimal path towards building decarbonisation. While DH network investments are bulky, DH reduces overall energy system costs and provides affordable heating solutions by leveraging surplus heat. However, with low DH deployment regions, there are barriers beyond technology and economics, including policy and regulations [251]. The thesis assumes a feasible annual DH growth rate of 10% to align with practical limitations. Although this rate exceeds the growth experienced by Sweden, Europe's fastest growing DH country [130], it nonetheless offers a realistic benchmark based on historical trends, which is a common approach to feasibility [250, 252].

The model shows an undervaluation of the Irish carbon tax, which could hinder a rapid energy transition. As the model fully explores technological options, socio-economic mitigation options, like the *sufficiency-first* approach, defined as a lifestyle change that minimises environmental impacts without compromising individual well-being [253], should be considered to reduce the mean sectoral marginal CO_2 emission price. Given the larger size of Irish dwellings compared to other European countries, this approach could substantially lower energy and materials [254–256].

Although the findings provide critical insights into potential decarbonisation strategies, it is vital to acknowledge that these results were obtained within specific boundaries. In the following section, the inherent strengths and limitations are discussed.

5.4.1 Strengths

This chapter investigates the role of DH in cost-optimal decarbonisation pathways in energy systems with little or no existing DH, using Ireland as a case study. The thesis uses an accessible model [257] and framework [91]. Furthermore, the model inputs [238] and results [239] of this thesis are open access, while results can be viewed on a web-based dashboard[4]. This adheres to the principles of FAIR (Findability, Accessibility, Interoperability, and Reusability) scientific research [258] promoting transparency and facilitating broader engagement with the findings.

This thesis builds on previous research in energy systems by being the first to incorporate average DH distribution costs into Ireland's ESOM based on the Heat Roadmap Europe methodology [187]. The thesis also uses the latest DH generation and heating demand densities specific to Ireland [141, 237], national climate targets

[4]https://epmg.netlify.app/tim-dh-study-2023/results/overview/

[52], and sectoral carbon budgets with the action plan [227]. An interesting finding of this thesis is that surplus heat generated by data centres could be effectively used to enhance and strengthen Ireland's decarbonisation pathways.

A significant strength of the thesis is showcasing the energy sector coupling ability in the model framework, allowing us to examine the inter-sectoral effect of DH. The inclusion of a scenario with no DH enables us to compare the scenarios directly to quantify the cost benefits of DH. The robustness of the results is improved by a cost distribution sensitivity analysis, which varies depending on connection rates. The connection rates cover a wide range, with only three different rates applied to simplify the model results while maintaining model insights.

The thesis develops an enhanced residential heating profile based on hourly gas and electricity consumption to represent energy usage accurately. TIM identifies economically efficient energy transition pathways and does not consider policy effects like a carbon tax. Excluding the carbon tax allows us to focus on the fundamental economics of the energy transition, unaffected by current policy specifics. The methodology can be utilised in any country with available Heat Roadmap Europe data, which is most European countries [104, 109] and an increasing number of countries outside Europe [122].

5.4.2 Limitations & Future Work

Although the thesis offers valuable information about Ireland's energy transition, it has limitations. It overlooks aspects like the economic value of surplus heat and the physical distance between surplus heat sources and building heat demands, which could require a GIS model to account for lengths precisely. The model also does not consider socio-economic facets of the energy transition, such as employment, health benefits or public acceptance.

In terms of geographical scope, the model utilises data from 369 potential DH zones before aggregating the data and employing a single region to reduce complexity. This approach limits understanding at finer geographic scales, such as the municipality level, where housing and planning policies are primarily implemented.

The chapter simplifies potential DH to a static 68 PJ [141], accounting for 52% of total building heat, in line with Irish studies suggesting $\geq$ 50% of Ireland's heat could be supplied by DH [127, 140, 141]. However, dynamic factors like thermal retrofitting, urbanisation, technological progress, and building obsolescence influence DH capacity. Due to data scarcity, the model excludes thermal retrofitting in the services sector. The study also does not consider adding new CHP plants in the power generation sector, focusing instead on surplus heating from retrofitting existing power plants, which tends to be more expensive than new CHPs [142]. These simplifications indicate areas for model refinement and future research.

5.5 Conclusions

The building sector, encompassing residential and service buildings, is characterised by a slow turnover of technology and infrastructure, making a swift energy transition a complex endeavour that necessitates strategic planning. The study explores the energy transition dynamics in a low-deployment DH region, using Ireland as a case study. The core questions driving this study are (i) What role can DH play in Ireland's fuel mix to achieve cost-optimal heat decarbonisation pathways? and (ii) At what level of DH connection rate does district heating become cost-effective? The research findings address these questions. DH annual growth is significant due to its ability to reduce the mean marginal CO_2 emission price by 13-25% compared to No DH. Furthermore, cumulative energy system savings in the DH-C10-90 scenario compared to the NoDH scenario reach €17.2 billion by 2050. The maximum share of DH permitted in the building heating fuel mix is 52%, and regardless of the DH connection rate, the findings consistently demonstrate that DH saturates the heat market in the optimal decarbonisation pathway before 2050.

This novel study incorporating DH into an ESOM for Ireland has shown DH as an integral component of an optimal decarbonisation strategy and identified a unique share of optimal DH supply sources. The share of GHG emissions from the building is significant; while Ireland's building decarbonisation heavily relies on electricity, expanding DH in Ireland shows that marginal emission prices and total energy system costs are reduced. Ireland's climate ambitions highlight the urgency of exploring alternative energy solutions [52], high household pre-tax electricity prices [49], and soaring energy poverty [48]. However, realising this energy transition necessitates strategic policy support, encompassing regulation, planning, and financial assistance. The vital role of continuous research and policy innovation in this area and the importance of socio-economic considerations are underlined.

Chapter 6

Advancing Cost-Optimal Residential Decarbonisation Pathways: An Examination of Heat Pumps and Thermal Efficiency

Residential energy consumption represents a significant fraction of the global energy matrix. It is responsible for 22% of total energy consumption and contributed 17% to global energy-related CO_2 emissions in 2020 [259]. There has been a steady decline in residential energy floor area intensity (MJ/m^2) by approximately 1% per year since 2010. However, this trend is counteracted by the expansion of the residential floor area, which has increased more than double that of the intensity reduction [260]. As a result, there has been a 50% increase in residential CO_2 emissions over the last three decades [261]. A substantial shift is necessary to curb this escalating trajectory and align with net-zero strategies.

The *European Green Deal* is the EU strategy to address climate change. Its primary objective is to reduce GHG emissions by at least 55% by 2030 compared to 1990 levels. As part of this effort, each EU member state must achieve a renewable energy share of 49% in buildings by 2030, including a mandatory annual increase of 1.1% [262]. Concurrently, the EU *renovation wave* strategy, a fundamental component of the *European Green Deal*, seeks to accelerate energy renovations [163]. From 2012 to 2016, the EU averaged a rate of 12.3% in annual residential thermal retrofits per floor area, with 1.3% dedicated to deep thermal retrofits (>30% energy savings). In Ireland, the rates were 8% for all thermal retrofits and 0.7% for deep thermal retrofits during the same period [263].

As part of the national climate policy, Ireland publishes the annual CAP [66, 227], which sets out a roadmap to meet the national target of reducing GHG emissions by 51% by 2030, compared to 2018 levels [52], surpassing EU climate target ambition. To achieve climate targets, Ireland aims for an 80% share of electricity from renewable sources by 2030, an effort expected to reduce carbon intensity from 340 gCO_2/kWh (in 2020) to 118 gCO_2/kWh [45]. The residential sector is a central focus of the CAP and has two primary goals. First, the use of fossil fuels in new dwellings should be phased out. Second, the building fabric of 500,000 dwellings (representing 30% of all dwellings) should be enhanced to meet the B2 standard in the Building Energy Rating (BER). The BER is Ireland's EPC, forming part of the legislative framework under the EPBD. CAP 2024 includes a heat pump target of 400,000 installations in dwellings and the deployment of district heating DH in high-density areas [66].

The EPC databases are central to the EU's EPBD. The national EPC databases store energy performance data from EPCs, offering an efficiency rating from A (most efficient) to G (least efficient). The type of EPC data to be collected nationally depends on each member state. Different specifications of energy-related variables are applied to different calculation methods, resulting in different EPC labels and ranges throughout the EU. In addition, there are various levels of public accessibility due to data protection regulations at the member-state level [36]. Nevertheless, EPCs have become a fundamental building energy tool by influencing market behaviour and providing vast data to researchers and policymakers [264].

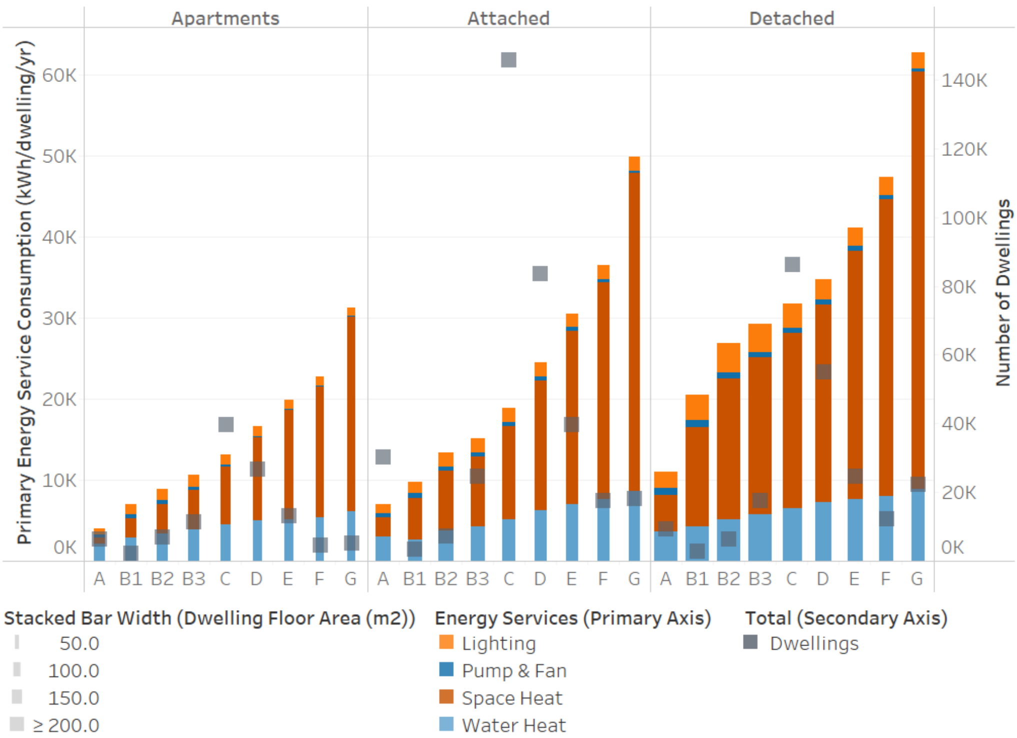


Figure 6.1: Filtered EPC database (August 7th, 2023) illustrating primary energy consumption of each energy service across dwelling types and BER labels. The width of the bars represents the average floor area of dwelling in that BER cohort, and the square markers display the corresponding number of EPC records on the secondary axis.

The Irish EPC database[1] is open source and accounts for over 1 million dwellings, representing 62% of all Irish dwellings. The Irish EPC database includes more than 200 variables for each dwelling, such as construction and EPC assessment dates, floor areas, fabric U-values, ventilation rates, and heating fuel type and efficiency. Irish EPCs also detail energy and CO_2 emissions associated with each energy service of heating, cooling, lighting, and the operation of pumps and fans, providing a broad and varied range of information. Fig. 6.1 provides an overview of the Irish EPC database. The Dwelling Energy Assessment Procedure (DEAP) calculates the primary energy by adding the energy delivered to a residence and an allowance, known as the primary energy factor, which represents the energy overhead required for the extraction, processing, and transportation of the fuel or energy carrier [265]. The primary energy variable (kWh/m^2/yr) is the most significant factor in the EPC database, as it determines the BER label and the expected total primary energy consumption. The total primary energy is classified into one of the 15 potential BER labels, shown

[1] https://ndber.seai.ie/BERResearchTool/ber/search.aspx

in Table 3.1. This categorisation system is customised to Ireland's specific context. However, the extensive EPC database has inaccuracies in the dataset as a result of the use of established default values [40] and the fact that expected internal temperatures may differ significantly from reality [37, 38, 46].

This study aims to answer two important policy questions: (i) Is Ireland's current *fabric-first* approach the most cost-effective pathway to achieve residential decarbonisation? (ii) What other strategies can be identified for residential decarbonisation? Here, an enhanced version of Ireland's energy system model [57] has been developed to address research questions and better understand the most effective way to decarbonise the residential sector and energy system.

The layout of the rest of this chapter is as follows: Section 6.1 explains the methodology used to explore the heat pump and thermal efficiency nexus in the residential sector and presents the scenarios, data handling process and calculations. Section 6.2 outlines the results of the study. Section 6.3 discusses the strengths and limitations of the study. Section 6.4 summarises the conclusions and identifies potential future work.

6.1 Methodology

The following sections outline the modelling framework, describe how HLIs are calculated to determine the energy rating distribution across various building archetypes and detail the scenario development.

The total heat loss from a dwelling is quantified by the Heat Loss Coefficient (HLC) [266] or the Heat Transfer Coefficient (HTC) [267], measured in watts per kelvin (W/K). This metric is a function of the peak heat loss per unit floor area, considering the external design temperature, internal design temperature [153], and losses due to the building's fabric and ventilation [155]. For Ireland, an external design temperature of -3°C is considered, alongside an average internal temperature derived from the proportion of living and non-living areas, which are assumed to have internal design temperatures of 21°C and 18°C, respectively [265]. The Heat Loss Indicator (HLI) is defined as the HTC or HLC normalised by the floor area (W/K/m^2). The fabric and ventilation heat loss components are explained further and illustrated in Eq. 6.1 and Eq. 6.2.

- **Fabric Heat Loss ($\mathbf{Q}_f$)**: This component is based on evaluating U-Values and thermal bridges. It is observed that standard default U-Values are used for approximately one-third of dwellings in Ireland's EPC database, indicating a level of approximation regarding the thermal fabric quality. Default values are applied when building fabric details are unavailable or not economically viable to obtain [40].

$$Q_f = A \cdot U \cdot \Delta T \tag{6.1}$$

Where fabric heat loss (Q_f) is calculated from its envelope area (A), U-Value of the envelope (U), and temperature difference (ΔT).

- **Ventilation Heat Loss ($\mathbf{Q}_v$)**: This calculation employs either of two strategies: a permeability test, utilised in 10.6% of cases, or the implementation of default coefficients as outlined in Table D.4. This permeability test offers an alternative to adopting predetermined structure, flooring and draught-proofing infiltration rate values. However, other default values, shown in Fig. 6.2 are still applied when using the permeability test approach.

$$Q_v = V \cdot ACH \cdot \Delta T \cdot 0.33 \tag{6.2}$$

Ventilation heat loss (Q_v) is derived from the interior volume (V), air changes per hour (ACH), ΔT, and a conversion factor (0.33).

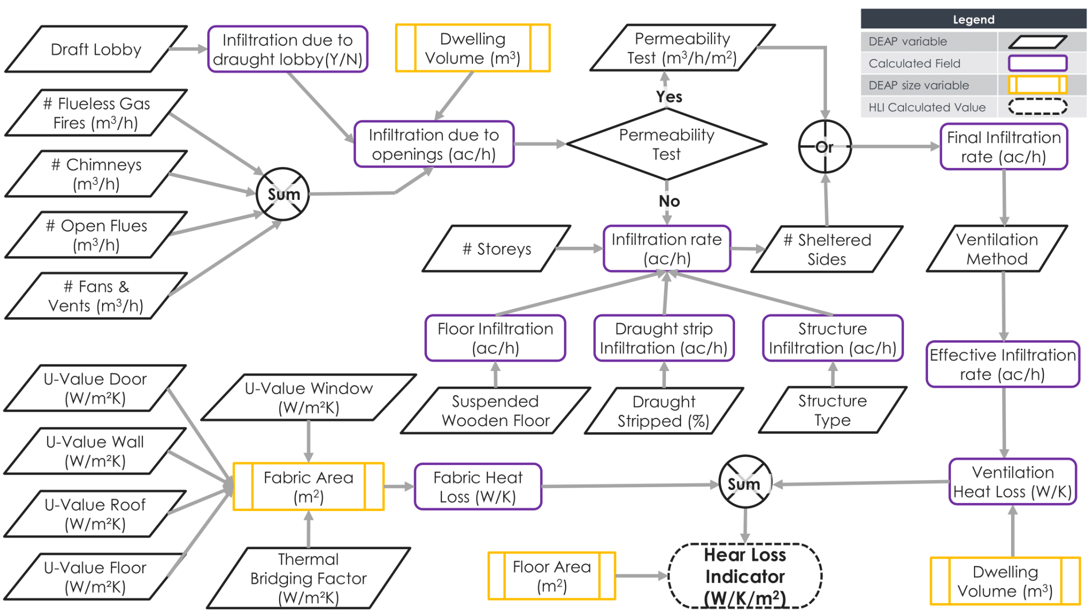


Figure 6.2: Schematic overview of Heat Loss Indicator (HLI) calculation, derived from DEAP [265] and employed in the study

The HLI, an important outcome of the DEAP model [265], is not available in the EPC database. However, all components of the HLI are present. In this study, to quantify an HLI, a reverse calculation of DEAP's Excel computational pathway using the coefficients adopted by DEAP is carried out. The process of obtaining the HLI consists of four steps:

- The EPC database is first downloaded and then filtered using the guidelines outlined in Table 3.2. This filtering process is carried out using an open-source Tableau Prep workbook [268]. The workbook is designed to ensure that the pre-processing methodology is reproducible and adheres to the principles of FAIR scientific research [258]
- Data from the Tableau Prep workbook is translated into Tableau, where it is organised to exhibit the mean (μ) HLI across nine BER labels and three building archetypes. These results are shown in Table D.1.
- The standard deviation (σ) for each category, based on its BER label and building archetype, is calculated and shown in the same table.
- After obtaining the mean and standard deviation for each group, the cumulative distribution function of a normal distribution is applied in the model, as shown in Eq. 6.3.

$$P(HLI \leq x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(HLI-\mu)^2}{2\sigma^2}} \, dHLI \tag{6.3}$$

  Where P(HLI $\leq$ x) denotes the cumulative probability that the HLI value is less than or equal to x. μ is the mean of the normal distribution and σ is the standard deviation of the normal distribution. These results are shown in Table D.2 for seven selected HLI values.

This systematic pre-processing and analysis of the EPC database allowed us to derive the HLI distributions across different BER labels and building archetypes. Detached dwellings with more exposed exteriors tend to have higher HLIs compared to apartments [269]. The variations in average HLIs across different dwelling types and their respective BER labels are illustrated in Fig. 6.3.

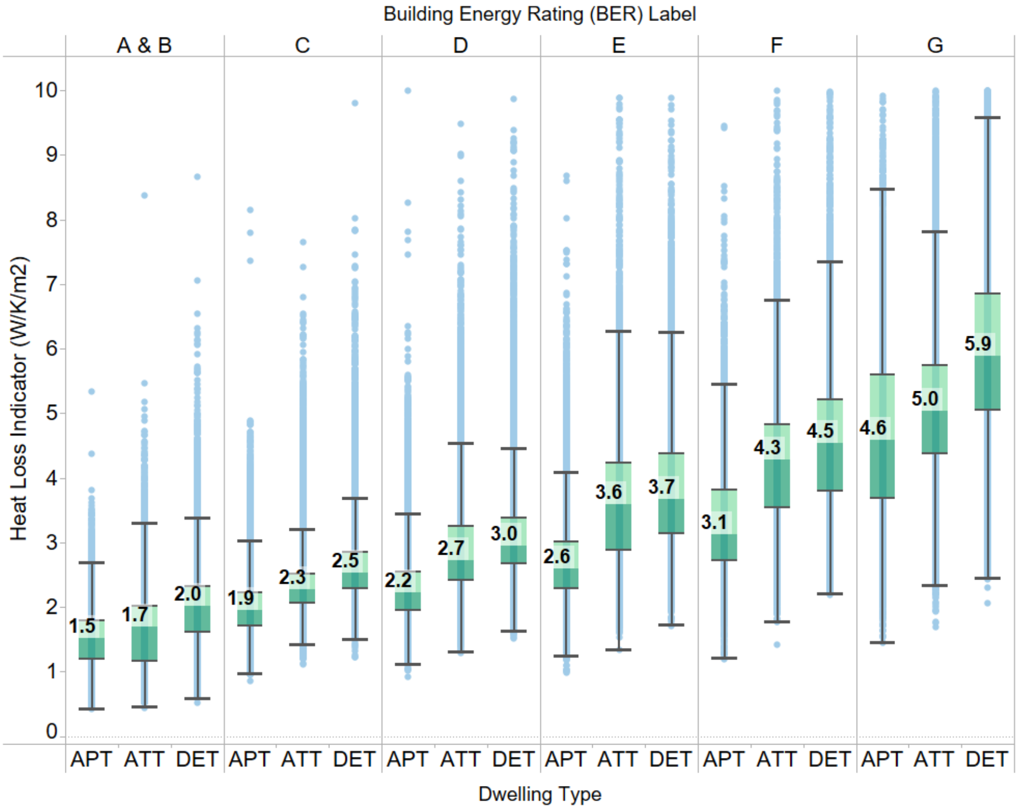


Figure 6.3: Distribution of HLI and median HLI across apartment (APT), attached (ATT), and detached (DET) dwellings for BERs A&B and C-G

To be eligible for an electric heat pump subsidy in Ireland, a dwelling's HLI should be a) $\leq$ 2.3 W/K/m^2 and meet specific fabric and infiltration standards, or b) have an HLI strictly $\leq$2 W/K/m^2. Only 23.46% of dwellings in the EPC database meet the $\leq$2 W/K/m^2 standard. This value increases to 23.48% when all dwellings that have an HLI of $\leq$2.3 W/K/m^2 and meet other standards are included. Less than 1% of dwellings with an HLI between 2 and 2.3 W/K/m^2 qualify for the subsidy. If the HLI threshold were increased to $\leq$2.3 W/K/m^2 with no other conditions, 41.36% of dwellings in the EPC would be eligible for the subsidy. If the threshold were further increased to $\leq$3 W/K/m^2 or $\leq$4.5 W/K/m^2, the percentage of qualifying dwellings would be 72.23% and 81.26%, respectively. In this study, the impact that an HLI threshold of $\leq$2.3 W/K/m^2 and $\leq$ 3 W/K/m^2 could have on the decarbonisation of the residential and overall energy sector in Ireland is explored.

This study includes various heat pump technologies, such as electric ground-source, air-source, and hybrid air-source, as technological inputs in the model. The details of the residential heat pump technologies by source in this model are summarised in Figure D.1. However, the scenario results show that only electric air-to-water source heat pumps are selected in the cost-optimal pathways. Therefore, all further references to 'heat pumps' in this chapter should be explicitly understood as electric air-to-water source electric heat pumps.

This thesis defines a heat pump as *optimal* when its efficiency aligns with the design standards. *Optimal* heat pump efficiency is calculated based on a flow temperature of 55 °C and validated through empirical field studies [270]. In the HLI scenarios, the proportion of dwellings eligible for optimal heat pumps varies by energy rating category and building archetype, as detailed in Table D.2. This variability is directly related to the proportion of dwellings with an HLI less than or equal to the predefined scenario threshold.

The model also explores the concept of 'sub-optimal' heat pumps, which are defined as heat pumps that fail to reach the designed efficiency in buildings with high heat loss. This inefficiency necessitates using larger heat emitters and increased flow temperatures, leading to higher costs and reduced system efficiency. SEAI has identified a correlation between a dwelling's HLI and the efficiency of air source heat pumps [126]. Table 6.1 presents an overview of heat pump installations' efficiency and cost implications per dwelling and BER used in this study. Only A and B BER-rated dwellings can accommodate optimal heat pumps in non-HLI scenarios. However, in HLI scenarios, a certain percentage of dwellings in each BER range can accommodate optimal heat pumps depending on the HLI threshold specified in that particular scenario. Moreover, for existing dwellings exceeding the heat pump HLI threshold, optimal heat pump installation becomes feasible following a thermal retrofit, effectively reducing the HLI, as illustrated in Fig. 6.4.

Table 6.1: Efficiency and cost metrics for air-to-water electric heat pump systems by dwelling type and BER in 2018, 2030, 2040 and 2050.

	BER	Efficiency (COP)				Cost (k€)				kW
		2018	2030	2040	2050	2018	2030	2040	2050	
Apartment	AB	3.07	3.21	3.34	3.43	9.11	9.11	8.19	8.19	15
	C	2.92	3.05	3.18	3.26	9.68	9.68	8.77	8.77	15
	D	2.77	2.89	3.01	3.10	10.25	10.25	9.34	9.34	15
	E	2.62	2.74	2.85	2.93	10.84	10.84	9.93	9.93	15
	F	2.39	2.50	2.60	2.67	11.02	11.02	10.11	10.11	15
	G	2.17	2.27	2.36	2.43	11.20	11.20	10.29	10.29	15
Attached	AB	3.07	3.21	3.34	3.43	8.53	7.76	7.06	6.99	20
	C	2.89	3.02	3.15	3.23	9.07	9.07	8.21	8.21	20
	D	2.66	2.78	2.89	2.97	9.60	9.60	8.75	8.75	20
	E	2.50	2.61	2.72	2.79	10.15	10.15	9.30	9.30	20
	F	2.35	2.45	2.56	2.63	10.32	10.32	9.47	9.47	20
	G	2.20	2.30	2.39	2.46	10.49	10.49	9.64	9.64	20
Detached	AB	3.07	3.21	3.34	3.43	9.85	8.96	8.15	8.07	30
	C	2.64	2.76	2.87	2.95	10.47	10.47	9.48	9.48	30
	D	2.52	2.63	2.74	2.82	11.08	11.08	10.10	10.10	30
	E	2.41	2.52	2.62	2.69	11.72	11.72	10.74	10.74	30
	F	2.29	2.39	2.49	2.56	11.92	11.92	10.93	10.93	30
	G	2.18	2.28	2.37	2.44	12.11	12.11	11.13	11.13	30

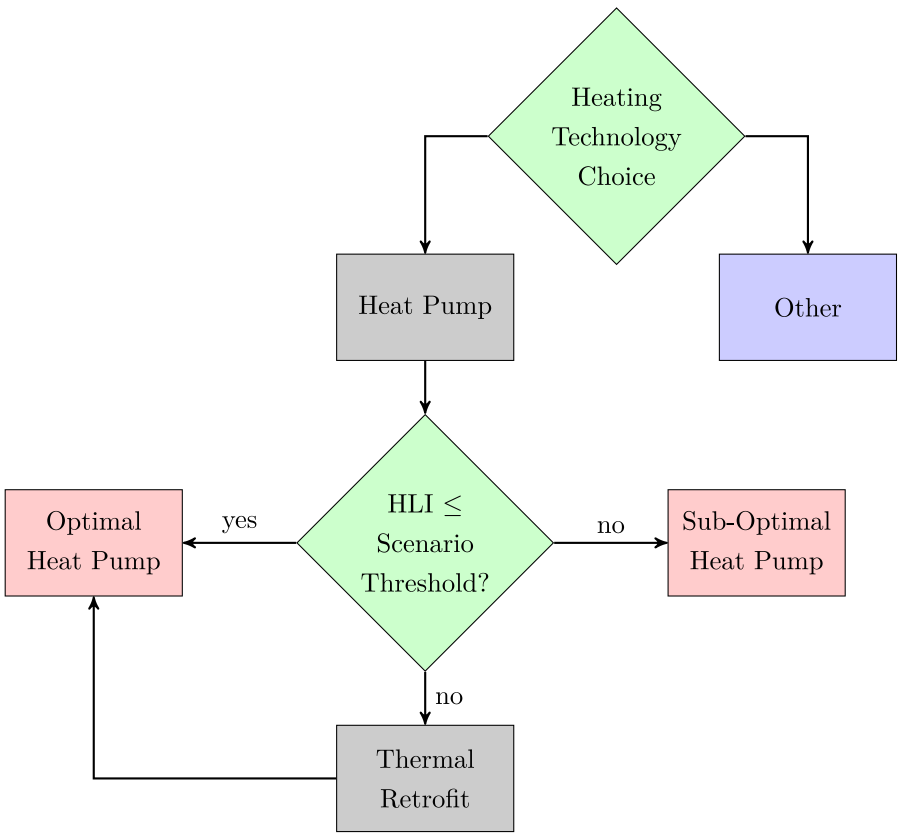


Figure 6.4: Modelling decisions to distinguish between sub-optimal and optimal heat pump pathways

In line with the initial version of TIM [46, 57], any thermal retrofit will bring a dwelling up to the post-thermal retrofit energy demand, equivalent to a B2-rated dwelling. The expected energy savings of each pre-thermal retrofit BER rating considers the rebound effect and is evaluated in Table B.1. Instead of considering the specific work performed during the thermal retrofit upgrade, a holistic approach is chosen, where the average cost is considered that takes a dwelling from a pre-retrofit to a post-retrofit BER B2 rating [46].

6.1.1 Scenarios

The scenarios developed in this chapter are designed to provide insight into the role of heat pumps in residential decarbonisation. These pathways are aligned with Ireland's current climate targets, guided by two consecutive 5-year carbon budgets [193] and working towards net-zero emissions by 2050. To achieve climate goals in the short term, the two carbon budgets, CB1 and CB2, are defined and extend from 2021 to 2025, and 2026 to 2030, respectively. In CB1, the model incorporates all fuel consumption for years preceding 2023 based on historical national energy balances. It is important to note that the model could not find a solution for CB1. In the two years that have already passed, 2021 and 2022, adequate reduction of GHG emissions was not achieved, and the model cannot reach the target for years 2021-2025 in the remaining three year period. To ensure that the model can find a solution, the targets from CB1 and CB2 are combined, along with their respective sectoral emission limits, into a single ten year target for 2021-2030. The national provisional CB3 target for 2031-2035 is also used in the model. Four sectoral emission ceiling constraints for the residential sector are forecast, as shown in Table 6.2. Note that TIM does not cover all sectors, only the energy sectors, resulting in an aggregate sector emission that is less than the national total.

Table 6.2: The model incorporates national carbon budgets, sectoral emission ceilings of energy sectors, projected residential sector ceilings, and net-zero target (MtCO_2eq). P denotes provisional, while F indicates forecast values.

Sector	**CB1 & 2** (2021-30)	**CB3** (2031-35)	**CB4** (2036-40)	**CB5** (2041-46)	**CB6** (2046-50)	**2050**
Electricity	60	-	-	-	-	-
Transport	91	-	-	-	-	-
Residential	52	17_F	13.3_F	9.3_F	5.2_F	-
Services	12	-	-	-	-	-
Industry	54	-	-	-	-	-
Total	**495**	**151**$_P$		-	-	**0**

The scenario development is guided by the optimal heat pump threshold and the availability of sub-optimal heat pumps, detailed in Table 6.3. Previous iterations of TIM used the BER rating as the selection criteria for optimal heat pumps. However, it is more accurate to use the HLI. In this study, TIM is updated so that optimal heat pumps can be selected according to the dwelling's HLI. The reference scenario, scenario B2, was used in previous versions of TIM and required a minimum BER rating of B2 for heat pump installation in an existing dwelling. Previous TIM studies did not include sub-optimal heat pumps [46, 57, 180]. To enhance the analysis, the B2SO scenario is developed, a variant of B2 that incorporates sub-optimal heat pumps. In scenarios HLI 2.3 and HLI 3, the HLI thresholds for selecting optimal heat pumps are $\leq$ 2.3 and $\leq$ 3 W/K/m^2, respectively. This chapter includes the integration of District Heating (DH) in each scenario, following the methodological approach described by Mc Guire et al. [180]. This integration is motivated by recent studies highlighting DH's significant potential, primarily due to the abundance of surplus heat in Ireland's urban areas [127, 140, 141]. A 10% annual growth in DH in Ireland is assumed [180], which positions Ireland as the fastest-growing country in Europe. This study considers that 90% of buildings within DH zones will be connected to the DH network, while the remaining 10% will not.

Table 6.3: Scenarios developed in this study.

Scenario	**Optimal Heat Pump Threshold**		**Sub-optimal HP**
	HLI	**EPC**	
B2	-	A1-B2	No
B2SO	-	A1-B2	Yes
HLI 2.3	$\leq$ 2.3 W/K/m^2	-	Yes
HLI 3	$\leq$ 3 W/K/m^2	-	Yes

6.2 Results

The results focus on three main areas: heating technology, the residential sector, and the implications of heat pumps on cost-optimal pathways of the entire energy sector.

6.2.1 Heating Technology

The model assumes each dwelling has a wet central heating system with radiators, leading to the exclusivity of the ten outlined space heating technologies in Fig. 6.5; only one heating technology can be selected per dwelling. Dwellings with a C to G BER rating can also have a thermal retrofit to elevate their status to a B2 BER rating, lowering their space heating requirements. Fig. 6.5 presents the number of new installations of different heating technologies and thermal retrofits in the residential sector for various scenarios and decades. This figure does not include the HLI 3 scenario, which shares substantial similarities with HLI 2.3. Instead, Fig. 6.6 compares HLI 2.3 and HLI 3.

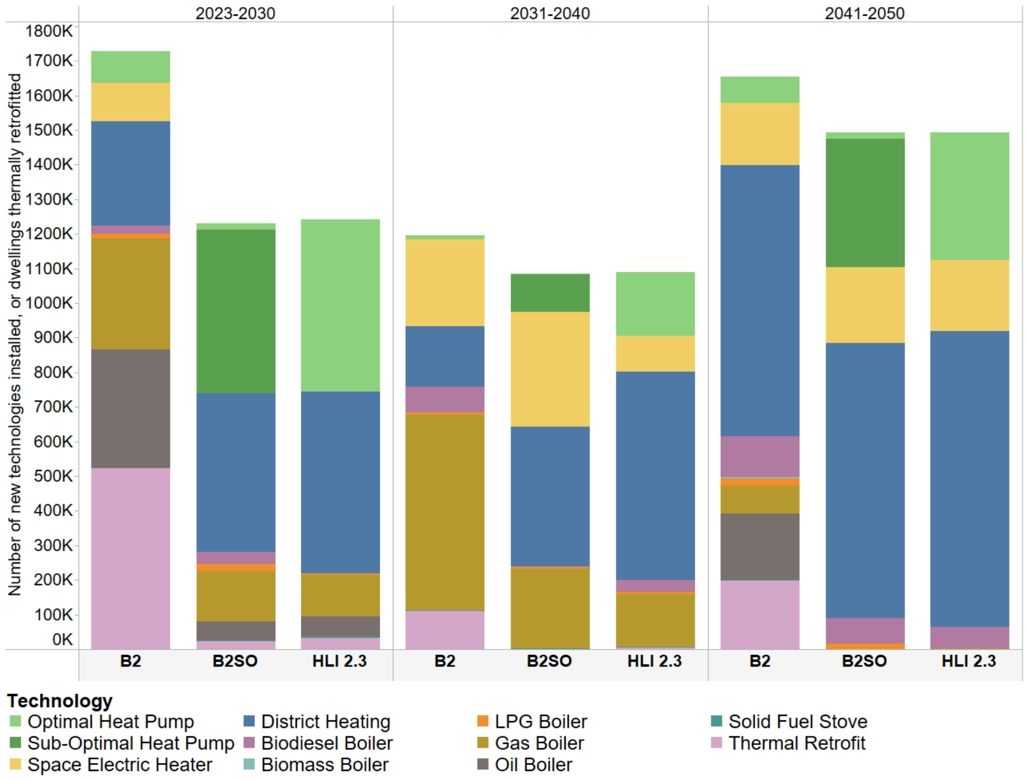


Figure 6.5: New residential heating technology and thermal retrofit evolution for selected periods in B2, B2SO, and HLI 2.3 scenarios.

In the first decade of model results (2023-2030), there are significant variations of heating technologies across the scenarios. The most cost-effective way to meet climate targets in the B2 scenario is to rapidly reduce less efficient heating systems that use coal and peat through thermal retrofitting and switching to oil boilers. While optimal heat pumps are incorporated into the B2 scenario's energy mix following the completion of necessary thermal retrofitting, the primary focus of these retrofits is to diminish the reliance on coal and peat. The B2SO scenario invests significantly in sub-optimal heat pumps, and by doing so, thermal retrofitting is not required. Additionally, the B2SO scenario displays a reduced uptake of gas boilers compared to the B2 scenario, a shift attributable to the greater availability of heating technologies, i.e. sub-optimal heat pumps. The HLI 2.3 scenario, which accommodates optimal heat pumps in dwellings with an HLI of ≤ 2.3 $W/K/m^2$, registers a higher uptake of optimal heat pumps without the need for sub-optimal heat pumps. Similar to

B2, the HLI 2.3 and B2SO scenarios also invest in oil boilers in the first decade to minimise dependence on less efficient and carbon-intensive coal and peat, ensuring alignment with the 2030 climate objectives. However, in these scenarios, investment in oil boilers gradually transitions to gas boilers in the second decade and eventually biodiesel boilers in the third decade, supported by electrification and the growth of district heating as the timeline progresses.

The results indicate that the HLI 2.3 and HLI 3 scenarios are broadly similar. There are subtle distinctions, as shown by the new technology and the thermal retrofit differences in Fig. 6.6. The HLI 3 scenario, which allows for optimal heat pumps in a dwelling with an HLI of ≤ 3 W/K/m^2, indicates a higher investment in heat pumps than in the HLI 2.3 scenario. However, the amount of additional heat pumps is 25,000 over the model's time horizon, which is a difference of approximately 2%, indicating that a higher HLI only marginally increases optimal heat pumps, suggesting that an HLI of 2.3 may be close to optimal. Furthermore, in HLI 2.3, with fewer heat pumps, 11,500 more dwellings are supplied by district heating, 6,500 more electrical heaters, 1,000 more biodiesel boilers, and 5,500 more fossil fuel boilers are required to compensate for the shortfall.

On the contrary, the HLI 2.3 scenario has 30,000 more investments in thermal retrofitting over the model's time horizon compared to HLI 3; this is front-loaded with 13,000 extra in the first two years. In the HLI 3 scenario, there are more heat pumps and fewer thermal retrofits, leading to a slight decrease (<1%) in the average marginal CO_2 emissions price compared to HLI 2.3. The details of this comparison are in Table 6.5. The projected increase in annual average sectoral marginal CO_2 emission price from 2027 to 2030, as shown in Fig. 6.12, indicates limited flexibility to lower emissions due to the lack of low-cost options and ambitious climate targets for 2030.

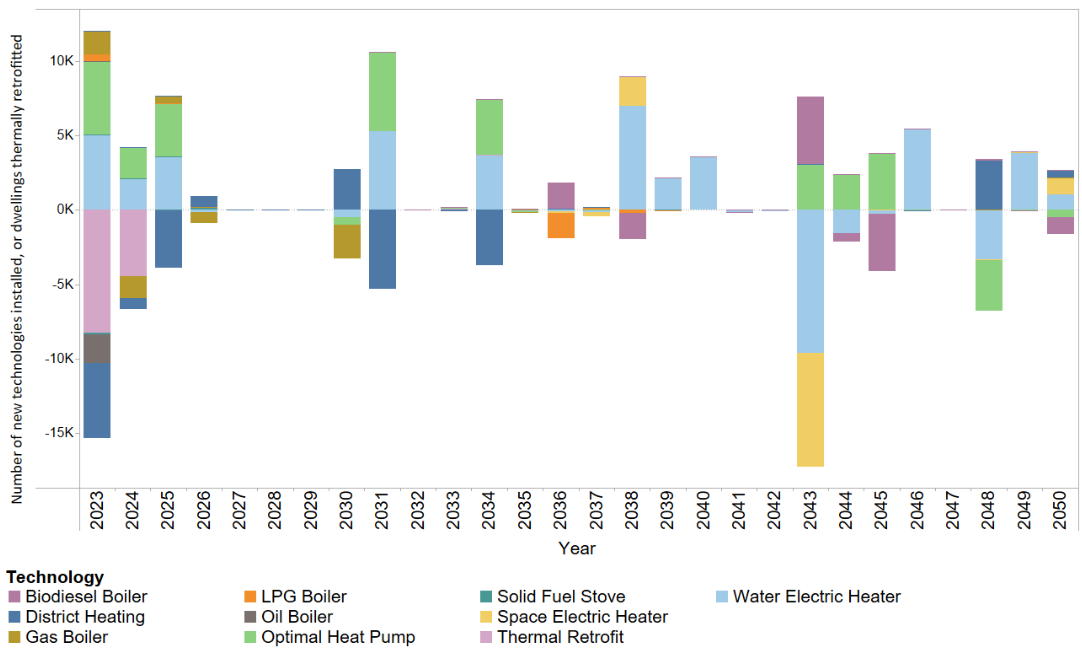


Figure 6.6: Comparison of new capacity additions in residential heating technology and thermal retrofits across HLI 2.3 and HLI 3 scenarios over the model timeline. Positive values indicate a higher new capacity in HLI 3

To examine the impact of various scenarios on energy archetypes, Fig. 6.7 presents the cumulative number of optimal and sub-optimal heat pumps and thermal retrofits over the model's time horizon for the B2, B2SO, and HLI 2.3 scenarios. The HLI 2.3 scenario strongly relies on optimal heat pumps, with a small number of F and G-rated dwellings undergoing thermal retrofitting. The B2 and B2SO scenarios similarly allocate optimal heat pumps in A & B-rated dwellings. Across the remaining energy archetypes, the B2 scenario has more optimal heat pumps than the B2SO scenario. The B2SO scenario incorporates sub-optimal heat pumps, predominantly in the higher energy-performing dwellings, such as C and D-rated dwellings, with a smaller portion appearing in lower-performing dwellings of F and G. As per constraints, no sub-optimal heat pumps are seen in B2. The HLI 2.3 scenario avoids sub-optimal heat pumps due to more dwellings suitable for optimal heat pumps without thermal retrofitting.

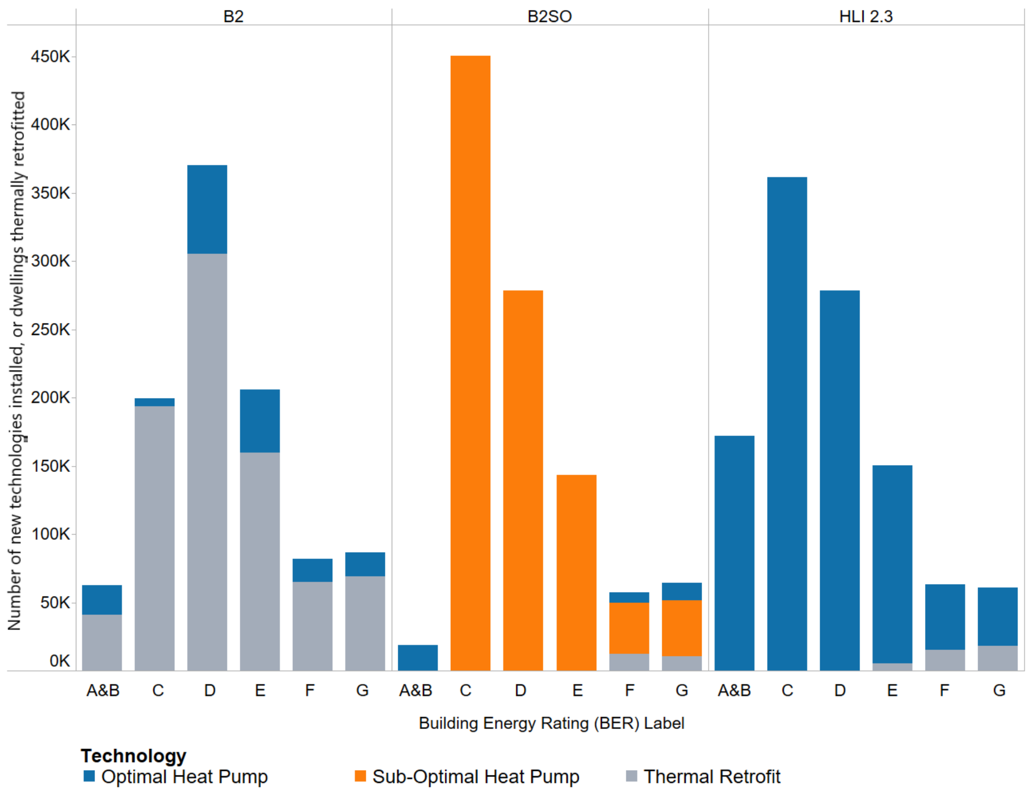


Figure 6.7: The number of new optimal and sub-optimal heat pumps and thermal retrofits in the B2, B2SO, and HLI 2.3 scenarios, broken down by BER label

The B2 scenario involves carrying out 834,000 thermal retrofits. The approach is front-loaded and focuses on coal and peat-heated dwellings. The B2SO and HLI 2.3 scenarios adopt a targeted strategy, focussing only on dwellings with E, F, and G ratings. This focused approach yields significantly fewer thermal retrofits over the time horizon, with 23,000 in B2SO and 38,000 in HLI 2.3. The results of these scenarios highlight the relationship between policy, the thermal efficiency of buildings, and the adoption of heat pumps.

6.2.2 Residential Sector

The previous section explored various heating technologies. Now, the focus shifts to understanding how heating technologies integrate within the residential sector, including examining the impact of various scenarios on the residential fuel mix and the roles played by heat pumps and thermal retrofits. This section provides a general overview of the findings. A comprehensive overview of the results from this chapter is available, detailing the variations in thermal retrofits across different building and energy cohorts for each scenario[2].

[2]https://epmg.netlify.app/HLI/results

Attached and detached dwellings with D and E BER ratings primarily undergo thermal retrofits. Less efficient F and G are also targeted for thermal retrofitting, albeit to a lesser extent because of the exponential rise in the thermal retrofit cost. However, thermal retrofits begin on the poorest thermal efficiency apartments post-2030. The results have shown variations in the number of heat pumps across different scenarios. However, the distribution of heat pumps within each type of dwelling is not uniform. The modelling indicates that district heating presents a cost-optimal solution in urban areas. Consequently, district heating is prioritised in urban settings, which typically have fewer detached dwellings. On average, in a cost-optimal pathway, approximately 68% of new heat pumps are installed in detached homes, 26% in attached homes, and 6% in apartments.

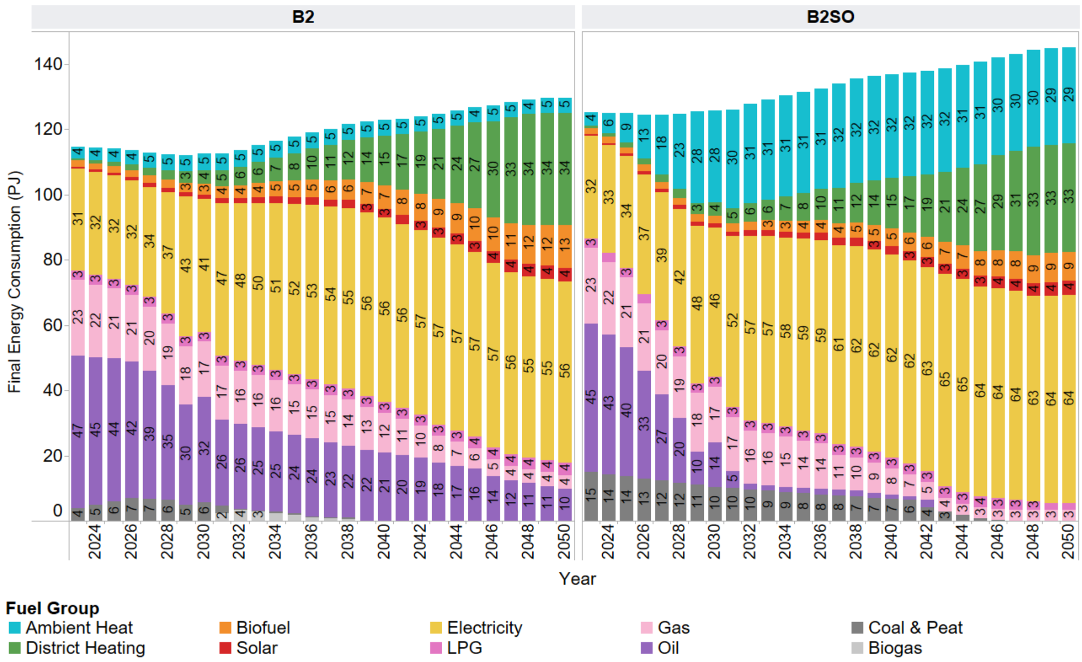


Figure 6.8: Annual residential fuel pathways in the B2 and B2SO scenarios

It should be noted that despite the constant demand for residential energy services in all scenarios, B2 consumes less fuel compared to B2SO. This is due to the significant use of thermal retrofits in B2, which reduces the final energy consumption, as illustrated through the lower stacked bar charts in B2 shown in Fig. 6.8. Although the B2SO scenario exhibits increased final energy consumption overall, a portion of this is derived from ambient heat. Ambient heat refers to the renewable energy heat pumps extract from the environment. In the results, only air-source heat pumps emerge, which absorb energy from the surrounding air, as opposed to heat pumps that utilise ground or water sources. More electricity is also consumed in B2SO due to the allowance of sub-optimal heat pumps. Compared to B2SO, B2 requires higher oil consumption in all years after 2030. B2 also requires higher consumption of other fuels such as LPG and gas. In B2SO, dependence on oil is almost entirely eliminated by 2043.

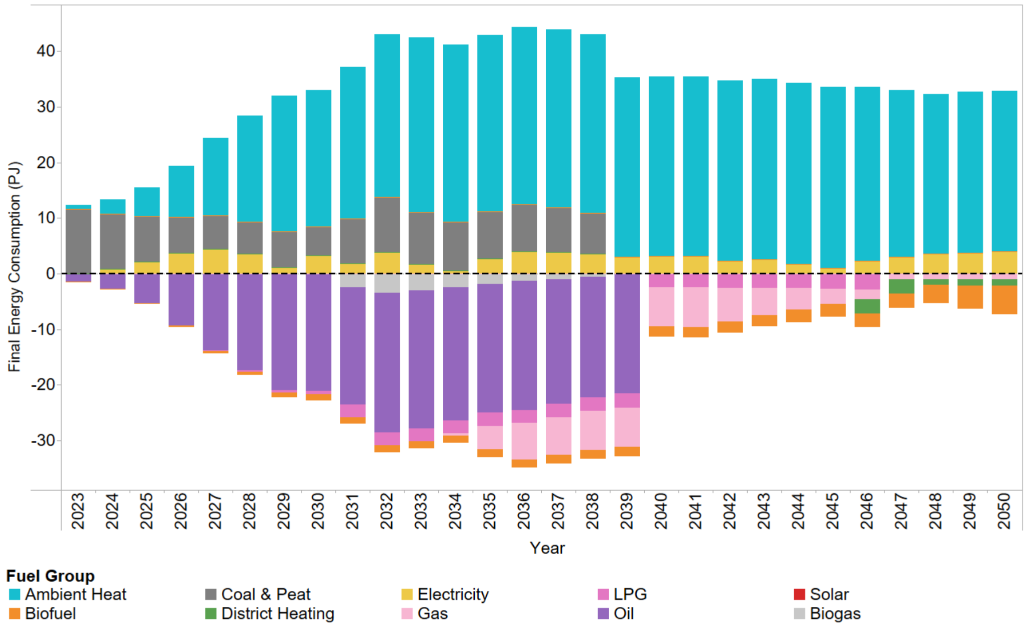


Figure 6.9: Comparison of residential final energy consumption by fuel in the B2 and HLI 2.3 scenarios: positive values indicate higher consumption in HLI 2.3, negative values indicate lower consumption in B2

A comparison between HLI 2.3 and B2 is shown in Fig. 6.9. In the HLI 2.3 scenario, the decline of coal and peat consumption is similar to the B2SO scenario, exhibiting a more gradual reduction than in the B2 scenario. Throughout the model's time horizon, HLI 2.3 registers a final energy consumption that exceeds B2 by 442 PJ. Specifically, electricity consumption in the HLI 2.3 scenario is higher by 75 PJ, and its ambient heat uptake surpasses B2 by 721 PJ. The B2 scenario records 299 PJ of oil, 69 PJ of gas, and 41 PJ of LPG consumption higher than HLI 2.3, while coal consumption is lower by 128 PJ. Despite HLI 2.3's increased dependence on coal and peat, HLI 2.3 results in financial and emission reductions. In summary, transitioning from B2 to HLI 2.3 scenario increases final energy consumption but involves replacing oil with renewable ambient heat.

The residential direct CO_2 emission pathways, which exclude electricity as it is sourced from the power sector, are illustrated for each scenario in Fig. 6.10. Again, because of the similarity to HLI 2.3, HLI 3 is omitted.

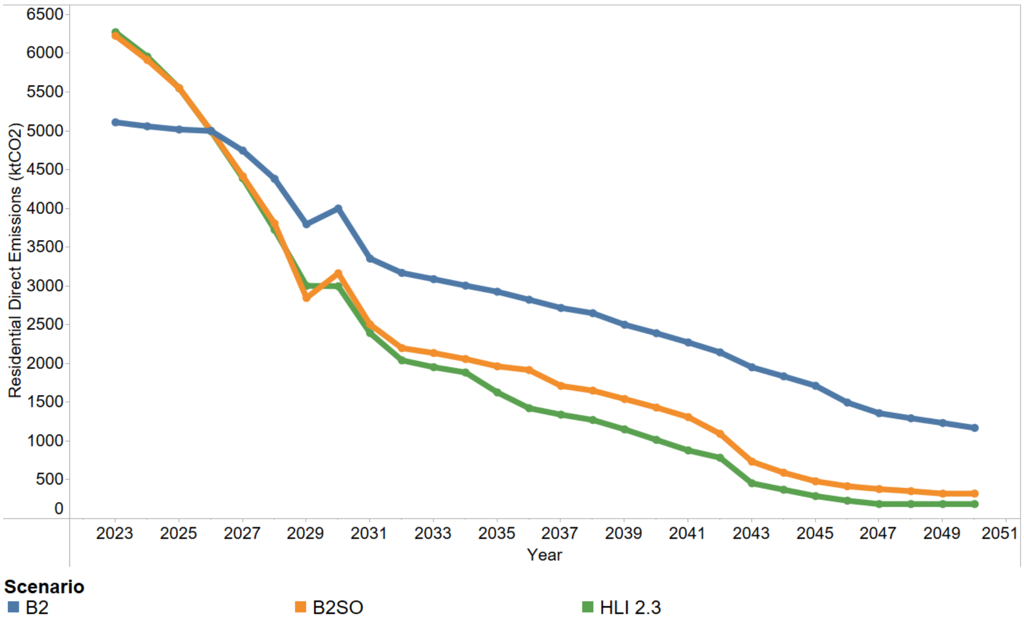


Figure 6.10: Direct CO_2 emissions from the residential sector for each scenario, with emissions from electricity treated as indirect. HLI 3 is excluded due to its similarity with HLI 2.3

The direct residential emission trajectories of HLI 2.3 and B2SO exhibit a similar trend until 2030. However, scenario B2 has a lower value of direct residential CO_2 emissions in 2023 due to the increased number of thermal retrofits, which initially resulted in reduced consumption of coal and peat, as discussed previously (Fig. 6.8). Beyond 2030, the optimal CO_2 emission trajectories diverge, leading to varying cumulative emissions, all achieving climate targets set out in Section 6.1.1. The cumulative emissions for each scenario, both up to and including 2030 and post-2030, are detailed in Table 6.4. The B2 scenario records the highest cumulative emissions, and B2SO sees a notable reduction in comparison. However, the HLI scenarios are the least emitting, as per Table 6.4 and the least expensive, as shown in Fig. 6.11.

Table 6.4: Cumulative CO_2 emissions for each scenario, both up to and including 2030 and post-2030

Scenario	$\leq$ 2030	$>$ 2030
B2	37.1 $MtCO_2$	45.1 $MtCO_2$
B2SO	36.9 $MtCO_2$	25.1 $MtCO_2$
HLI 2.3	36.9 $MtCO_2$	19.9 $MtCO_2$
HLI 3	36.9 $MtCO_2$	19.9 $MtCO_2$

6.2.3 Energy System

Fig. 6.11 shows the annualised energy system cost by sector for each scenario. The maximum and minimum annualised energy system cost per scenario in the selected years are denoted by black dashed lines.

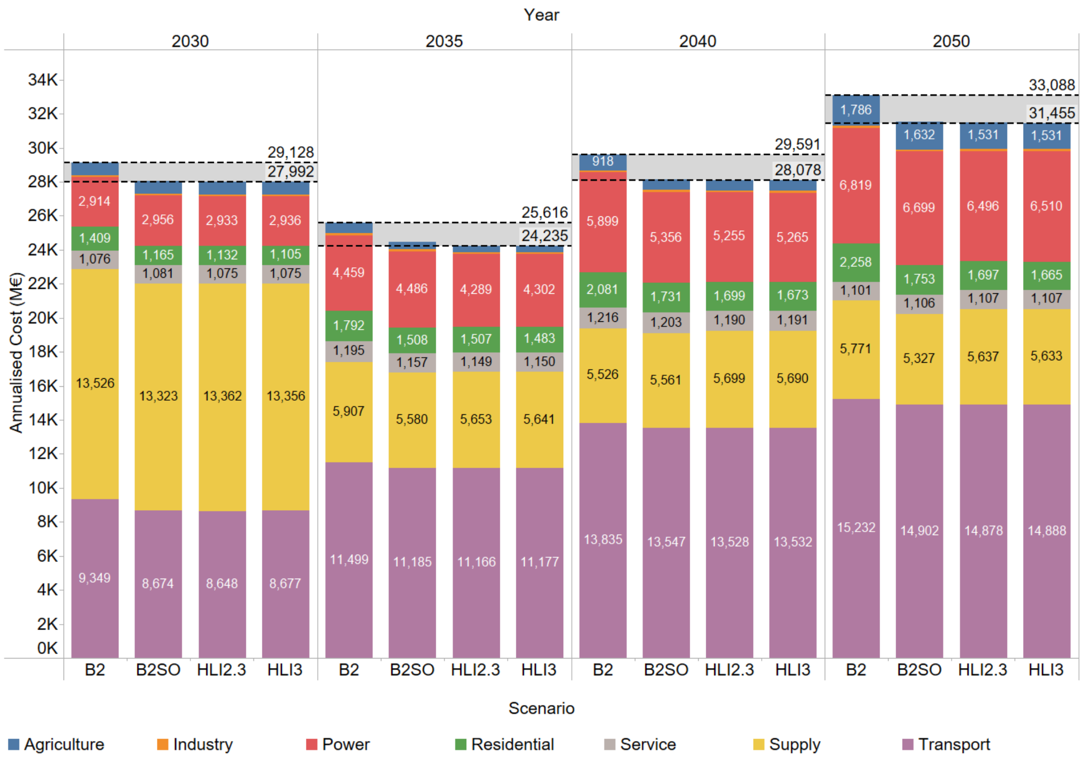


Figure 6.11: Annualised system costs by energy sector for the years 2030, 2035, 2040, and 2050, with maximum and minimum annualised energy system cost range indicated by the dashed lines.

Based on the analysis, the B2 scenario consistently shows the highest annualised energy system costs among all selected scenarios due to strict *fabric-first* constraints. The other three scenarios, B2SO, HLI 2.3, and HLI 3 have similar annualised system costs, with the B2SO scenario being slightly higher. The difference between the B2 scenario and the average of the other scenarios varies from €1.12 billion in 2030 to €1.6 billion in 2050.

In 2030, the supply sector, which includes the supply, transportation, and distribution of energy, incurs the highest annualised sectoral costs due to Ireland's dependence on fossil fuels. The transport sector has the second-highest annualised system cost up to 2030, and from 2035 it becomes the sector with the highest cost across all scenarios. By 2030, the power sector's annualised system cost ranks third highest. Heat pump constraints not only affect the residential sector but also have implications for other sectors. For example, less heat pumps are selected by the model for scenario B2 due to the stricter heat pump constraints. To ensure that climate targets are met for B2, an increase in investments in battery driven electric vehicles is observed, resulting in higher transport costs for B2 compared to other scenarios.

When evaluating the financial implications of meeting climate targets, the annualised cost encompasses overall expenses. The average sectoral marginal CO_2 emission price provides insight into the average expenditure required to abate the final tonne of CO_2 in each energy sector. Given its emphasis on the immediate expense of offsetting the subsequent emission unit, the marginal price is an instrument for informing short-term decision making. Fig. 6.12 shows the annual average sectoral marginal CO_2 emission price for each scenario over the model's time horizon.

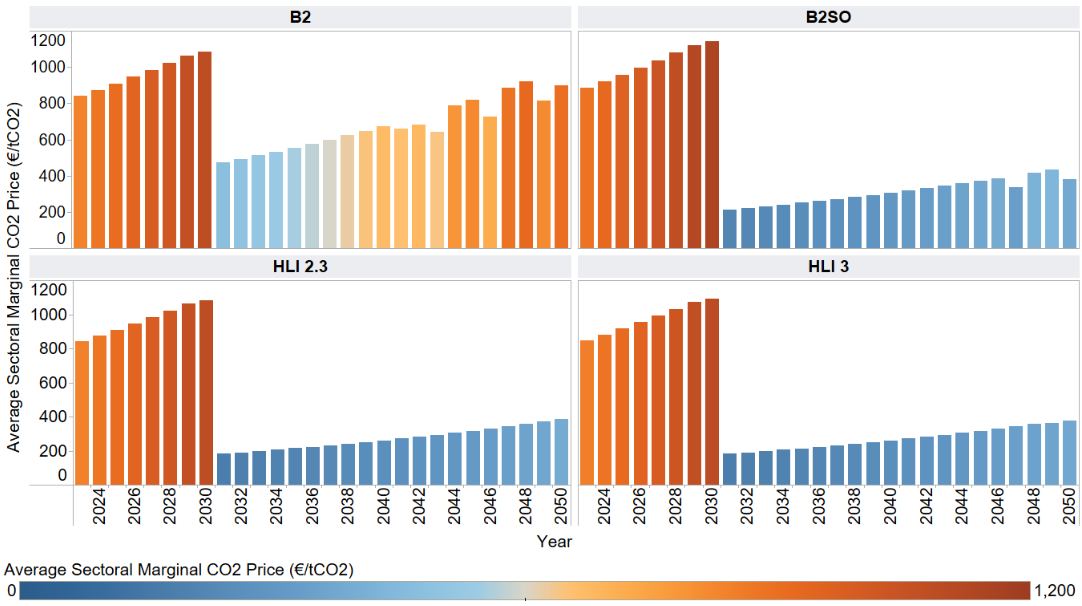


Figure 6.12: Annual average sectoral marginal CO_2 emission price for each scenario over the model's time horizon in €/tCO_2

The high average sectoral marginal CO_2 emission price consistent across all scenarios in Fig. 6.12 is caused by Ireland's ambitious carbon budgets in the period to 2030 and current high per-capita emissions [271]. Although the B2 scenario may seem aligned with other scenarios in terms of its average sectoral marginal CO_2 emission price upto 2030, a closer examination indicates that it has the lowest marginal sectoral CO_2 emission prices in services, power, and transport compared to all other scenarios[3]. However, this is counterbalanced by the high CO_2 emission price in the residential sector, explaining why the B2 average sectoral marginal CO_2 emission price is similar

[3]https://epmg.netlify.app/HLI/results

to other sectors up to 2030. After 2030, because there are fewer residential heating options available in the B2 scenario due to more stringent residential constraints, the cost to abate the final tonne of CO_2 is higher. The results are presented in terms of the average sectoral marginal CO_2 emission price to explore the overall effect of heat pumps in the broader energy system. A detailed breakdown of sectoral CO_2 emission prices is available online[3].

Based on the information presented in Fig. 6.12, Table 6.5 presents the mean of the average sectoral marginal CO_2 emission prices for two periods: up to and including 2030, and post-2030. Up to 2030, the mean price is €981 ± 4% /tCO_2, with minimal variation between scenarios. Post-2030, there is a reduction in the mean price as a result of the eased climate targets, and there is a much larger variation between B2 and the other scenarios, with a mean value of €383 ± 76%/tCO_2. HLI 3 carries a higher risk of energy poverty due to heat pump performance uncertainty despite having a slightly lower mean price than HLI 2.3. As per the B2SO scenario, allowing sub-optimal heat pumps could significantly reduce costs post-2030 compared to the policy-driven B2 scenario. Across all scenarios, the cost benefits of relaxing heat pump constraints are only realised post-2030.

Table 6.5: Average sectoral marginal CO_2 emission prices up to and including 2030 and post-2030.

Scenario	≤ 2030	> 2030
B2	€/966 tCO_2	€/675 tCO_2
B2SO	€/1018 tCO_2	€/312 tCO_2
HLI 2.3	€/966 tCO_2	€/273 tCO_2
HLI 3	€/974 tCO_2	€/271 tCO_2

6.3 Discussion

This thesis primarily focuses on the techno-economics of the energy transition and optimises for the lowest overall system cost. The interplay between the residential sector and the wider energy system is evident from the results, emphasising the significance of a systems approach for mapping future energy transitions and associated trade-offs.

Ireland has adopted a *fabric-first* policy to reduce energy bills, improve thermal comfort, and reduce the need for high heat pump commissioning standards. This policy is beneficial to both the suppliers and the households. However, from a national energy system perspective, the strictness and rigidity of Ireland's *fabric-first* approach add barriers and is not cost-effective as it increases the overall cost compared to alternative scenarios explored in this study.

Our results show that implementing an HLI threshold of 2.3 W/K/m^2 can significantly reduce energy system costs compared to the current *fabric-first* approach. However, raising the HLI threshold from 2.3 to 3 W/K/m2 does not significantly reduce energy system costs. On the contrary, it may result in higher household energy bills. Therefore, an HLI threshold of 2.3 W/K/m^2 is recommended to provide low energy poverty risk at high energy system cost savings. The HLI scenarios result in lower overall costs and emissions than both B2SO and B2 scenarios without the need for investment in sub-optimal heat pumps.

6.3.1 Strengths

TIM excels in identifying the most cost-effective technological pathways for decarbonising Ireland's energy system. This capability stems from integrating the latest decarbonisation targets and covering the entire energy system. Utilising the most recent data from the SEAI, the chapter evaluates the efficiency of heat pumps and updates techno-economic assumptions. Additionally, ongoing pilot programs offer valuable data for refining future iterations of TIM. The study's scenario development provides insights, as it directly compares financial and technological pathways between hypothetical scenarios and the current policy scenario.

Residential energy consumption is accurately represented across the building archetypes and BER labels by calibrating the EPC database and accounting for district heating. The calibration incorporates internal temperature adjustments based on empirical data to consider socio-economic factors [46]. This study is founded on the recent work, which includes district heating in an Irish ESOM for the first time [180].

This study is novel by including heat pump performance in residences with varying HLI profiles, addressing a significant knowledge gap in research, and using Ireland as a case study. FAIR scientific [258] research principles are adhered to, emphasising transparency and reproducibility.

6.3.2 Limitations

It is important to note that the model has a perfect foresight assumption, which assumes that every individual is cost-rational and has complete knowledge of current and future techno-economic factors. This assumption deviates from reality and should be carefully considered during the analysis of the results [151, 272]. To bridge the gap between the model and reality, households must be better informed about heat pumps and whether their dwellings are suitable for installation [273]. The volatility of energy prices, influenced by various unpredictable variables, also makes it difficult to achieve such foresight.

The model finds the cost-optimal solutions for the overall energy system and not for individual households. This could be a challenge for households that face financial barriers. Additionally, the model does not consider the profit margins of energy producers, which is significant given that Ireland's household electricity pre-tax costs are among the highest in the EU-27 [49] despite having a substantial share of renewables on the electric grid.

The dependency of this study on Ireland's open-source EPC database to collect HLI data for dwellings results in a number of key limitations. Primarily, the database's tendency to rely on default values can fail to reflect the distinct characteristics of each dwelling accurately [40]. The existence of an 'energy performance gap'—the difference between expected and actual primary energy use—additionally undermines the data's dependability [37, 46]. The method employed to compute HLC or HTC, crucial for determining HLI, is fraught with uncertainties. A study on building fabric performance gaps revealed that the measured HLI was, on average, 10% higher than the calculated HLI [267]. These uncertainties stem from various factors, including solar radiation fluctuations, temperature variances inside and outside the building, material heat retention capabilities, changing infiltration rates, and moisture [266, 267]. Such factors significantly complicate accurately measuring a dwelling's heat loss or gain, presenting substantial challenges in accurately assessing energy performance.

The model's design overlooks the building capacity among current contractors and other industry stakeholders. Additionally, the model fails to consider the financial implications of transitioning households from single to three-phase power supplies, which can incur additional costs when adopting heat pumps. The study assumes all dwellings have wet central heating systems with radiators as heat emitters.

Achieving the optimal pathways outlined in this thesis entails households being fully aware of their dwelling's energy use and their heating technology options. Furthermore, the thesis does not account for the profits of energy suppliers, necessitating electricity price regulation to achieve optimal decarbonisation pathways.

6.4 Conclusion

This research introduces a novel methodology by integrating the latest data on heat pump performance, which is influenced by building heat loss, into an energy system model. Analysis of how this affects energy system cost-optimal decarbonisation pathways has not been widely studied in the existing literature. Particularly in Ireland, this research gap holds significance due to the commitment to a stringent *fabric-first*approach, propelled by challenges of dwelling thermal inefficiency, elevated electricity costs, and escalating energy poverty. The results reveal that the current fabric-first methodology, replicated by the B2 scenario, is not cost-optimal compared to the other scenarios developed.

The B2 scenario aims to reduce carbon emissions but is limited by the current fabric-first approach. This approach allows optimal heat pumps to be installed in 23.5% of dwellings without thermal retrofitting. The HLI 2.3 and 3 scenarios allow optimal heat pumps to be installed without a thermal retrofit in 41.4% and 72.2% of dwellings, respectively. The B2 scenario, while incorporating an increasing share of district heating and electricity, is unique in that it also involves the immediate retrofitting of coal and peat-heated dwellings. However, this shift is offset by a continued reliance on oil heating in the future. This complex transition underscores the need for other sectors to step up their efforts and reduce their emissions in order to achieve the ambitious goal of net-zero.

The alternative B2SO pathway depicted in Fig. 6.8 demonstrates that including sub-optimal heat pumps raises the proportion of ambient heat and supports a more feasible continued reduction of all fossil fuel heating. Despite this, the number of thermal retrofits is low, focusing primarily on thermally inefficient dwellings. The HLI 2.3 scenario, illustrated in Fig. 6.9, is similar in fuel mix to the B2SO, where more ambient heat is observed to replace oil heating. However, the heat pumps are considered to perform at optimal levels as the heat loss is still low in HLIs below 2.3. The HLI 3 scenario does not result in much change compared to the HLI 2.3 scenario. The results of all scenarios indicate that phasing out inefficient and high carbon-intensity coal and peat are crucial to achieving climate targets.

Our findings illustrate that the optimal heat pump HLI threshold influences the overall cost of the system. However, the cost benefits of relaxing heat pump constraints are only realised post-2030 across all scenarios. Over the model horizon, as shown in Fig. 6.11, the cumulative system costs for B2, B2SO, HLI 2.3, and HLI 3 are €404 billion, €391 billion, €389.7 billion, and €389.5 billion, respectively. The average sectoral marginal CO_2 emission prices, shown in Fig. 6.12, not only act as a barometer for the expense of mitigating additional CO_2 but also provide critical insights into the 2030 climate target's aspirations. All scenarios highlight similarities in solar, electricity, and district heating in the residential fuel mix, making them robust options due to their prioritisation in cost-optimal pathways. The inclusion of district heating and its reliance on high energy density demand areas highlights the significance of spatial energy planning.

Despite expectations of lower electricity prices due to increased renewables [54], Ireland consistently faces some of Europe's highest pre-tax domestic electricity prices [49]. The model assumes non-profit operation by electricity providers, akin to district heating companies, offering a unique insight into the potential role of profit regulation to encourage heat pump adoption and provide energy cost assurances.

It is essential to acknowledge a substantial knowledge gap: homeowners often need more information on the suitability of their dwellings for heat pumps. There is no universally accepted *heat pump readiness* indicator. Although specific research initiatives are exploring the concept of *heat pump readiness* [170], addressing this knowledge gap is imperative to enable homeowners to make decisions. The need for a heat pump readiness analysis at the international level is evident in understanding what makes a dwelling heat pump ready and how this compares nationally. Future research should thus examine country-specific policies to enhance the understanding of heat pump readiness and better inform policy and homeowner decision-making.

The thesis suggests that thermal retrofits contribute more significantly when fewer heating options are available; those thermal retrofits focus on the dwellings with the highest emissions, i.e. peat and coal heated dwellings. The *fabric-first* approach is an option to reduce energy poverty by lowering energy consumption and protecting against fluctuations in energy costs and the risk of low-quality heat pump installation. Although the current *fabric-first* approach has its benefits, it is not cost-optimal. Various levels of commitment to the *fabric-first* approach have been explored to balance its benefits against the associated costs.

This study focuses on optimising the techno-economics of the *fabric-first* approach, but it is worth noting that equal importance should be given to *energy sufficiency*, which refers to meeting the basic energy needs of people while also respecting ecological limits [274]. Energy sufficiency measures can have a lsignificant effect and can even extend beyond the confines of construction or building renovation [244]. These measures involve more than just reducing energy usage, encompassing behaviour change, with the potential for a more profound societal impact. Energy sufficiency initiatives also promise to address social equality concerns and serve as a highly effective means to mitigate marginal CO_2 prices.

In summary, this study examines the consequences of various technological and policy scenarios within the residential sector and the wider energy system. The findings emphasise the importance of adopting an energy system approach to energy planning and spatial policy design that combines economic viability and environmental sustainability. Although the insight shows that heat pumps could play a pivotal role in decarbonisation, regulating residential electricity prices and providing households with the necessary details to make informed choices is essential to realise the cost-optimal pathways. In order to broaden the scope of this study, it is crucial to incorporate all types of buildings, including commercial and public buildings, which are currently lacking in transparency and detail. Subsequent research should conduct a comprehensive evaluation of these non-residential buildings to gain a more complete understanding.

Chapter 7

Conclusions

Throughout this thesis, I have explored and improved the residential sector of the Irish TIMES energy system optimisation model. Specifically, I have updated the residential sector methodology to reflect residential energy consumption more accurately and to account for temperature variation among dwellings, which better reflects the impacts of thermal retrofitting. Building on this new methodology, I have incorporated district heating to investigate its effects on the built environment and the entire energy system. With this enhanced methodology and district heating representation, I explored the *fabric-first* policy approach and provided evidence-based policy analysis for Ireland's energy system's cost-optimal decarbonisation pathway.

Ireland's ambitious climate targets make it necessary to rapidly decarbonise residential heating in all explored scenarios. The thesis highlights that thermal retrofitting is predominantly adopted in scenarios characterised by ambitious climate targets, especially where a high level of thermal efficiency is a prerequisite for using electricity heat pumps and where alternative heating options are limited. In such contexts, thermal retrofitting is mainly implemented in coal and peat-heated dwellings. However, the adoption of thermal retrofitting in achieving cost-optimal residential decarbonisation is more limited when a broader array of heating technologies, such as district heating or sub-optimal heat pumps, is available. This limitation is primarily due to the high costs of CO_2 abatement associated with thermal retrofits, which are further exacerbated by rebound effects. The thesis also highlights the cost-effectiveness of using surplus heat for district heating, which leads to insights into regional energy system planning. The success of electricity decarbonisation and its continuation means that electricity is the cornerstone of residential decarbonisation, among other sectors. The combination of insights has led to a triad solution that includes thermal retrofitting, district heating, and individual heat pumps to reach climate targets cost-optimally. While each peer-reviewed chapter has unique conclusions, this chapter merges all the findings and addresses the six research questions in detail. I also discuss how this thesis has improved energy system modelling and offers policy insights and future research directions.

This thesis presents a novel approach by evaluating the techno-economic aspects of energy systems within the Irish residential sector. It uses a newly developed least-cost energy system model that approximates real-world scenarios. While the direct impacts of energy policy—namely energy and emissions metrics—are examined, this thesis recognises that the broader economic [13, 17], social [14, 275, 276], and health [222, 277] implications merit further attention. Although these aspects extend beyond the current scope of the thesis, incorporating the least cost decarbonisation roadmap can assist in maximising broader benefits. These aspects represent crucial areas for future research, particularly through model soft-linking, which enhances policy insights. For instance, a fabric-first approach can facilitate energy savings, improve residents' health and quality of life, and stimulate economic growth by creating jobs in the construction, manufacturing, maintenance and renovation sectors [23]. Integrating these externalities with traditional energy and carbon metrics is essential for a comprehensive assessment of policy efficacy.

7.1 Research Questions

How do future technology developments affect Ireland's strategy for setting cost-optimal GHG targets in the residential sector?

Chapters 4 and 5 contain valuable insights into how future technological advancements can enable Ireland to establish cost-effective GHG targets in the residential sector. Chapter 4 demonstrates that biodiesel consumption is projected to increase to 3 PJ annually after 2030, which will suffice to cater to the space and water heating needs of over 100,000 households. The demand for heat pumps will continue to increase until 2040, after which the net-zero emissions in the power generation sector will influence the growth of heat pumps. The results indicate that adopting resistive electric heating becomes cost-optimal after 2040 and aligns with net-zero objectives due to low or negative CO_2 emissions. However, the study notes limitations: it does not account for challenges such as electricity distribution costs, peak electricity costs, or profits earned by electricity suppliers. Nevertheless, the study highlights that resistive electric heaters are increasingly viable in a cost-optimal pathway, especially in thermally inefficient dwellings unsuited for electric heat pumps. This insight differs from the SEAI heat study [127] and other European studies [187] suggesting discontinuing inefficient electric heating. Other studies have also recognised the significance of integrating non-heat pump electric heating into cost-optimised pathways, especially when combined with energy storage and the utilisation of surplus electricity [83]. Therefore, resistive electric heating could provide a cost-effective residential decarbonisation solution in the long term.

Chapter 5 highlights the potential of district heating in Ireland, where the utilisation of surplus heat could significantly reduce heating costs. This aligns with other European studies considering DH a low-cost decarbonisation option in urban areas [104, 108]. The findings indicate that DH can meet 26% of residential and 20% of service sector heating demands in Ireland with the optimal 90% connection rate. This is the first time DH has been incorporated directly into an ESOM for Ireland. These technological advancements, coupled with the immediate urgency of meeting 2030 climate targets and the post-2040 landscape of negative electricity emissions, mark a transformative phase in Ireland's residential sector.

How does using empirical internal temperature data, adjusted for energy-efficient dwellings, influence the optimal decarbonisation pathway compared to relying on EPC database defaults?

Chapter 4 highlights that the reliance on the EPC database for shaping Ireland's decarbonisation pathway warrants caution, especially considering its tendency to overestimate Irish residential energy consumption [38, 46, 100], a similar result found across European studies [33–36]. The EPC temperature scenario anticipates much higher reductions in residential final energy from 2018 to 2030 (29%), compared to the temperature-adjusted scenario (13% reduction only), which utilises empirical internal temperature data adjusted for energy-efficient dwellings. This is because thermally inefficient dwellings have lower internal temperatures than assumed in the EPC database, whereas thermally efficient dwellings have higher internal temperatures than considered in the EPC database calculations [37]. The temperature-adjusted scenario offers a more accurate reflection of actual current energy usage patterns and potential energy reductions. By comparing the two scenarios, it becomes clear that the expected EPC energy savings from thermal retrofitting are overestimated because they do not account for empirical internal temperatures. The default temperature scenario suggests that 647,000 dwellings should undergo thermal retrofits, resulting in an energy saving of 109 PJ by 2030. However, in the temperature-adjusted scenario, where 607,000 dwellings should undergo thermal retrofits, only 51 PJ of energy are saved because of the rebound effect [151], which has been widely researched but is not often captured in ESOMs [278].

What role can District Heating play in Ireland's fuel mix to achieve cost-optimal heat decarbonisation?

Chapter 5's examination of DH highlights its crucial role as a complementary solution to electrification in Ireland's built environment decarbonisation plan. By harnessing surplus heat [108, 109, 141] to supply DH, Ireland could reduce average sectoral marginal CO_2 emission prices by 13% to 25%, depending on the connection rate and growth constraints. Studies in Ireland [103] and other European countries [119, 136, 228, 279, 280] have demonstrated similar results. The analysis suggests that DH could satisfy up to 26% of the heating needs in the residential sector and 20% in the service sector with a 90% connection rate. DH offers several benefits beyond heat decarbonisation, including alleviating energy poverty, improving energy security, and freeing the electricity supply to enable cost savings in other sectors. Therefore, DH is fundamental in achieving a more cost-effective energy system decarbonisation pathway in Ireland. However, establishing spatial energy policies, regulations, and financial support for implementing DH will be necessary to achieve optimal decarbonisation.

At what connection rate does district heating become cost-effective?

DH connections are necessary in designated zones to ensure feasibility [111]. Chapter 5 of this thesis examined the impact of varying DH connection rates (30%, 50%, and 90%) on decarbonisation pathways. As with previous research [120, 281, 282], the study shows that lower connection rates prioritise buildings in high heat density areas, resulting in shorter pipelines per heat unit sold. On the other hand, higher connection rates lead to longer distribution pipelines but increased heat capacity. The marginal distribution costs (C_d in €$/GJ$) reflect the investment cost associated with specific connection rates. The research indicates that a connection rate of at least 30% is economically viable, as market saturation is achieved at all rates above this threshold. However, the optimal connection rate is 90%, highlighting the need for spatial energy system planning to expedite the implementation of DH in viable regions.

Does Ireland's existing *fabric-first* approach align with the cost-optimal pathway for achieving residential decarbonisation?

Chapter 6 shows that Ireland's current *fabric-first* approach to residential decarbonisation is not aligned with cost-effective strategies. The current stringent approach [54], requiring a BER of B2 or equivalent, contrasts with alternative pathways that allow for variations in optimal heat pump thresholds based on HLI levels and/or use *sub-optimal* heat pumps. While beneficial in enhancing thermal comfort and reducing heat loss, the *fabric-first* approach results in elevated costs post-2030, with an average sectoral marginal CO_2 emission price of €675 per tCO_2 [152, 153]. The alternative pathways explored in this thesis incorporate flexible heat pump thresholds based on HLI levels and allow sub-optimal heat pumps. The adoption of these sub-optimal heat pumps could bring down the CO_2 emission price to €312 per tCO_2, with potential further reductions to €273 per tCO_2 through HLI threshold adjustments [146, 147]. These findings highlight the need for Ireland to reassess its fabric-first approach by accounting for the latest research, which suggests minimal improvements in fabric efficiency are cost-optimal [166–168]. The new approach could better align with known heat pump performance [126], comparative European standards [54, 169] and address competing labour in the housing crisis [55].

How does the Heat Loss Indicator threshold for optimal heat pump performance affect optimal residential decarbonisation pathways?

The HLI threshold is a guiding metric in allocating household heat pump subsidies. At present, the threshold stands at $\leq 2\ W/K/m^2$ or $\leq 2.3\ W/K/m^2$, with restrictions pertaining to maximum U-values for walls, roofs, windows, and infiltration rates. Recent research has shed light on the efficient operation of heat pumps in less thermally insulated dwellings [155], indicating that there is room for flexibility in the HLI threshold [54]. Chapter 4 shows that raising the HLI could accelerate the adoption of heat pumps, expediting the decarbonisation of the residential sector. The results show that adjusting the HLI thresholds to ≤ 2.3 and ≤ 3 W/K/m^2 with no further fabric conditions can reduce cumulative energy system cost by 28.2 to 28.3% compared to current practices. Despite not aligning with current installation guidelines [152, 153], adjusting the HLI threshold to $\leq 2.3\ W/K/m^2$ with no other conditions is a low risk [54, 169] with substantial energy system cost savings. Minimal cost differences exist between the scenarios with HLIs of 2.3 and 3 $W/K/m^2$. Further pilot test projects and empirical data collection are necessary to investigate the performance of heat pumps in dwellings with varying HLI to better inform energy system modelling.

7.2 Contribution of Thesis & Insights for Policymakers

The research has contributed to advancing the open-source TIMES Ireland Model (TIM) methodology and insights, specifically in the residential sector. The thesis offers a framework that can be utilised to refine other national models. The findings offer critical insights into the interplay between built environment energy dynamics and the broader energy system, that could facilitate more informed climate policy decisions. The results offer overarching insights into the whole energy system instead of absolute answers, emphasising that energy modelling leans more towards an art rooted in scientific principles than a scientific discipline.

The research in this thesis was funded by the CAPACITY (Climate Action Pathways & Absorptive Capacity) project, which is led by the Department of Environment, Climate, and Communications and aims to deepen understanding of decarbonisation strategies. This research is a foundation for evidence-based climate policy and has played a role in formulating carbon budgets and developing sectoral ceiling limits, influencing critical governmental discussions [193]. The following key policy insights were derived from my research.

1. **Spatial Energy System Planning**

   Enhancing cost-optimal pathways for decarbonising energy systems requires a regional energy system policy and planning approach. National residential energy policies fail to account for geographical and inter-sectoral dynamics. The limitation of the current national residential planning focus becomes particularly evident when examining patterns such as the high uptake of heat pump subsidies in Dublin, a city with significant district heating potential [112]. Regional planning would identify areas suitable for specific heating technologies, helping to prioritise subsidies and investment in a region-specific approach. For example, limiting heat pump subsidies in cities with high district heating potential could lead to a more cost-effective pathway for residential decarbonisation. In other regions where district heating is less feasible, thermal retrofitting and heat pumps may be a more viable and appropriate energy solution. Spatial energy system planning could also support identifying and optimising other region-specific energy sources, such as geothermal and wind energy, and demands, such as transport and industry.

2. **Strategic Thermal Retrofitting**

   Thermal retrofitting is costly to abate CO_2 emissions, especially when accounting for the rebound effect. My findings challenge the conventional approach of extensive thermal retrofitting and suggest focusing on strategically thermal retrofitting the most inefficient dwellings to a high standard. Addressing immediate, cost-effective solutions such as loft insulation and draft-proofing can offer significant benefits at low investment, aligning with optimal decarbonisation [166–168]. Implementing a stepped policy approach to gradually increase the minimum BER to a moderate standard, similar to the approach adopted by other countries, can result in more significant co-benefits and prove to be more cost-effective and socially equitable than setting ambitious targets for thermal retrofitting in terms of both quantity and quality.

3. **Reevaluating the Heat Pump Subsidy Threshold**

   It is necessary to reassess the heat pump subsidy thresholds to better align the energy system transition with cost-optimal decarbonisation pathways. My research, based on the latest heat pump performance data [126], shows that Ireland's current *fabric-first* approach limits flexibility in decarbonisation pathways and is not cost-effective. Adjusting the HLI threshold upwards could lead to significant energy system cost savings, thereby optimising the integration and effectiveness of heat pumps in Ireland's journey towards sustainable energy.

7.3 Future work

As energy system modelling is an ongoing process, approaches must be continually updated to account for current energy system planning and policy complexities. It becomes increasingly clear that the path to optimal decarbonisation is multifaceted and continuously evolving, requiring ongoing investigation. In this section, I present potential directions for future research.

1. **Empirical Household Energy Data**

This thesis highlights the importance of utilising real-world household energy data. Although it can pose some challenges, obtaining this data is critical to achieving more accurate and reliable insights in energy system modelling. While the EPC serves as a crucial technical data source, it was never designed for research purposes and tends to overestimate national energy consumption. Through my research, it became clear that incorporating empirical data into the model leads to significant changes in insights into the residential energy sector. More robust and realistic optimisation pathways are identified with improved empirical data by analysing household energy consumption across different dwelling archetypes, EPC ratings, and regions. Accurately reflecting internal temperature variations is crucial for informed policy-making and anticipating the outcomes of retrofitting initiatives and energy consumption trends.

2. **Spatial Resolution** is a pivotal component in advancing the capabilities of the TIM model. Currently, TIM's capacity spans from analysing a single region to multiple regions, capturing data across Ireland's 26 county municipalities. This breadth, though significant, can be deepened to derive even more insights. Rather than merely increasing the number of regions, a move that might exponentially increase the complexity of the TIM model, a more strategic enhancement lies in its integration with a GIS. Combining TIM with GIS could provide valuable insights for geographically sensitive technologies, such as wind energy or district heating, permitting a richer, layered understanding of spatial data. Several existing GIS resources offer promising platforms for such integration, such as the Irish Heat Atlas [141], CSO[1], and SEAI[2]. These GIS platforms cover many databases, such as EPC ratings, bioenergy, district heating, geothermal, heat demand, hydropower, wind and solar. Utilising these resources, future versions of TIM could provide an unparalleled level of valuable spatial information for future decarbonisation pathway optimisation.

3. **Soft-Linking of Models** for future work is essential to broadening the scope of the thesis. The residential sector in the TIM was designed alongside the LEAP to ensure structural compatibility, facilitating easier integration in future research. By using LEAP simulation outputs as inputs for the TIMES optimisation model, and vice versa, the granularity and accuracy of energy system analysis can be enhanced. However, it is important to note that this integration can be challenging and may have limitations, especially when incorporating outputs from infrastructure simulation models like PLEXOS,

[1]https://visual.cso.ie/?body=entity/ima/cop/2022
[2]https://www.seai.ie/technologies/seai-maps/

which offer valuable forecasts on future gas and electricity prices. Despite these potential challenges, such a layered analytical approach is vital to fortifying the robustness of insights into Ireland's energy decarbonisation pathway. Additionally, extending soft-linking beyond energy metrics to economic, social and health metrics is essential for a comprehensive assessment of policy efficacy. Integrating TIM with other established Irish non-energy models, such as the Ireland Environment, Energy and Economy (I3E) macroeconomic model [283], already incorporated in some Irish energy modelling [249], will further improve policy insights.

4. **Effective Stakeholder Engagement**, from consumers to policymakers, is crucial for enhancing understanding of household energy decisions and socio-economic factors. This engagement helps bridge the gap between theoretical modelling and practical implementation. Policymakers can develop effective policies by integrating data-driven insights into public perception and household-specific factors, such as occupancy behaviour and internal temperatures. Refining model constraints by understanding different perspectives helps ensure that models accurately reflect energy usage and align with real-world needs.

5. **Energy Storage** is on the rise as renewable sources continue to expand their capacity. While these sources are environmentally friendly, they also introduce variability into the energy supply, making it necessary to improve and expand energy storage capabilities. The peak demand and overall energy system costs could be reduced by integrating energy storage in the power generation and residential sectors. Although the current temporal resolution in TIM is sufficient, it is crucial to account for storage solutions in the model.

6. **Energy Sufficiency** is gaining prominence in energy system optimisation modelling due to its minimal investment requirements and mitigation potential. Unlike vehicles, which face higher taxes with size increases, Ireland's housing policies currently impose no penalties for expanding dwelling size, and 71.4% of the Irish population are considered to live in dwellings that are too large [62]. The considerable promise shown by TIM in the realm of energy sufficiency [244] merits a more profound investigation.

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Appendix A

Appendices

A.1 The role of carbon budgets in translating the Paris Agreement into national climate policy: Discussion Paper

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The role of carbon budgets in translating the Paris Agreement into national climate policy

Discussion Paper

Jason Mc Guire, Fionn Rogan, Hannah Daly, James Glynn, Olexandr Balyk and Brian Ó Gallachóir

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Key Messages

- A Global Carbon Budget is the total estimated cumulative CO2 that the world can emit while staying within a certain global temperature target, e.g. 1.5C, 2C
- To align national climate ambition with both Article 2 (1.5C & 2C temperature target) and Article 4 (carbon neutrality by 2050) of the Paris Agreement, countries can develop a national carbon budget consistent with a Global Carbon Budget, based on an "effort sharing methodology"
- On its own, a net-zero emission target (e.g. in 2050) may not align with a Global Carbon Budget
- For governance purposes, national carbon budgets can be sub-divided into time periods (e.g. 5 years) and allocated to sectors (e.g. transport, buildings, public sector, etc.). This allocation process needs to be analytically robust, transparent, and involve wide stakeholder consultation
- In this document, we propose an approach to building a national carbon budget for Ireland based on this framework, compare with international experience and discuss open issues.

Executive Summary

Two articles of the Paris Agreement are particularly relevant to countries as they seek to mitigate their impact on global warming. Article 2 sets a target for long-term temperature stabilisation, seeking to hold the increase in global average temperature to "well below 2 °C above pre-industrial levels, while pursuing efforts to limit the temperature increase to 1.5 °C". Article 4 includes a target to "peak greenhouse gases (GHGs) as soon as possible" and thereafter to achieve "rapid reductions" in emissions so that sources of emissions are balanced by sinks (i.e. achieving net zero emissions) in the second half of the 21st century. Despite the ratification of the Paris Agreement, there is no political or scientific consensus on precisely how these targets should be translated into national decarbonisation trajectories. As a result, countries are developing and setting their own carbon reduction strategies in different ways: increasingly, countries are implementing net-zero targets for mid-century. Although consistent with Article 4, given the linear relationship between warming and cumulative net emissions of long-lived GHGs, net-zero target dates only specify when temperatures are stabilised, but not at what temperature. To comply with Paris Agreement temperature goals, international and national climate action policy must have regard to cumulative reductions in GHG emissions, not just single year targets. Broadly, this requires a carbon budget approach.

In this discussion paper we review some of the ways that a carbon budget approach has been used in climate action policy. One approach is based on developing a so-called Climate Science Carbon Budget derived from a Global Carbon Budget (GCB) associated with a particular temperature goal and an equitable effort-sharing approach to share the GCB. This is contrasted with other approaches including national frameworks for climate policy such as the UK's net zero emissions by 2050 where the carbon budgets are for a shorter time period (i.e. 5 years). We call this latter approach Climate Policy Carbon Budgets, that is carbon budgets that aren't derived from a global temperature target, but instead from national decarbonisation trajectories. This discussion paper also explores approaches to developing decarbonisation pathways for Ireland which are consistent with the Paris Agreement using a carbon budget approach. This discussion paper outlines a broad approach to generating a national long-term climate science carbon budget for Ireland and translating it into five-year sectoral carbon budgets. The process for developing such carbon budgets will require an appropriate set of robust energy system modelling tools, that are iteratively developed and examined, together with an extensive stakeholder engagement process. This discussion paper concludes with some reflections on the governance arrangements for setting, monitoring, and reviewing carbon budgets.

1 Introduction

The near linear relationship between cumulative CO2 emissions and global temperature warming, means that the remaining cumulative amount of CO2 which can be emitted to stay within a global temperature limit can be quantified. This is the Global Carbon Budget (GCB) (see Table 1) and this forms the scientific basis of Article 2 of the Paris Agreement, that is keeping global average temperatures "well below 2 °C above pre-industrial levels, while pursuing efforts to limit the temperature increase to 1.5 °C".

Article 4 adds to Article 2 of the Paris Agreement, while both aim to limit global warming, Article 4 is focused upon the net-zero target, by stating that global peaking of GHGs should be as soon as possible, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century. Article 4 also states that this target should be achieved on the basis of equity and that developed countries should take the lead in climate mitigation.

The Paris Agreement does not prescribe a single GCB, nor does it indicate how countries should determine their national carbon budgets. Adherence with both Articles 2 and 4 of the Paris Agreement will require a transparent and equitable method for developing a national carbon budget as an allocation from the GCB, notwithstanding the challenges that "the more a national target is derived from the global situation, the less it will take account of national circumstances, and vice versa" [1].

Box 1: What is the Global Carbon Budget and how is it related to global warming?

The Global Carbon Budget (GCB) is defined as the *future* (or remaining) *cumulative CO_2 emissions consistent with a given warming limit* [2]. Climate modelling studies have established a robust near-linear relationship between global warming and cumulative carbon dioxide (CO_2) emissions since industrialization [2]. The Transient Climate Response to cumulative carbon Emissions (TCRE) metric was developed to represent this connection. Essentially, the TCRE estimates for every 42 $GtCO_2$ (approx. the global annual CO_2 emissions) emitted, the global temperature will increase by between 0.009°C to 0.011°C [3].

Since the Paris Agreement, a lot of analysis has been undertaken to understand what the remaining GCB is, consistent with a given warming limit. The TCRE was used in the IPCC 1.5°C Special Report in 2018 to develop Table 1. To have a 67% chance of limiting temperatures to 1.5°C, the remaining global carbon budget from 2018 onwards is between -500 and 1,340 $GtCO_2$, with 420 $GtCO_2$ the most probable GCB. The uncertainty is largely due to climate cycle feedbacks, and non-CO_2 GHG emissions. The quantity of the GCB is also dependent on the amount of overshoot (if any) towards a temperature warming limit. Table 1 assumes no overshoot, as the TCRE is only applied up to peak warming temperature.

Temperature limit target	**Probability of remaining below limit**	**Remaining Carbon Budget ($GtCO_2$)**
1.5°C	67%	**420 (-500 to 1,340)**
1.5°C	50%	**580 (-340 to 1,500)**
2°C	67%	**1,170 (250 to 2,090)**
2°C	50%	**1,500 (580 to 2,420)**

Table 1: Global Carbon Budgets and Uncertainties [3] Remaining Global Carbon Budgets from 2018 with associated probability of remaining within the given temperature limit. Given values are centre estimate, bracket values represent minimum and maximum (i.e. uncertainty range). Negative values indicate CO_2 emission limits reached

The conceptual simplicity of TCRE and of carbon budgets led to the prominent presentation of these concepts in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [4], [5].

Looking ahead, the Sixth Assessment Report (AR6) of the IPCC will again review the GCB and perform a "global stocktake" in 2023, to inform and support nations as they update and enhance their mitigation actions, and to enhance international cooperation for climate action [6]. The latest climate models suggest higher climate sensitivity than previously thought, meaning additional warming is expected over the twenty-first century [7].

This paper grapples with the challenge of formulating a national decarbonisation strategy for Ireland, which is consistent with the two relevant Paris Agreement articles. Section 2 of this paper expands on the science of carbon budgets and discusses the allocation of the GCB to different countries (so-called effort-sharing approaches). Section 3 contrasts this approach with one where short-term carbon budgets are determined by long-term decarbonisation targets, specifically net-zero targets. Section 4 analyses a number of country case studies for their approach to setting mitigation targets and carbon budgets. Section 5 then discusses an approach to setting a long-term carbon budget for Ireland, and a methodology for translating this into five-year carbon budgets and allocating carbon budgets to different sectors. Finally, Section 6 discusses open questions and factors relating to the science-policy interface.

2 Climate Science Carbon Budgets

A large part of international climate negotiations have revolved around how to equitably share the GCB, or the '*carbon-quota pie',* across countries. We introduce the term *Climate Science Carbon Budgets* as a term to describe this process, starting with a global temperature target and GCB implied from climate science, and using an effort-sharing methodology to allocate a long-term carbon budget to an individual country (See Figure 4). National long-term carbon budgets derived in this way are quantified for CO_2 only, based on the simple linear relationship between cumulative emissions of CO_2 and global temperature (see Box 1). Since all GHGs contribute to global warming [8] two broad methods have been developed to account for non-CO_2 GHG emissions in climate mitigation policy. The established method involves converting other GHGs into a CO_2 equivalent metric (GWP_{100}); however, a more recent metric that treats non-CO_2 GHGs as a separate category (GWP*) has been developed (See Box 2).

Climate change is a classical "commons problem", where the negative effects of emissions are shared across the world. This underlies the historic difficulty in agreeing national climate targets. There are large variations in per-capita CO_2 emissions, both annually and historically, across different nations, with high levels of emissions typically associated with high economic development. However, the negative effects of climate change will be felt at different levels of severity by all nations and the effects are expected to sustain for future generations. This inequality has not been resolved.

Rationing or allocating the remaining GCB between countries can be a sensitive topic – should we focus on the remaining carbon budget only or also take into account historical emissions and fully apply the polluter pays principle? In addition, should we allocate on the basis of a country's wealth or also take into account other factors that determine each country's effort-sharing ability (i.e. should we include differences based on fuel resources, vulnerability to climate change, human rights issues, energy demands and social acceptance)?

Box 2: The Global Warming Potential (GWP) metric

Each GHG has a unique lifetime in the atmosphere and a different warming potential. In an effort to make the global warming potential of different GHGs easily comparable, the Global Warming Potential (GWP) metric is used. The GWP of CO_2 is 1, which is the benchmark that other more or less potent GHGs are measured. The GWP of different gases is commonly compared over 20 years and 100 years.

Emissions reporting under the United Nations Framework Convention on Climate Change (UNFCCC) now requires the use of 100-year Global Warming Potential (GWP_{100}) to account for all gases as carbon dioxide equivalent (CO2eq) quantities. GWP defines the cumulative impacts that the emission of 1 kg CH_4 or N_2O could have on the planetary energy budget relative to 1 kg reference CO_2 gas over a certain period of years [9].

A new usage of GWP, denoted GWP*, allows emissions of short-lived and long-lived climate pollutants (SLCP & LLCPs) to be more consistently expressed within a single metric by equating a change in the emission rate of an SLCP as equivalent to a single emissions pulse of a long-lived pollutant.

When discussing cumulative emissions of CO_2 and non-CO_2 emissions, there is no cumulative GWP metric. The concept of an "emissions budget" cannot be extended to CO2eq emissions as conventionally calculated [10].

The concept of CO2eq emissions is deeply embedded in climate policy. Relating emissions using GWP* allows all emissions to be considered in a common cumulative framework [10], within a given time horizon only.

There are several approaches proposed to determine how to downscale the global carbon budget to determine national carbon emission budgets. Some of the main effort-sharing approaches include the following:

- **Grandfathering or inertia** - prior annual emissions increase future emission entitlements so that a transition is feasible for all countries.
- **Equality** – the remaining global carbon budget is shared equally among the global population.
- **Brazilian Rule Historical** – historical emissions are used in deriving the equitable share of the all-time GCB; some countries are in 'carbon debt' (e.g. Ireland is in debt to a 1.5°C per capita GCB).
- **Contraction & Convergence** - where national per-capita emissions converge to a global average and emissions then contract at the same rate to net zero following global average pathways.
- **Ability to pay** – based on the ability to afford to reduce emissions.
- **Development rights** - considers both responsibility and capability; aims to reach a dignified level of sustainable human development for all.
- **Cost-optimal** – considers the least-cost decarbonisation options for the global energy system [11].

To contribute to international climate negotiations, different effort-sharing approaches (or rules) have been used by researchers to enable an equitable approach to allocate the GCB across countries. Different effort-sharing methodologies influence the resulting carbon budget. Some approaches lead to what might be called politically unlikely outcomes, for example the Brazilian rule where developed countries with high historical emissions are allocated a negative carbon budget, a consequence of the equity principle underlying the effort-sharing approach.

Approaches requiring extreme sudden changes may not be politically or practically feasible and countries will likely choose an effort-sharing methodology which suits their own ambitions. This highlights the need and challenge of a globally harmonised approach. Extensive discussions in forums such as the UNFCCC are likely to be needed to share the decarbonisation effort transparently and equitably. It is likely that broad framework of the Sustainable Development Goals (SDGs) will play a role in these discussions.

3 Climate Policy Carbon Budgets

In contrast to the approach described in the previous section where a global carbon budget is used to calculate a carbon budget for an individual country along with an effort-sharing methodology, *Climate Policy Carbon Budgets* are developed by countries where the long term carbon budget is derived from national decarbonisation trajectories. For example, under the Climate Change Act 2008, the United Kingdom legislated for an 80% reduction in GHG emissions by 2050 relative to 1990 levels, which was subsequently used to establish five-year carbon budgets to provide short term goals aligned with a long term target. More recently, the UK has increased their long-term ambition and legislated for a net-zero target for 2050, which has decreased the UK's five-year carbon budget quantities. However, the UK's long-term cumulative carbon budget to 2050 is not defined and no effort-sharing methodology is applied a national total carbon budget, so its share of the '*carbon-quota pie'* is not explicitly derived. Section 4.4 reviews in more detail the UK process of developing and governing carbon budgets.

The EU has also taken a *Climate Policy Carbon Budget* approach. As part of the climate and energy policy framework for 2020, member states agreed on a 20% reduction target in GHG emissions outside the emissions trading scheme (ETS) relative to 2005 levels. These non-ETS GHG emissions broadly cover emissions from transport, buildings, agriculture, and low energy intensive industry. Member states agreed on binding annual emission allocations (AEAs) in an effort-sharing agreement (Decision 406/2009/EC) for the period 2013-2020. The total amount of AEAs effectively provided each member state with a non-ETS GHG budget for this period, which aggregated non-ETS CO_2 emissions and non-CO_2 GHG emissions using the GWP_{100} metric. The EU adopted the same approach for the 2030 target for non-ETS GHG emissions (Regulation 2018/842), by setting AEAs for each year in the period 2021-2030 for all member states. The effort-sharing of each member state is based upon GDP/capita, which is then adjusted to reflect cost-effectiveness. The EU has recently agreed an increased 2030 ambition of a 55% reduction in GHG emissions in the context of legislating for a 2050 net-zero GHG target.

In both these examples from the UK and EU, C*limate Policy Carbon Budgets* have been effectively used to flexibly deliver different decarbonisation rates within a multi-annual time window. They can also be reviewed on an ongoing basis to consider greater ambition and/or mitigation potential from technological progress. However, in the context of the Paris Agreement, if national long-term ambition is aligned only with Article 4 (net-zero target), alignment with Article 2 (long-term temperature stabilisation) is not guaranteed. For a detailed explanation of why see the following Section 3.1. To date, most national long-term decarbonisation targets have not been derived from a given temperature target or global carbon budget, nor do they explicitly consider effort-sharing approaches to equitably sharing the GCB. Because *Climate Policy Carbon Budgets* are not formed in a way which states a share of the '*carbon-quota pie*', they tend to be non-compliant with Article 2 of the Paris Agreement [12].

An example of the implications of using a *Climate Policy Carbon Budget* approach can be seen in analysis of the first round of Nationally Determined Contributions (NDCs), which were a key part of the Paris Agreement. If all first round NDCs were fully implemented, there is a 67% probability that the global average temperature would increase by 2.9°C–3.4°C by 2100 [13]. The NDC registry shows that none of 196 member states explicitly defined a cumulative national carbon budget in their NDC target, although both Armenia and Costa Rica have defined emission budgets up to 2050. Furthermore, many NDC target typologies are used [14], some of which are non-quantitative and unmeasurable.

An important difference between *Climate Policy Carbon Budgets* and *Climate Science Carbon Budgets* is that the former are often defined in terms of carbon dioxide equivalent (CO_2eq), which makes an equivalence between CO_2 and non-CO_2 GHG emissions (see Box 2), something *Climate Science Carbon Budgets* don't do.

3.1 Relationship between net-zero GHG targets and carbon budgets

Article 4 of the Paris Agreement includes an objective to achieve a balance between anthropogenic GHG emissions by sources and removals by sinks in the second half of this century. This is increasingly referred to as a net-zero GHG target. Over 100 countries are currently considering a 2050 net-zero GHG targets as a long-term mitigation target [15]. The EU is proposing a net-zero GHG target by 2050 under the EU Green Deal, which is yet to be enshrined in law [16]. Currently only UK, France, Sweden, New Zealand, Hungary and Denmark have set legally-binding net-zero targets [16].

A key insight from climate modelling is that limiting the global mean temperature rise to 1.5°C above pre-industrial levels requires that global GHG emissions must reach net-zero by between 2045 and 2060 [17], while also requiring high levels of short-term ambition and an "overshoot". In a climate modelling context, an overshoot is defined as *"the dependence of the magnitude and duration of possible temporary exceedance of temperature targets"* [18].

However, achieving net-zero is a necessary but not sufficient requirement for meeting Paris Agreement ambitions, specifically the temperature stabilisation target (Article 2). This is because different possible emissions trajectories between now and the net-zero date, and the level of negative emissions, thereafter, lead to very different cumulative CO_2 emissions and therefore climate forcing. Figure 1 illustrates this point, showing three different decarbonisation trajectories which achieve net-zero by 2050. However, the temperature rise associated with the "late action" trajectory is double that of the "early action" trajectory. Hence, for Article 2 and the temperature stabilisation target, the *path* to net zero is at least as important as the *date* we get there.

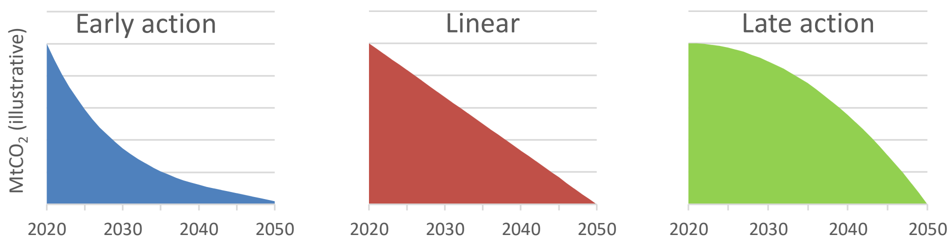

Figure 1: Illustrative decarbonisation trajectories to 2050: each pathway above reaches the same 2050 goal of net-zero CO2 emissions, but in the Late Action pathway, cumulative emissions are double that of the Early Action pathway, leading to double the warming impact.

4 How do different countries use carbon budgets?

This section reviews a number of countries which use or are planning to use carbon budgets.

4.1 France

France's long term decarbonisation plan establishes a linear trajectory toward a net zero GHG target in 2050 [19]. The governance of achieving this target makes use of short term (4-5 year) carbon budgets, which are economy wide and sectorally disaggregated. The French government legislated for carbon budgets via the Energy Transition for Green Growth Act in 2015. The Act contains a net zero emissions target by 2050 across all GHGs. The short-term sectoral carbon budgets are legally binding for the public sector only [20].

Inspired by the UK's independent Committee on Climate Change (CCC), France set up its equivalent *Haut Conseil pour le Climat* in May 2019, with a purpose to provide an independent perspective on the government's climate policy, issue advice on five-year carbon budgets, and assist in the implementation of France's national low-carbon strategy (SNBC) which sets out an economic decarbonisation roadmap.

The first SNBC, published in 2015, defined the first three sectoral and national carbon budgets for France for the periods 2015-2018, 2019-2023 and 2024-2028. The first carbon budget was only for a 4-year period, but following that, all carbon budgets are over five-years. The 2015-2018 carbon budget was exceeded by 62 $MtCO_2eq$ or 14% [21]. In a review of the first carbon budget, chair of the *Haut Conseil pour le Climat,* Prof. Corinne Le Quéré remarked that "the initial efforts are worthy, but they are clearly insufficient and have not produced the expected results" [21]. In setting carbon budgets, France has adopted a *Climate Policy Carbon Budgets* approach, it has not used a global carbon budget or effort-sharing approach.

4.2 New Zealand

In November 2019, the New Zealand government introduced the Climate Change Response (Zero Carbon) Amendment Act [22] to legislate for carbon budgets and introducing a legally binding 2050 net-zero GHG target.

The Climate Change Commission of New Zealand was established in December 2019 to provide independent, evidence-based policy advice to help New Zealand transition to a zero emissions economy. At the time of writing, New Zealand has not yet agreed national carbon budget quantities. The first carbon budget period will be 2022-2025 and every five years thereafter.

New Zealand have declared their net-zero GHG target will exclude biogenic methane; however, they have a separate target to reduce biogenic methane emissions by 24–47% below 2017 levels by 2050 [23]. New Zealand has a large agricultural sector which emits more methane as a share of total GHG (38%) than the OECD average (9%).

Despite aiming to achieve Article 4 of the Paris Agreement (Net-Zero by 2050), because New Zealand's cumulative carbon budget, GCB, or effort sharing methodology is not defined, the country can be said to be using a *Climate Policy Carbon Budget.*

4.3 Denmark

Danish climate law does not establish a national carbon budget. Instead, it sets legally-binding targets to reduce GHG emissions by 70% in 2030 compared to 1990 levels and to becoming a climate neutral society by no later than 2050 [24]. The targets are part of the 2020 Climate Act which also strengthens Denmark's existing independent Danish Council on Climate Change, sets annual climate reporting obligations by government to the parliament, commits Denmark to international climate engagement, and requires periodic national climate target setting accompanied by a climate action plan.

As part of their input to the Climate Act, The Danish Council on Climate Change recommended that the climate targets set by the Climate Act should translate to a long-term national carbon emission budget of 325-425 Mt CO_2[25]; the range is due to range in the GCB, which is 420-570 GtCO_2. While both GCBs aim to limit global warming to 1.5°C with a 67% probability, the range in GCB is due to uncertainty in additional warming which has already occurred. This national carbon budget is calculated based on the effort-sharing equality principle, with a population of around 0.075% of the world's population, Denmark can emit 0.075% of the GCB. Denmark's long-term carbon budget of 325-425 Mt CO_2[25] is then converted by the Danish council on climate change to include all GHGs, this value is 325-525 Mt CO_2eq[25]. The assessment uses a hybrid of *Climate Science Carbon Budgets*, as the national carbon budget is based upon a GCB and an effort-sharing methodology and *Climate Policy Carbon Budgets,* as all GHGs are considered (see Box 2).

According to the Climate Act, the government must set a national climate target every five years with a ten-year perspective [24]. The first climate plan should be prepared in 2020. This climate plan should focus on the 2030 target and also set an indicative target for 2025. Following this, a new climate plan should be prepared every five years. This means that the next climate plan should be prepared in 2025 with the aim of reaching the 2030 and 2035 targets. The overview of this process is outlined below [25]. The Danish Council on Climate Change recommends a framework with single year targets set every five years.

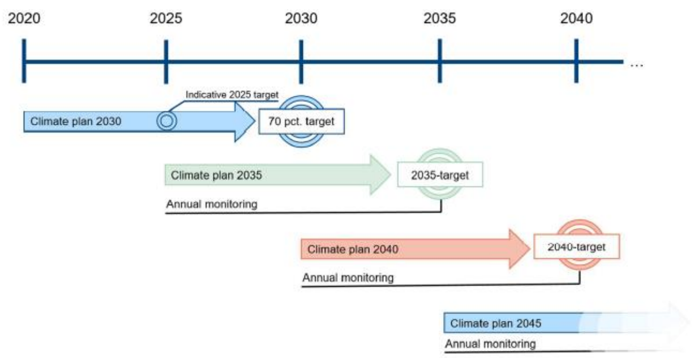

Figure 2 Denmark's Climate Council framework of the climate policy [25] This schematic outlines the 10-year Climate Plans

Ireland's recently approved Programme for Government stated about setting carbon budgets "In setting the second carbon budget for 2026-2030, we will not yet be in a position to identify all the emerging technologies, changing scientific consensus or policies to meet our full ambition. This will require a further allocation within the overall carbon budget, subject to intense evaluation. This approach, which mirrors the Danish model, will be reflected in the Climate Action (Amendment) Bill and in future iterations of the Climate Action Plan."

In Denmark however, the approach is not based on carbon budgets. In their input to the Climate Act, the Danish Council on Climate Change recommends a framework with single year targets set every five years (I.e. setting a 2035 target in 2025, a 2040 target in 2030, etc.). Although, using carbon budgets is an option, the Danish Council on Climate Change considers that the increased complexity of these budgets and the mixed experience from other countries outweigh the benefits.

4.4 United Kingdom

The UK was the first country to introduce legally binding carbon budgets in 2008. The UK government are advised by the Committee on Climate Change (CCC), who recommend sectoral and total quantities for five-year carbon budgets, 12 years in advance. The carbon budgets account for both CO_2 and non-CO_2 GHG emissions. In calculating the UK's targets, the CCC stated they do not start from an assumption that the world will meet the Paris Agreement's temperature goal. Instead, they have identified a UK target that they say is within reach and best supports an increase in global effort, consistent with bringing the expected temperature rise down from the current trajectory [26]. Using the term we introduced in Section 3, the UK has a *Climate Policy Carbon Budget*.

The UK's carbon budget trajectory follows a simple near linear pathway towards a net-zero GHG emissions target by 2050. However, as already stated this linear myopic approach is not informed by an optimal long-term scenario based on a GCB effort-sharing approach. Such an approach was investigated by Pye et.al, who showed that for more ambitious targets, a convex curve rather than a linear trajectory was more optimal [27].

The CCC monitors progress with annual reports, conducts and commissions analysis on climate policy topics (such as infrastructure needs, economic impacts, forestry, sectoral impacts, etc) and collaborates with a wide range of organisations.

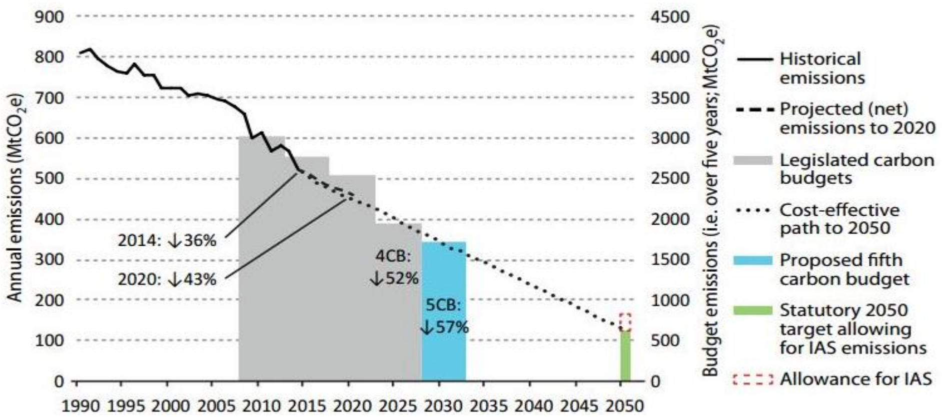

Figure 3: UK'S Five-Year Carbon Budget Trajectory [11]

Due to the longer history of UK's carbon budgets, there is a greater capacity to learn from their approach, therefore this section will cover in detail the setting and managing of UK's national carbon budgets. The UK is currently in their third carbon budget (2018-2022). The first and second carbon budgets were successful as their net actual emissions were less than the emission budget by 1% and 14% respectively [28]. International Aviation and Shipping (IAS) emissions are not currently included in the UK's carbon budgets (current carbon budgets have a 120 $MtCO_2eq$/year allowance for IAS, see Figure 3). If IAS emissions are excluded in future carbon budgets then the UK will need negative emissions in 2050 to offset IAS emissions, so the UK can achieve net-zero GHG 2050 target. Peatlands, which occupy 12% of UK land area [29] will be included into annual accounts from 2020, which will convert land use, land-use change & forestry (LULUCF) from a carbon sink to a carbon source [30].

4.4.1 Modelling & governance – setting a budget

The CCC provide detailed advice to the government regarding the future energy system and decarbonisation. This analysis includes an assessment of the investment and financing needs, technical innovation, evolution of societal or individual behaviours, timing of deliveries, co-benefits, infrastructure and leadership by key actors [30]. To provide robust advice, the CCC obtains decarbonisation modelling results from a range of tools and organisations; a key modelling tool is UK TIMES [31]. The CCC are 95% confident that modelling uncertainty in projections 20 years ahead is limited to 34% [33], this uncertainty is reduced with shorter projections. The 8% over-estimation in 2009 of UK's second carbon budget (2013-2017) was mainly due to changing economic activity which was based on an eight-year projection. The amount of GHGs emitted is measured each year by the UK's National Atmospheric Emissions Inventory (NAEI). The NAEI measure emissions data implied an uncertainty range of 154 $MtCO_2eq$ in the second carbon budget from 2013 - 2017 [33], which is a margin of error of 6%.

4.4.2 Ex-post analysis

The CCC provide feedback and ex-post analysis on decarbonisation polices. Three external factors that are isolated are economic activity, energy prices, and air temperature. This in turn helps the CCC to isolate the effectives of the combined policies and determine the policy gap. The policy gap looks at the difference between the outturn conditions (what happened) and the counterfactual conditions (forecast when carbon budget was set). The UK achieved their second carbon budget (2013- 2017) by 14% or 384 $MtCO_2eq$. This achievement was largely due to an accounting change in the UK's share of the Emissions Trading Scheme (ETS); the UK's carbon budget accounts for both ETS and non-ETS emissions. The UK's ETS allowances for the 2013-2017 period was set in 2009 at 1,078 $MtCO_2eq$. However, this was set before the EU ETS changes had been finalised and following legislation changes, this was revised downwards to 782 $MtCO_2eq$ [33]. The reduction of emissions in the ETS sector created 296 $MtCO_2eq$ of "headroom" in the non-ETS sector of the UK's second carbon budget, which combined with the economic downturn, meant the UK easily achieved their second carbon budget. This highlights that carbon budgets are impacted by many factors, not just policy implementation. In this example, factors outside the UK's control (the ETS) compensated for domestic policy underachievement, which was only brought to light by ex-post. Ex-post analysis is an essential component of effective carbon budget governance.

4.4.3 Flexibilities

The CCC analysis and target of net-zero by 2050 recommend against reliance on flexibilities. After over performing of UK's second carbon budget the CCC stated *"Carrying over any surplus risks further papering over the cracks of not implementing satisfactory measures to put the UK on course to achieve its long-term and ambitious target of net zero by 2050."* However, the UK government uses three flexibilities to help manage carbon budgets, these are:

Flexibility	Description
Carry forward over-achievement from earlier budgets	The Act allows for Government to carry forward overachievement from one carbon budget to the next.
Carry back from later carbon budgets	The Act allows for the Government to increase the carbon budget in one period with a corresponding tightening of the next carbon budget. This 'borrowing' is limited to one per cent of the later carbon budget.
Use international carbon credits (EU ETS)	The Act allows for the purchase of international carbon credits to contribute to meeting carbon budgets but with a limit on the use of these credits set 18 months in advance of the relevant carbon budget

Table 2: UK Carbon Budget Flexibilities [28]

5 A national decarbonisation strategy consistent with the Paris Agreement

In this section, an approach for developing a carbon budget in an Irish context is outlined. The two broad approaches that have been described so far - *Climate Science Carbon Budgets* and *Climate Policy Carbon* Budgets - are compared (i.e.– See Figure 4). While both approaches have merits and have contributed in different ways to climate mitigation, a key difference is that a *Climate Science Carbon Budget* is informed by global climate modelling which informs global climate targets; by contrast, a *Climate Policy Carbon Budget* is not directly linked to global climate modelling. By consistent with the Paris Agreement, we mean compliance with both Articles 2 (1.5°C and 2°C temperature limit) and Articles 4 (a balance between GHG sources and sinks by 2050).

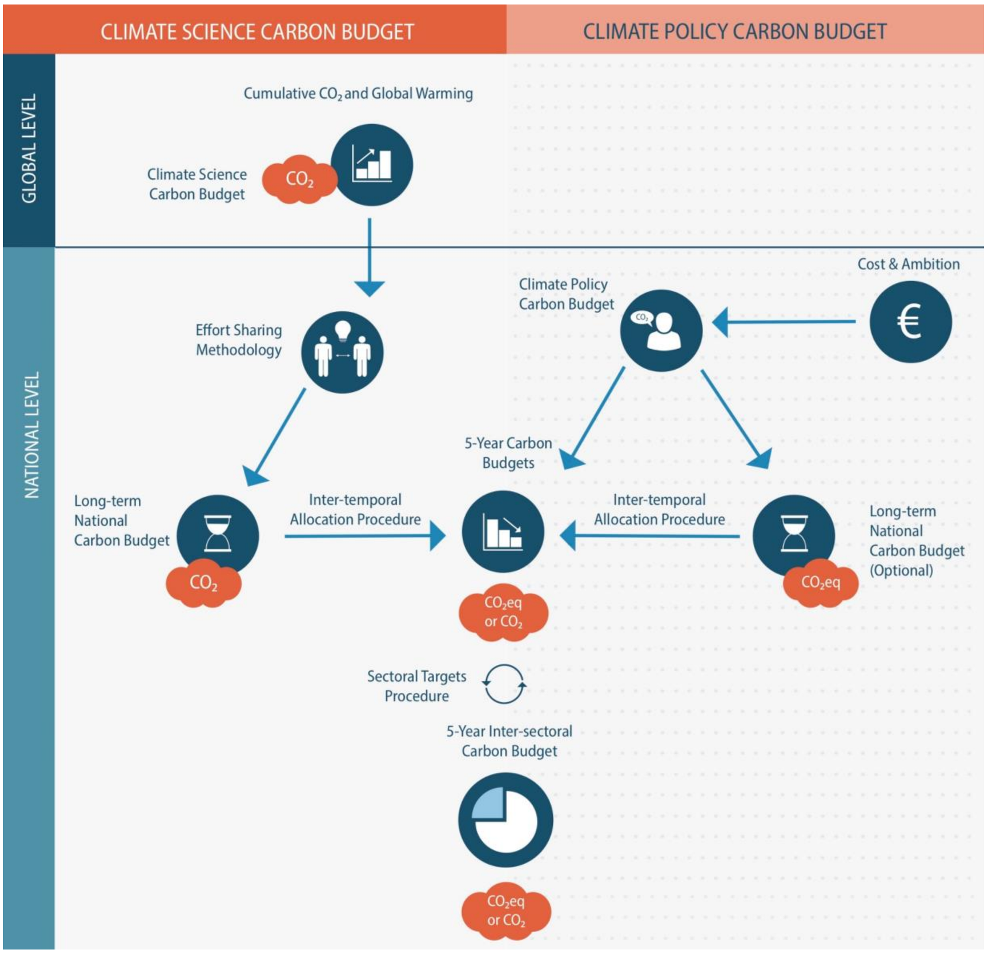

Figure 4 Flowchart to derive five-year carbon budgets The flowchart outlines the steps in the two approaches to obtain five-year carbon budgets. The left side represents the climate science approach and the right side represents the climate policy approach

Box 3: What are the benefits of using a carbon budget?
From a global perspective, the use of carbon budgets can provide essential transparency and clarity on whether or not compliance with the Paris Agreement will be achieved. One of the innovations of the Paris Agreement was the instrument of NDCs, whereby individual countries conducted and published their own analysis on decarbonisation pathways. In the first round of NDCs, seventy-eight member states defined a mitigation target compared to a *base year* and eighty-seven member states used a reduction target compared to *business as usual (BaU*) scenario. A weakness with both of these methods is the lack of clarity of absolute emission limits that both pathways achieve. As outlined in Section 3.1, different emission pathways with different cumulative emissions will have very different implications for global warming. Without the specification of a carbon budget in a country's NDC it is difficult to analytically aggregate the impact of the NDCs and to determine if their impact is consistent with the temperature target of the Paris Agreement. Carbon budgets provide some additional benefits to the common NDC emission target types. Despite the absolute emissions being transparent within carbon budgets, the effort-sharing methodology is not transparent unless explicitly stated.

5.1 Global carbon budget and effort sharing methodology

The first step in using a carbon budget approach to align a decarbonisation strategy with the Paris Agreement is to choose a Global Carbon Budget and an effort sharing methodology to allocate a national long-term carbon budget. Section 2 provided an overview of the Global Carbon Budget (Box 1) and a summary of the main effort sharing methodologies.

Since the choice of effort sharing methodology will influence what quantity of the Global Carbon Budget will be allocated nationally, many considerations are likely to influence this decision. These considerations could include climate justice, intergenerational equity, and how the Global Carbon Budget is likely to change over time as different countries achieve different levels of decarbonisation. How a national allocation of the Global Carbon Budget is defined, whether as a quantity of carbon or a % share of the total, could be consequential. If a national target is to be defined in terms of a global carbon budget, something to that be considered and agreed in advance is how (or whether) the national target is updated in response to changes in global decarbonisation progress.

5.2 Inter-temporal and inter-sectoral national carbon budgets

Once a national long-term carbon budget is established, the challenge is to allocate how to "spend" the budget, over time (giving a decarbonisation trajectory) and over different sectors. The national carbon budget can thus be allocated to short-term or "inter-temporal" carbon budgets (typically in five-year periods) and further subdivided by sector into "inter-sectoral" carbon budgets. A five-year national carbon budget timeline more closely aligns with elected government timelines than long term targets, a feature which will possibly add political accountability for each inter-temporal and inter-sectoral carbon budget.

5.3 Ireland

Previously, Ireland's long-term national climate strategy was based on the 2015 National Climate Policy Position of an at least 80% reduction in energy related CO_2 emissions by 2050 (compared to 1990) and "an approach to carbon neutrality in the agriculture and land-use sector, including forestry, which does not compromise capacity for sustainable food production". The Climate Action Plan (2019) included a range of decarbonisation policy measures, a commitment to increase Ireland's decarbonisation ambition to net-zero greenhouse gas emissions by 2050, an outline of a new governance regime of five-year carbon budgets, and a strengthening of the Climate Change Advisory Council (CCAC).

The recently approved Programme for Government cited Denmark's climate action model, which it recommended that Ireland mirrors (Section 4.3). If Ireland was to derive a national carbon budget based upon population similar to Denmark, then Ireland's long-term carbon budget would be in the range 275 – 360 $MtCO_2$, which complies with a 67% probability of limiting global temperature to 1.5°C above pre-industrial temperatures (uncertainty due to additional warming which has already occurred).

5.3.1 National long-term carbon budget

This section describes in more detail some of the *stages* in setting a *Climate Science Carbon Budget* for Ireland. Developing carbon budgets for Ireland is an iterative process which will require extensive discussions on choices, exclusions, effort-sharing approach, issues and assumptions from all stakeholders to provide a transparent long-term carbon budget which can be easily absorbed by all stakeholders (Section 6 outlines some discussions for Ireland).

As previously mentioned, the first step in determining a national carbon budget is to choose a GCB. Figure 5 shows two GCB associated from the IPCC for 1.5°C and 2°C. It is worth noting the very large difference that 0.5°C makes to these GCBs. Some preliminary results of assigning Ireland's long-term carbon budget from these GCBs are shown in Table 4. We present a range of different numbers in this section to highlight the importance of the *process* of developing a carbon budget decarbonisation pathway.

5.3.1.1 Effort sharing methodologies

Two different national carbon budgets for Ireland are shown here based on two different effort sharing methodologies: the Regensburg Model and the Extended Smooth Pathway Model (ESPM). The Regensburg Model [27] is primarily based upon the Contraction and Convergence (C&C) approach, which is outlined in Section 2. While the EPSM [2] is based on a weighted distribution of population, which is the equity approach outlined in Section 2, and emissions which is the grandfathering approach outlined in Section 2. Both models are available to download at [34].

The preliminary results indicate that if Ireland is to equitable comply with a 67% probability of limiting global warming to 1.5°C, then the maximum CO_2 budget is *263* $MtCO_2$ using the Regensburg Model and *225* $MtCO_2$ using the ESPM. These preliminary calculations do not include land use, international aviation and shipping (IAS) emissions, non-CO_2 emissions or negative emissions i.e. net carbon emissions only.

Ireland emits about 40 $MtCO_2$/year [35] this means we can continue to emit at similar levels for 5 – 9 years until we exceed our fair-share of the remaining 1.5°C GCB (not including historical budget, in which Ireland is in 'carbon debt'). The 67% probability of limiting global warming to 2°C results are also shown below. To comply with the 2°C warming limit, Ireland can continue to emit at similar levels for 18 – 22 years until we exceed our fair-share of the remaining 2°C GCB.

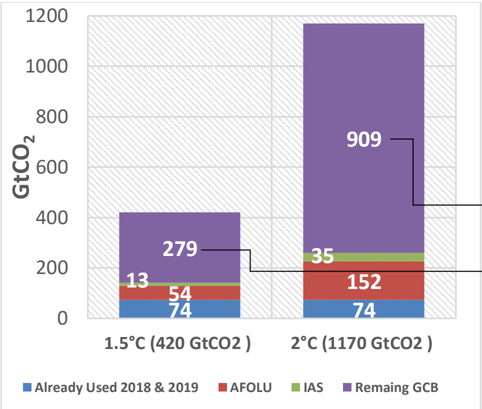

Figure 5 Two GCB [3] which provide a 67% probability of limiting global warming to their respective warming targets.

Effort-sharing methodology (and GCB)	National Carbon Budget 2020-2100 ($MtCO_2$)
Regensburg Model ($279\ GtCO_2$)	251-263
Regensburg Model ($909\ GtCO_2$)	834 - 857
ESPM ($279\ GtCO_2$)	225
ESPM ($909\ GtCO_2$)	734

Table 4: Ireland's Long-Term Carbon Budget using two GCB and two effort-sharing models [34] calculations applied to Ireland from 2020

Ireland's first 2050 climate target (an 80% reduction in CO_2 emissions and carbon neutrality in forestry and agriculture) and Ireland's latest 2050 climate target (net-zero GHG emissions) equate to two very different carbon budgets. Similarly, different carbon budgets arise from two 2030 targets: a 30% reduction in non-ETS GHG emissions (an EU derived target) and a 7% p.a. average GHG reduction from 2021-2030 (Programme for Government). Figure 6 outlines the four different potential carbon budgets arising from combining these different 2030 and 2050 targets. A key insight here is that greater levels of GHG reductions before 2030 (e.g. 7% p.a. reduction) leads to a significant overall reduction in Ireland's longer term (i.e. 2021-2050) carbon budget.

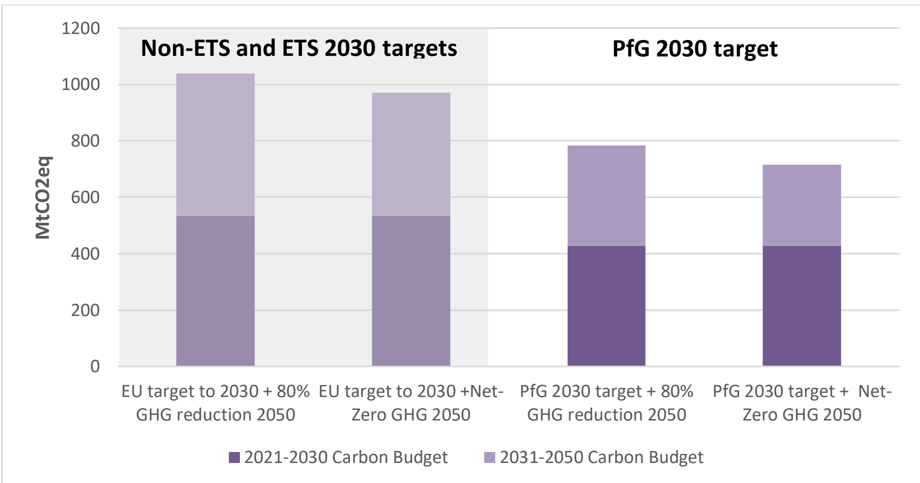

Figure 6 Ireland's Carbon Budget (2021-2050) using two different 2030 targets and two 2050 targets

5.3.2 National climate mitigation pathway to 2030

Ireland's 2021-2030 climate mitigation pathway is fundamental to Ireland's long-term carbon budget. Ireland's current legally binding non-ETS GHG emission targets from 2021-2030 and Europe's 2.2% annual reduction of ETS GHG emissions from 2021-2030 can provide the foundation to forming Ireland's carbon budgets up to 2030, in that complying with EU targets will be the minimum effort goal or maximum carbon budget. Ireland's recent programme for government have agreed to a commitment of 7%/year on average reduction in overall GHG emissions from 2021 to 2030 (a 51% reduction over the decade) and to achieving net-zero emissions by 2050. Figure 7 below shows three carbon budgets, one carbon budget is from Non-ETS and ETS 2030 targets, which are EU derived targets and two carbon budgets are from the PfG 2030 targets, one low carbon budget with annual consistent reductions and one high carbon budget which allows for increased emissions (late action scenario) but still complies with the PfG 2030 target by having an average 7%/year GHG reduction and 51% GHG reduction over the decade.

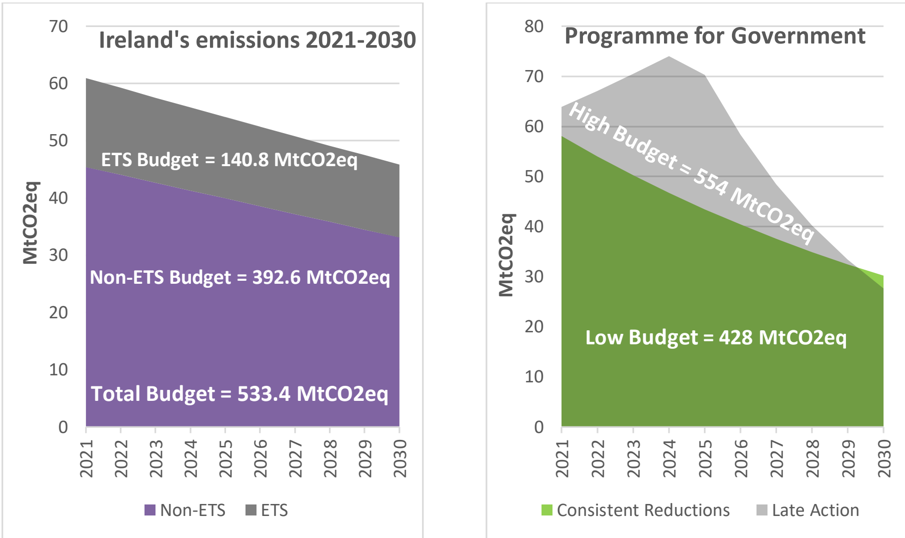

Figure 7 Ireland's 2030 targets and respective Carbon Budgets

For Ireland to comply with the current 2030 EU targets (i.e. a 30% reduction), this would equate to a budget of 533.4 MtCO2eq from 2021-2030. The new programme for government does not define a carbon or GHG budget, so with annually consistent reductions of 7%, the GHG budget would be approximately 428 MtCO2eq; however, in an extreme scenario it could be higher than EU 2030 targets; this would happen if Ireland increased GHG emissions, then reduced GHG emissions at a maximum rate of 17%/year (see Figure 7 – Late Action). Although this High Budget scenario is very improbable, it is included here to show that a climate pathway based on an average annual reduction could still have a larger than allowable carbon budget, which would make a difference to levels of global warming.

Based upon a 428 MtCO2eq budget (i.e. a 7% linear per annum reduction), the first 5-year carbon budget (2021-2025) would be expected to be about 252 MtCO_2eq and the second carbon budget (2026-2030) about 176

$MtCO_2eq$. According to the EPA if Ireland is to continue on a With Existing Measures (WEM) pathway to 2030, Ireland is likely to emit 644.76 MtCO2eq [36]. To comply with current EU 2030 targets (i.e. a 30% reduction) Ireland will need to emit 17% less GHG emissions compared to WEM. For Ireland to comply with an average 7%/year GHG reduction to 2030 target, between 14–34% less emission would be required compared to WEM.

The Climate Action Plan 2019 provides higher detail in the Non-ETS sector emissions savings and the EU flexibilities up to 2030. Figure 8 below shows some sectoral division of the cumulative savings required in the 2021-2030 period. Ireland also has a large LULUCF allowance, which can be used to offset emissions if forestry (carbon sinks) is planted. This information should be used in calculating five-year carbon budgets.

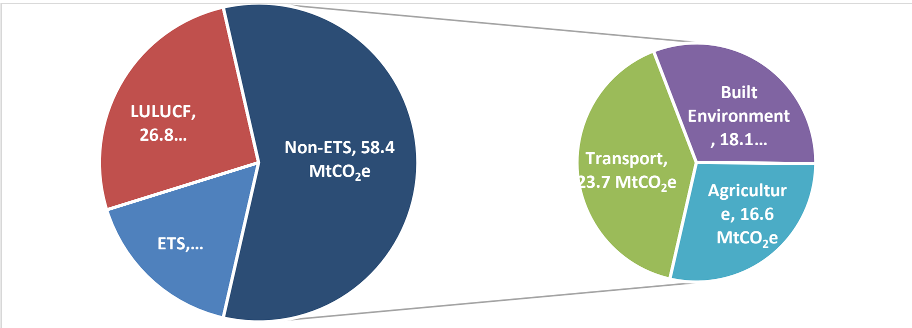

Figure: 8 Climate Action Plan 2019, cumulative emission savings 2021-2030 [37]

Further work on Ireland's GCB effort-sharing and climate mitigation pathways up to 2070 was done by Glynn et al. 2019 [38]. Thirty-eight scenarios were considered, and the GCB effort-sharing was based on equitable per capita shares (equality approach) of the remaining GCB. A range of national carbon budgets and scenario variants were used to account for uncertainty in climate mitigation policy choices. The results produced show a range of variation in optimal pathways with given budget constraints, with the 376 $MtCO_2$ budget also showing a difference between early action and delayed action (i.e. starting in 2025) in Figure 9.

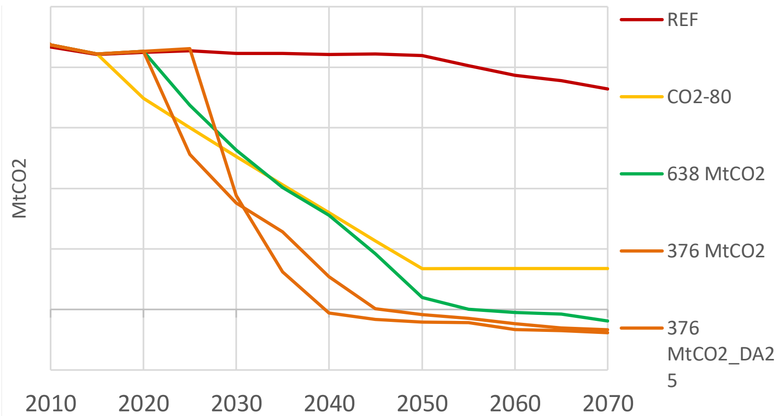

Figure 9: Energy system CO_2 emissions pathways for Ireland [38]. The reference emissions pathway up to 2070 can be compared to a 638 $MtCO_2$ national carbon budget and a 376 MtCO2 national carbon budget (Early & Delayed Action).

The modelling results suggest that an optimum decarbonisation pathway for a cumulative carbon budget follows a convex trajectory shape rather than a linear trajectory [38]. Significant additional detail about the modelling behind Figure 9 is available in the linked publication.

5.3.3 Ireland's carbon budget governance

Ireland's carbon budget governance structure has not yet been fully implemented, nor has the inter-temporal and inter-sectoral ambition being quantified yet. Based on the Climate Action Plan 2019 and the anticipated new Climate Action Bill, a hypothetical governance structure is outlined in Figure 10. This outline is intended to stimulate discussion. Given the reach of carbon-based energy into all parts of Irish life and society, it is important that all stakeholders can have an input, so that Ireland's carbon budget governance is transparent for all. The figure has colour coded organisations/activities depending on whether it is part of the setup and/or managing of carbon budgets.

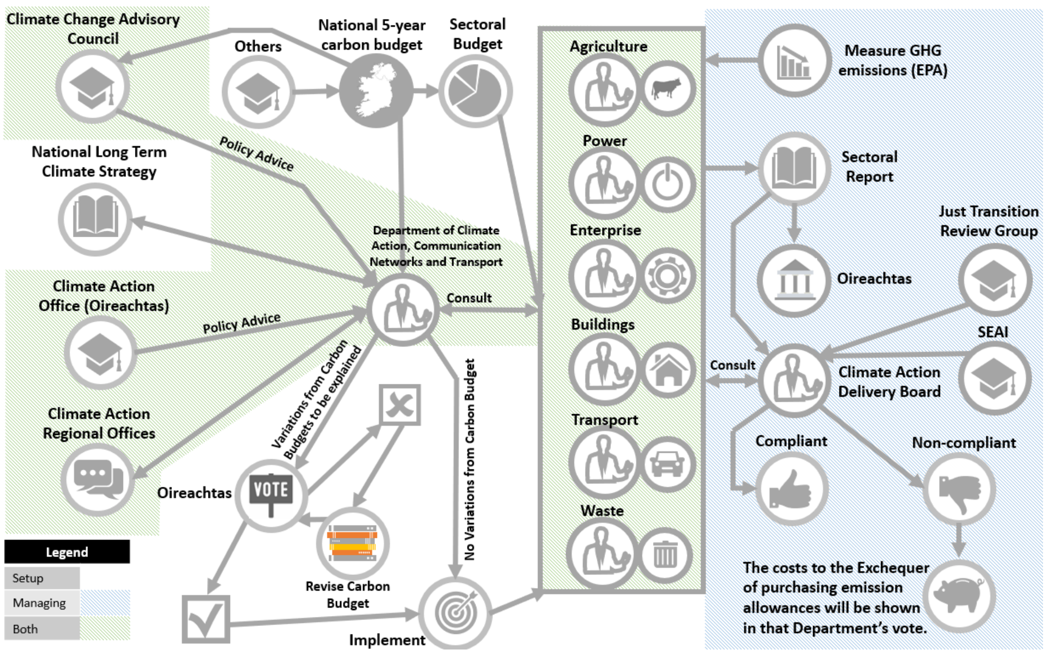

Figure 10: Hypothetical Carbon Budget Governance Structure For Ireland

6 Discussion

In this final section, we first briefly discussion the relationship between analytical energy modelling and the policy-making process, highlighting some of the principles and practices that can make this process more effective (section 6.1). Then we give a brief survey of a range of open issues related to the process of developing a carbon budget for Ireland (section 6.2). This section summarises a number of open questions and important considerations (accounting, technical, procedural) that we believe must be addressed if the process of forming a carbon budget is to be equitable and robust.

6. 1 The energy policy-modelling interface

Robust quantitative analysis and information is an important ingredient in the energy and climate policy making process. But energy modelling should *support* the policy making process rather than *determine* its contents; the policy-making process is best served by being evidence-informed rather than evidence-based [39]. This means the interface between energy modelling and the policy making process should be an iterative one that incorporates regular review and feedback as new issues and questions emerge.

According to the climate policy architecture put in place by the Paris Agreement, each nation takes responsibility for developing their own climate targets and climate mitigation pathway. Each country will take into account their own unique circumstances and will have their own combination of different energy system modelling tools and processes for developing policies, i.e. processes that include discussions between researchers, consultants and government to assess optimal and feasible national climate mitigation pathways.

Mindful of this diversity, Strachan et. al, 2016 provide an idealised energy modelling-policy interface (Figure 11) that would capture insights from an expert user group based on a modelling platform (B), incorporate interdisciplinary external review by wider stakeholders (C), and comprehensive quality assurance, version control and documentation (D). These insights would be fed into future model improvements and applications by coupling model-development to funding and policy cycles (A). There are a broad set of viewpoints on the overall role of modelling in the policy process, studies that actually examine the energy modelling–policy interface acknowledge the weak links between provision of insights and policy-maker needs [40].

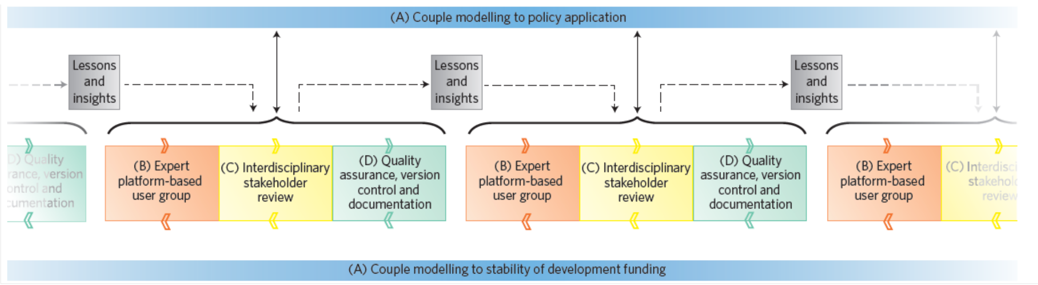

Figure 11: Idealised energy modelling–policy interface with full iterative feedbacks ([19])

6.2 Open Issues

6.2.1 Global carbon budget

In this discussion paper we have created a distinction between *Climate Policy Carbon Budgets* and *Climate Science Carbon Budgets.* This distinction was made to explain different types of carbon budgets that have been devised and adopted by different countries. For countries to adhere to Article 2 of the Paris Agreement, i.e. "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" some use of a global carbon budget that is consistent with these targets will be required.

However, this is not a simple process. As shown in Box 1, there are a number of global carbon budgets for different temperature targets (2°C or 1.5°C) and each of these targets has a range of carbon budgets associated with different probabilities (50%, 67%) of being achieved. *Which of the global carbon budgets should Ireland choose?*

Once a carbon budget is chosen, the question arises of how an individual country (e.g. Ireland) apportions a share of that budget, i.e. what effort sharing methodology is used? Section 2 outlines the main effort sharing methodologies that have been used. Each effort sharing methodology and associated global carbon budget will provide different results. *Which effort sharing methodology should Ireland choose?*

Furthermore, these carbon budgets are true for a point in time but will inevitably change over time as different countries perform differently. It should be made clear when adopting a global carbon budget, what will happen in the future as circumstances change [1],[2].

Climate science carbon budgets are CO_2 only, which is scientifically robust, while using an effort sharing methodology to equitably divide the GCB. Climate science carbon budgets do not include all GHGs, and therefore may require either separate non-CO_2 GHG targets and/or the use of the GWP* metric. The particular share of non-CO_2 emissions in a country's inventory of emissions will also affect the level of uncertainty for the overall carbon budget.

Finally, like all science, climate science is constantly evolving, so provision should be made for changes that may arise because of this.

6.2.2 National emission categories - what to include or exclude?

In theory, a carbon budget will account for all activities in a country that produce or sequester carbon-based emissions. In practice, decisions will be made about what to include or exclude in a national carbon budget. The ramifications of these decisions could have big impacts on a national carbon budget. For example, activities with an international dimension such as aviation and shipping could represent a very large share of a national carbon budget. We outline some of the considerations and questions below.

Should biogenic methane be included or excluded from the carbon budgets? This is a consequential question for Ireland. As shown in Figure 12, Ireland has a 21% share of GHG emissions from methane, which is one of the highest shares of non-$C0_2$ GHGs in the world. The OECD average is 9%. If biogenic methane is included in a carbon budget, that will be proportionally less is available for other sectors. New Zealand has a 38% of GHG emissions methane, the highest in the world. New Zealand has taken the approach of not including biogenic methane in their national carbon budget.

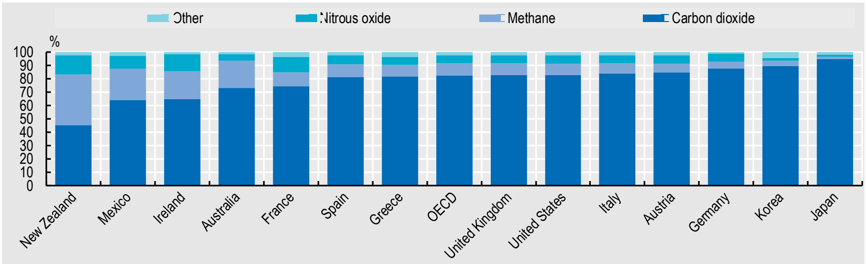

Figure 12: type of GHG emissions by OECD nation (source: OECD)

How should emissions associated with land-use be accounted for? Because Greenhouse Gas emissions associated with LULUCF can contribute to global warming, they are included in the Paris Agreement, which (in Article 4) cites the target of "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". EU legislation also addresses LULUCF emissions with a number of key policy changes coming into effect during 2021-2030.
While compliance will be required with EU legislation, the timing of these regulations might occur later than 2021. For example, the scope of LULUCF will extend to include all wetlands from 2026 [41]. Therefore the question arises, *when should LULUCF be included in a carbon budget for Ireland?*

Should international aviation and shipping (IAS) sector be included? Currently, international aviation and shipping are not included in Ireland's national emissions accounting by the EPA. This is consistent with many other countries. To date, efforts at decarbonising international aviation and shipping have been through international agreements led by industrial representation of these industries. UK and Denmark, two countries that have legislated for long-term net zero climate targets, do not currently include IAS in their targets; however, both countries plan to include IAS in later budgets. For Ireland, international shipping emissions are very small whereas international aviation emissions are very large.

How should the ETS and non-ETS sectors be incorporated a long-term carbon budget? Until the year 2030, Ireland's emissions are subject to separate ETS and non-ETS targets, though there is some flexibility permitted in using allocations from the ETS for the non-ETS. For the period after 2030, there is at present no mandatory targets for either ETS and non-ETS sectors. Therefore, how or whether the ETS/non-ETS distinction will be dealt with post 2030 remains open.

What flexibilities will be designed into the system? The UK has allowed for 3 carbon budget flexibilities which are outlined in section 4.4.4. What flexibilities should be used in achieving Ireland's carbon budgets? Ireland currently has Non-ETS GHG budget flexibilities within the EU. Ireland's Climate Action Plan accounts for the non-ETS GHG budget flexibilities. Current non-ETS flexibilities include banking, borrowing, and buying and selling between Member States, other flexibilities include access to EU ETS allowances and credits from the land use sector.

6.2.3 Governance

Many questions remain about the process of forming, agreeing, monitoring, managing compliance, and updating carbon budgets. A transparent plan on the steps and stakeholders involved in setting overall and sectoral carbon budgets will be necessary. Some of the issues highlighted in Section 6.1 will be pertinent here, e.g. *how and when will formal analytical modelling be used and how will it be balanced with discussions and negotiations between departments?* Additional questions that arise include: *should sectoral carbon budget be set at the beginning of a carbon budget along with the carbon budget or should allowances be set every year to provide more flexibility? Who is accountable for reducing emissions? Who is accountable to monitor progress and how shall slow progressing sectors proceed?*

6.2.4 Consistency with EU climate goals

While the topic of consideration here is a national carbon budget for Ireland, it will be important for any Irish decarbonisation policy goals to be consistent with current, planned or anticipated EU climate goals. Ireland's track record on compliance with EU climate and energy goals is poor. To achieve compliance with 2020 climate and energy targets, Ireland will likely be required to purchase of credits which will divert resources from investment that would achieve decarbonisation. Further future non-compliance would be similarly costly.

Recently, the EU goals for 2030 of a 40% reduction in overall GHG emissions (compared to 1990) was increased to a 55% reduction. For Ireland, the old target (a 40% reduction) was converted to a national target of a 30% reduction, with a number of flexibility measures permitted. Under The Green New Deal proposal, this 2030 target was to be increased to either 50% or 55%. Recent discussion in the European Parliament have called for increasing the 2030 target to a 60% or 65% reduction, although there is not consensus on this change. Given these dynamics, it will be important for any Irish national carbon budget to have consideration for a pathway that is consistent with these more ambitious medium-term goals or have a mechanism to adjust national/temporal/sectoral carbon budgets when circumstances change.

The EU's 2050 long-term strategy is "to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions". Analysis underpinning this long-term goal uses global carbon budgets (from AR5) that are consistent with global temperature targets of "below 2°C or 1.5°C"; however, the long-term target is still framed in terms of a single year (i.e. 2050) rather than a cumulative amount of emissions (i.e. a carbon budget). This could change when revised global carbon budget estimates from AR6 are released.

6.2.5 National energy system circumstances

The headline goals of The Paris Agreement are the 1.5 degree and 2-degree global temperature targets, but achievement of these goals is also acknowledged to rely on "different national circumstances", i.e. what is feasible. For the energy system, assumptions about resources, costs, and capabilities will influence what is feasible and at what cost. Some of these factors are inherently uncertain (e.g. the future price of oil), however other factors are well within the domain of national decision-making and will be influenced and policy-making and policy supports. Some factors include: the range of carbon tax up to 2030, the projected amount of data centres, the domestic bioenergy resource, the potential for district heating, the potential for carbon capture & storage (CCS), offshore wind capacity, etc.

6.2.6 Social discount rate

Economic evaluations of future investments use a % discount rate as standard practice. The social discount rate is a way of comparing the future value of an investment with the same investment today. The higher the discount rate, the lower the perceived value of future investments. Discount rates are used as an evaluation metric. They are composed of consideration of risk and the changing value of money. The outcomes of most evaluations are extremely sensitive to discount rate values. Therefore, transparency about what the discount rate is and how it was calculated are very important.

Ireland's social discount rate is recommended at 3.7% or rounded up to 4%, which is based upon the Social Time Preference Rate (STPR) equation using methodology from [42] *based on calculations from* [43]. The equation has two components. The *time preference* component comprising pure social time preference (δ) and catastrophic risk (L). The *wealth effect* component, where μ is the elasticity of the marginal utility of consumption and g is the rate of per-capita consumption growth.

Energy systems modelling analysis on Ireland's carbon budget, which varied social discount rates, showed that

Ireland's first two carbon budgets varied by up to 20%, when a social discount rate between 3% - 7% was applied [44]. This is a significant change and therefore the social discount rate is a highly sensitive variable and it should be openly discussed.

The UK Greenbook states "*Policies or projects which involve long term effects may require a different approach. This can be particularly important for policies expected to have significant environmental effects"* [42]. The UK Greenbook has set a default social discount rate of 3.5% in the UK. The UK recommended discount rate for risk to health and life is 1.5%. The health social discount rate is applied to projects which will affect a person's quality of life known as Quality Adjusted Life Years (QALYs), which combines both longevity and level of health in a single measure. It is worth discussing – does climate change effect our longevity or quality of life? Applying the same to Ireland, by excluding the 'wealth effect' the social discount rate of 3.7% would fall to **1.4%.**

Human rights and ethical debates around intergenerational considerations have revolved around discounting future generation in climate mitigation projects. Ireland's ***time preference*** value is focused on values around 1% [43], this means if Ireland is to consider future generations to have equal value to the current generation, then the social discount rate applied should be about **2.7%.**

Combining both health and intergenerational considerations, would mean Ireland's social discount rate should fall to about **0.4%**. *What value or range of values should be set for Ireland's social discount rate?*

This question is partly being addressed by Action 9 of the Climate Action Plan "*Reform the Public Spending Code to increase the shadow price of carbon and introduce more robust consideration of climate impacts in project appraisal*". As part of this, the Irish government recently published updated guidance on using discount rates.

6.2.7 Consumption based emissions

The UN method for measuring national GHG emissions is based on territory emissions only, for example an iPhone's materials are sourced from different parts of the globe and manufactured in China. The GHG emissions from the production of an iPhone used in Ireland, are not associated with Ireland's GHG emissions as the emissions were not produced in Ireland's territory. But consumption-based emissions would account for this. Denmark plan to include policy initiatives which can contribute to reducing the total climate footprint of imported goods, thereby reducing global emissions. However, the consumption footprint is not included in meeting the target [25]. *Should and if so, how should Ireland incorporate consideration of with consumption-based emissions*

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Appendix B

Chapter 4

B.1 Additional Data

Table B.1: The matrix illustrates the temperature adjusted annual energy savings, by percentage, from pre-retrofit EPC rating on the horizontal axis to the post-retrofit EPC rating on the vertical axis. Shallow retrofits ($\leq$ 35% energy savings) are in yellow, deep retrofits ($>$ 35% energy savings) are in orange, and red is considered infeasible ($>$ 75% energy savings). TIMES Ireland Model only retrofits to a B2 EPC standard.

		Pre-Retrofit EPC							
		G	F	E	D	C	B3	B2	B1
Post-Retrofit EPC	A	83%	73%	67%	57%	38%	46%	35%	17%
	B1	79%	68%	61%	48%	25%	35%	22%	
	B2	**73%**	**59%**	**49%**	**33%**	**4%**	**17%**		
	B3	68%	50%	39%	19%	0%			
	C	72%	57%	47%	30%				
	D	60%	38%	25%					
	E	47%	18%						
	F	35%							

Table B.2: Probability of apartment dwelling EPC rating based on construction year, the values represent $\frac{EPC_{e,y,a}}{EPC_{y,a}}$ in Eq. 3.4

Year	A	B1	B2	B3	C	D	E	F	G
Before_1919	0.0005	0.0021	0.0066	0.0139	0.0865	0.1618	0.1889	0.1447	0.3950
1919-1945	0.0007	0.0075	0.0457	0.0689	0.1646	0.1775	0.1614	0.1100	0.2636
1946-1960	0.0069	0.0146	0.0434	0.0553	0.1610	0.2085	0.1843	0.1139	0.2122
1961-1970	0.0097	0.0173	0.0692	0.0736	0.2060	0.2208	0.1484	0.0957	0.1593
1971-1980	0.0005	0.0014	0.0215	0.0305	0.2556	0.2809	0.2032	0.1009	0.1055
1981-1990	0.0002	0.0003	0.0035	0.0249	0.2278	0.3223	0.2589	0.1036	0.0585
1991-2000	0.0003	0.0016	0.0095	0.0293	0.3052	0.3728	0.2069	0.0546	0.0199
2001-2010	0.0049	0.0310	0.0938	0.1504	0.4272	0.2033	0.0711	0.0140	0.0042
Later_2010	0.7996	0.0837	0.0713	0.0246	0.0140	0.0039	0.0019	0.0004	0.0005

Table B.3: Probability of attached dwelling EPC rating based on construction year, the values represent $\frac{EPC_{e,y,a}}{EPC_{y,a}}$ in Eq. 3.4

Year	A	B1	B2	B3	C	D	E	F	G
Before_1919	0.0021	0.0027	0.0091	0.0245	0.1239	0.1974	0.2109	0.1458	0.2837
1919-1945	0.0019	0.0028	0.0102	0.0310	0.1835	0.2348	0.2046	0.1340	0.1973
1946-1960	0.0023	0.0050	0.0130	0.0305	0.1991	0.2585	0.2309	0.1312	0.1295
1961-1970	0.0032	0.0023	0.0100	0.0363	0.2757	0.3134	0.2021	0.0915	0.0654
1971-1980	0.0022	0.0024	0.0069	0.0382	0.3452	0.3329	0.1738	0.0619	0.0365
1981-1990	0.0010	0.0010	0.0069	0.0447	0.4263	0.3486	0.1198	0.0326	0.0190
1991-2000	0.0011	0.0043	0.0084	0.0469	0.4833	0.3389	0.0835	0.0250	0.0087
2001-2010	0.0045	0.0144	0.0438	0.1439	0.6330	0.1208	0.0303	0.0077	0.0016
Later_2010	0.9359	0.0391	0.0147	0.0064	0.0032	0.0006	0.0000	0.0000	0.0000

Table B.4: Probability of detached dwelling EPC rating based on construction year, the values represent $\frac{EPC_{e,y,a}}{EPC_{y,a}}$ in Eq. 3.4

Year	A	B1	B2	B3	C	D	E	F	G
Before_1919	0.0035	0.0036	0.0078	0.0159	0.0912	0.1570	0.1791	0.1422	0.3996
1919-1945	0.0044	0.0035	0.0083	0.0200	0.1059	0.1728	0.1762	0.1354	0.3734
1946-1960	0.0055	0.0053	0.0127	0.0215	0.1298	0.2189	0.1928	0.1353	0.2782
1961-1970	0.0061	0.0046	0.0118	0.0229	0.1770	0.2910	0.2240	0.1132	0.1494
1971-1980	0.0034	0.0027	0.0090	0.0270	0.2663	0.3586	0.1942	0.0729	0.0660
1981-1990	0.0027	0.0028	0.0091	0.0422	0.3641	0.3920	0.1285	0.0349	0.0237
1991-2000	0.0019	0.0027	0.0152	0.0754	0.5372	0.2911	0.0519	0.0163	0.0082
2001-2010	0.0081	0.0216	0.0643	0.1785	0.5903	0.1112	0.0172	0.0059	0.0029
Later_2010	0.8131	0.0868	0.0509	0.0295	0.0165	0.0029	0.0002	0.0002	0.0001

Table B.5: The future space and water heating technologies in TIMES Ireland Model are represented. The technology name is dependant on the building archetype, *"xyz"* is replaced by *"Apt"* for Apartments, *"Att"* for Attached, or *"Det"* for detached dwellings. The symbols indicate if that technology is available.

Technology		Apartments		Attached		Detached	
Name	Fuel/Description	Space	Water	Space	Water	Space	Water
Boiler or Stove							
R-SH_xyz_KER_N1	Oil	✓	✗	✓	✗	✓	✗
R-SW_xyz_KER_N1	Oil	✓	✓	✓	✓	✓	✓
R-SW_xyz_KER_N2	Oil/Solar	✗	✗	✓	✓	✓	✓
R-SW_xyz_KER_N3	Oil/Biomass	✗	✗	✓	✓	✓	✓
R-SH_xyz_GAS_N1	Gas	✓	✗	✓	✗	✓	✗
R-SW_xyz_GAS_N1	Gas	✓	✓	✓	✓	✓	✓
R-SW_xyz_GAS_N2	Gas/Solar	✗	✗	✓	✓	✓	✓
R-SW_xyz_GAS_N3	Gas/Biomass	✗	✗	✓	✓	✓	✓
R-SH_xyz_LPG_N1	LPG	✓	✗	✓	✗	✓	✗
R-SW_xyz_LPG_N1	LPG	✓	✓	✓	✓	✓	✓
R-SH_xyz_WOO_N1	Biomass	✓	✗	✓	✗	✓	✗
R-SW_xyz_WOO_N1	Biomass	✓	✓	✓	✓	✓	✓
R-SH_xyz_FPL_N1	Stove	✗	✗	✓	✗	✓	✗
R-SW_xyz_FPL_N1	Stove	✗	✗	✓	✓	✓	✓
R-SH_xyz_HVO_N1	Hydrotreated Vegetable Oil	✗	✗	✓	✗	✓	✗
R-SW_xyz_HVO_N1	Hydrotreated Vegetable Oil	✗	✗	✓	✓	✓	✓
Electrical							
R-SH_xyz_ELC_N1	Resistance Heater	✓	✗	✓	✗	✓	✗
Electrical Heat Pumps							
R-SH_xyz_ELC_HPN1	A-to-A	✗	✗	✗	✗	✗	✗
R-HC_xyz_ELC_HPN1	A-to-A	✗	✗	✗	✗	✗	✗
R-SH_xyz_ELC_HPN2	A-to-W	✓	✗	✓	✗	✓	✗
R-SW_xyz_ELC_HPN1	A-to-W	✓	✓	✓	✓	✓	✓
R-SW_xyz_ELC_HPN2	A-to-W w/Solar	✗	✗	✓	✓	✓	✓
R-SH_xyz_ELC_HPN3	G-to-W	✗	✗	✓	✗	✓	✗
R-HC_xyz_ELC_HPN2	G-to-W	✓	✗	✓	✗	✓	✗
Gas and Hybrid Heat Pumps							
R-SW_xyz_GAS_HPN1	Gas Absorption	✓	✓	✓	✓	✓	✓
R-SW_xyz_GAS_HPN2	Gas Engine	✓	✓	✓	✓	✓	✓
R-SW_xyz_GAS_HHPN1	Gas Hybrid	✓	✓	✓	✓	✓	✓
District Heating							
R-SW_xyz_HET_N1	Centralized	✓	✓	✓	✓	✓	✓
R-SW_xyz_HET_N2	Decentralized	✓	✓	✓	✓	✓	✓
Water Heat Only							
R-WH_xyz_ELC_N1	Resistance Heater	✗	✓	✗	✓	✗	✓
R-WH_xyz_ELC_N2	Solar Thermal	✗	✓	✗	✓	✗	✓
Retrofits							
R-FTFT-xyz_Shallow	Shallow Retrofit	✓	✗	✓	✗	✓	✗
R-FTFT-xyz_Deep	Deep Retrofit	✓	✗	✓	✗	✓	✗

B.2 Transparency Checklist

Table B.6: Completed transparency checklist applied to the TIMES Ireland model [27]

Reduced version of the ESS transparency checklist

Further info on how to apply the checklist can be found in our paper. See the 'full version' of the checklist in section "Tables".

	Criterion	Evidence	
		Transparency level	Comment or location in paper
General Information			
1.	***Author, Institution***	Each author and corresponding institution shown on page(s):	Chapter 2 - *Subtitle*
2.	***Aim and funding***	Info included on page(s):	Chapter 2 - *Acknowledgments*
3.	***Key term definitions***	A glossary is included on page(s):	Chapter 2 - Nomenclature & other key terms explained when introduced
Empirical Data			
4.	***Sources***	Sources of secondary data are shown on page(s):	Chapter 2 - *Applied Methodolgy & Data* Section
5.	***Pre-processing***	The data used had to be modified before being fed into the model. The procedure is indicated on page(s):	Chapter 2 - *Applied Methodolgy & Data* Section & Residential data Tableau Workbook
Assumptions			
6.	***Identification of uncertain factors***	Both qualitative and quantitative factors of uncertainty are considered on page(s):	Chapter 2 - *Applied Methodolgy & Data* and *Limitations Sections*
7.	***Uncertainty consideration***	Info included on page(s):	Chapter 2 - Applied Methodolgy & Data Section. The Internal temperature, behaviour & heat pumps in high heat loss dwellings requires further investigation.
8.	***Storyline construction***	Info included on page(s):	Chapter 2 - *Introduction* and *TIMES Ireland Paper* (Balyk,O. et al. 2022)
9.	***Assumptions for data modification***	Info included on page(s):	Chapter 2 - Applied Methodolgy & Data - calculation & assumptions defined
Model exercise			
10.	***Model fact sheet***	The key features of the model are described verbally on page(s):	Chapter 2 - TIMES Section
11.	***Model specific properties***	Model strengths and weaknesses are shown on page(s):	Chapter 2- Discussion & TIMES Sections
12.	***Model interaction***	Not applicable in this study	Only one one model in this study
13.	***Model documentation***	The model code is available elsewhere, as stated on page(s):	TIM Overview Paper, TIM input data, & Model framework (Balyk,O. et al. 2022)
14.	***Output data access***	Access to model output data is facilitated, as indicated on page(s):	https://tim-carbon-budgets-2021.netlify.app & Results CSV files
15.	***Model validation***	The validation method applied is shown on page(s):	Chapter 2 - Internal scurnity of data, calibration and results, before external reviewers feedback, followed by model updates.
Results			
16.	***Post-processing***	There was no need to modify the model output	Chapter 2 - Model outputs national results, which are not post-processed in this study.
17.	***Sensitivity analyses***	The results of sensitivity analyses are included on page(s):	Multiple sceanrios in web-based results on https://tim-carbon-budgets-2021.netlify.app & further sensitivity analyses will be carried out to address further research questions in the future
18.	***Robustness analyses***	The results of robustness analyses are included on page(s):	Model not compared to another Irish ESOM
Conclusions and Recommendations			
19.	***Results - recommendation - relationship***	Info included on page(s):	Chapter 2- Methodology Section
20.	***Uncertainty communication***	Info included on page(s):	Chapter 2- Methodology & Limitations Section

Appendix C

Chapter 5

C.1 Residential Heating Energy Demand

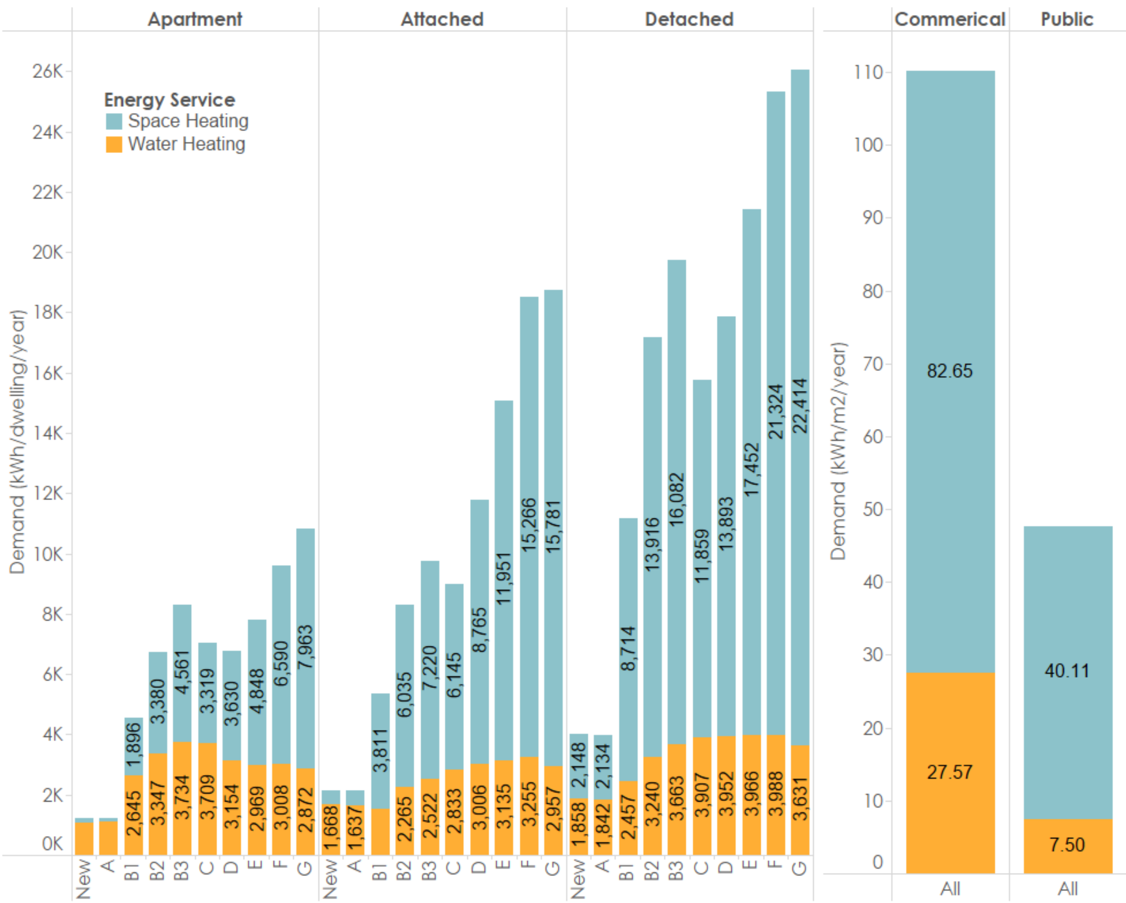

Figure C.1: Sectoral Building Heat Demand

$$_{2030}\theta_{r,a} =_{2018} \theta_{r,a} \cdot (1 + Average(\frac{\sigma_{r,a}}{\sigma_r}, \frac{\varepsilon_{r,a}}{\varepsilon_r})) \quad (C.1)$$

The projected number of residential building archetypes per region in 2030, $_{2030}\theta r, a$, is based on $_{2018}\theta r, a$ in Eq. 5.1 and averages two projections. The first projection, σ, relies on four years of historical trends (2018Q1 -2022Q1) from the CSO's new dwelling completion dataset, and the second projection, ε, is a standard exponential smoothing annual forecast up to 2030 [284]. The shares of the residential building archetypes post-2030 are extrapolated, and the total number of dwellings is calibrated with single-region projections [244].

C.2 District Heating Sources

Table C.1: Surplus large heat generation (PJ) per region in 2018, for regions not shown there is no surplus heat

	Group	
Region	Power	Industry
IE	44.63	10.26
IE-D	29.74	1.94
IE-LH	0	3.08
IE-MH	2.87	0
IE-CO	7.7	2.13
IE-LK	0	1.23
IE-WD	4.32	0
IE-G	0	0.11
IE-CN	0	1.78

C.3 District Heating Demand

Table C.2: The cumulative district heating market (PJ) per region and group

	Group			
Region	City	High Density	Medium Density	Low Density
IE	31.89	24.05	10.29	2.54
IE-CW	0	0	0.56	0.08
IE-D	20.99	2.81	0.78	0.01
IE-KE	0	2.67	0.75	0.1
IE-KK	0	1.31	0.14	0.05
IE-LS	0	0.74	0.04	0.07
IE-LD	0	0.42	0.08	0.02
IE-LH	0	1.62	0.06	0.1
IE-MH	0	1.84	1.43	0.03
IE-OY	0	0.74	0.21	0.08
IE-WH	0	0.51	0	0.03
IE-WX	0	1.29	0.26	0.12
IE-WW	0	1.18	0.67	0.14
IE-CE	0	0.97	0.12	0.09
IE-CO	4.59	1.68	1.11	0.28
IE-KY	0	0	0.9	0.18
IE-LK	2.34	0.05	0.52	0.22
IE-TA	0	1.16	0.26	0.04
IE-WD	1.39	0.32	0.31	0.08
IE-G	2.58	0.32	0.64	0.12
IE-LM	0	0.21	0.04	0.06
IE-MO	0	0.59	0.5	0.1
IE-RN	0	0.97	0.10	0.05
IE-SO	0	0.77	0.12	0.1
IE-CN	0	0.51	0.21	0.05
IE-DL	0	1.16	0.12	0.29
IE-MN	0	0.24	0.33	0.04

Table C.3: The average DH distribution capital cost, $\overline{C_{d,g}}$ (€$/GJ$), calculated using Eq. 5.3 using 50% marginal DH distribution costs

Region	Group: City	High Density	Medium Density	Low Density
IE	3.040723	3.230987	5.675036	12.17797
IE-CW	0	0	4.079347	10.63724
IE-D	3.13	4.361763	6.659351	20.5
IE-KE	0	2.450371	5.957186	13.79592
IE-KK	0	2.544552	8.917719	12.43099
IE-LS	0	2.575123	5.212489	12.07432
IE-LD	0	3.372581	7.292264	15.33812
IE-LH	0	2.756078	5.639586	12.94205
IE-MH	0	2.690948	5.316071	14.14505
IE-OY	0	2.899096	5.725699	11.66964
IE-WH	0	2.806688	0	11.7829
IE-WX	0	3.270049	7.020199	11.74984
IE-WW	0	3.348507	5.874322	14.2956
IE-CE	0	4.377439	7.918712	13.21995
IE-CO	2.94	3.227606	5.790422	9.940279
IE-KY	0	0	3.725437	11.53246
IE-LK	3.23	1.250088	5.69677	12.00908
IE-TA	0	4.294046	6.002946	12.4075
IE-WD	2.45	3.007417	7.323436	11.67405
IE-G	2.64	3.610388	5.693506	12.17226
IE-LM	0	3.6	6.999712	10.70055
IE-MO	0	2.95905	5.583608	13.99489
IE-RN	0	3.7757	6.184852	11.4581
IE-SO	0	2.917711	5.920865	12.16382
IE-CN	0	2.488326	6.262626	12.72998
IE-DL	0	3.285148	6.503342	12.32891
IE-MN	0	3.605867	5.032925	12.18051

Appendix D

Chapter 6

D.1 Heat Loss Indicator Calculated Input data

Table D.1: Combined Mean Heat Loss Indicator (HLI) and Standard Deviation (SD) for each Building Energy Rating (BER) group and dwelling archetype

BER	**Apartment**		**Attached**		**Detached**	
	Mean HLI	**SD**	**Mean HLI**	**SD**	**Mean HLI**	**SD**
A	1.00	0.273	1.15	0.342	1.36	0.213
B1	1.40	0.324	1.67	0.445	1.90	0.341
B2	1.58	0.268	1.84	0.457	2.13	0.307
B3	1.77	0.313	2.02	0.428	2.31	0.296
C	1.98	0.603	2.32	0.489	2.61	0.405
D	2.27	0.847	2.85	0.634	3.08	0.682
E	2.69	0.714	3.51	0.922	3.78	0.940
F	3.30	0.974	4.11	1.141	4.50	1.026
G	4.79	1.557	5.08	1.644	6.00	1.469

Table D.3: Calculated assumptions applied to the heat emitter upgrade cost and the fraction of actual to design efficiency by BER and dwelling type

BER	Heat Emitter Upgrade Cost (€)			Efficiency		
	Apartment	Attached	Detached	Apartment	Attached	Detached
AB	0	0	0	1.00	1.00	1.00
C	572	895	1,878	0.95	0.93	0.85
D	1,144	1,790	1,965	0.90	0.85	0.82
E	1,733	1,860	2,052	0.85	0.80	0.78
F	1,915	1,930	2,233	0.78	0.75	0.74
G	2,097	2,222	2,414	0.71	0.71	0.71

Table D.2: Cumulative distribution function probability results of a dwelling having a HLI less than or equal to selected a selected HLI for different BER groups and dwellings

	BER	HLI < 2.0	< 2.3	< 2.5	< 3	< 3.5	< 4	< 4.5
Apartment	A	0.99	1.00	1.00	1.00	1.00	1.00	1.00
	B1	0.97	1.00	1.00	1.00	1.00	1.00	1.00
	B2	0.94	1.00	1.00	1.00	1.00	1.00	1.00
	B3	0.77	0.95	0.99	1.00	1.00	1.00	1.00
	C	0.51	0.70	0.81	0.95	0.99	1.00	1.00
	D	0.38	0.52	0.61	0.81	0.93	0.98	0.99
	E	0.17	0.29	0.39	0.67	0.87	0.97	0.99
	F	0.09	0.15	0.21	0.38	0.58	0.76	0.89
	G	0.04	0.05	0.07	0.13	0.20	0.31	0.43
Attached	A	0.99	1.00	1.00	1.00	1.00	1.00	1.00
	B1	0.77	0.92	0.97	1.00	1.00	1.00	1.00
	B2	0.63	0.84	0.92	0.99	1.00	1.00	1.00
	B3	0.49	0.75	0.87	0.99	1.00	1.00	1.00
	C	0.25	0.48	0.64	0.92	0.99	1.00	1.00
	D	0.09	0.19	0.29	0.59	0.85	0.97	1.00
	E	0.05	0.09	0.14	0.29	0.49	0.70	0.86
	F	0.03	0.06	0.08	0.17	0.30	0.46	0.63
	G	0.03	0.05	0.06	0.10	0.17	0.26	0.36
Detached	A	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	B1	0.61	0.88	0.96	1.00	1.00	1.00	1.00
	B2	0.34	0.72	0.89	1.00	1.00	1.00	1.00
	B3	0.15	0.49	0.74	0.99	1.00	1.00	1.00
	C	0.07	0.22	0.39	0.83	0.99	1.00	1.00
	D	0.06	0.13	0.20	0.45	0.73	0.91	0.98
	E	0.03	0.06	0.09	0.20	0.38	0.59	0.78
	F	0.01	0.02	0.03	0.07	0.16	0.31	0.50
	G	0.00	0.01	0.01	0.02	0.04	0.09	0.15

D.2 Heat Loss Indicator assumptions

Table D.4: Ventilation and Heat Loss Parameters

Item & Formula	m3/h	ac/h
Ventilation - Infiltration due to Openings (α) [ac/h]		
No Draft Lobby		0.05
# Open Flue	20	
# Chimney	40	
# Fans & Vent	10	
# Flueless Gas Fire	40	
Ventilation - Infiltration due to Structure (β) [ac/h]		
# Storeys		(x-1)*0.1
Permeability Test	Test Result	
Structure type - Masonry		0.35
Structure type - Timber or steel frame		0.25
No Suspended Wooden Floor		0
Sealed Suspended Wooden Floor		0.1
Unsealed Suspended Wooden Floor		0.2
Percentage of Windows Draughtstripped		0.25-(0.2*(x/100))
Ventilation - Infiltration (γ) = α + β [ac/h]		
Number of Sheltered Sides (δ)		
Final Infiltration Rate (ϵ) = γ***(1-**δ***0.075)** [ac/h]		
Effective Ventilation (ζ) [ac/h]		
Natural Ventilation	0.51	
Positive Loft Ventilation	0.51	
Positive External Ventilation	0.5	
Extract Ventilation	0.5	
Mechanical - No Heat Recovery	0.66	
Mechanical - Heat Recovery	0.66	
Ventilation Heat Loss (η) = **0.33***ζ***Volume** [W/K]		
Fabric - U-Values (θ) [W/m^2K]		
Door	U-Value*Area	
Floor	U-Value*Area	
Wall	U-Value*Area	
Roof	U-Value*Area	
Thermal Bridging (ι) = **Total Area * Thermal Bridging Factor** [W/m^2K]		
Fabric Heat Loss (κ) = ι + θ [W/K]		
Heat Loss Indicator (λ) = (η+κ)**/Total Floor Area** [W/K/m^2]		

D.3 Additional Data

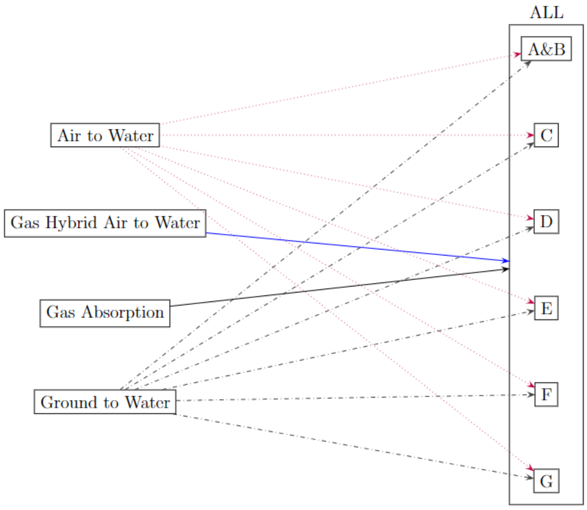

Figure D.1: Heat pump technology options are available for specific BER labels or ALL, which includes all the BER options. The BER label A&B indicates optimal heat pump performance, which is subject to variation according to the HLI threshold.