Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland

Ankita Gaur[a,b,*], Olexandr Balyk[a,b], James Glynn[c], John Curtis[d,e], Hannah Daly[a,b]

[a]*MaREI, The SFI Centre for Climate, Energy and the Marine, Environmental Research Institute, University College Cork, Co. Cork, Ireland, T23 XE10*
[b]*School of Engineering and Architecture, University College Cork, Co. Cork, Ireland*
[c]*Center on Global Energy Policy, Columbia University, New York, NY 10027, USA*
[d]*Economic and Social Research Institute, Sir John Rogerson's Quay, Dublin, Ireland, D02 K138*
[e]*Trinity College Dublin, Ireland*

Abstract

Typically, energy system decarbonisation scenarios neglect the mitigation opportunities from reducing and restructuring energy service demands (ESDs), focusing instead on technology and fuel substitutions. Models tend to be designed to factor technologies explicitly while ESD shifts are under-represented given that they are typically driven by non-economic factors. However, existing literature suggests that the scale and speed of decarbonisation required to limit global warming to 1.5°C at the end of the century requires a shift in energy demands, to avoid the need for large-scale negative emission technologies. This can be brought about by major structural changes in drivers of demand such as transport mode shifting, substituting emission intensive materials like cement, and reducing building heat demand through behaviour and efficiency.

Ireland, the subject of this paper, has legislated one of the most ambitious decarbonisation targets in the world: the need to understand the role of demand shift is paramount. To fill this gap, the Irish Low Energy Demand (ILED) mitigation narrative is developed and applied to the TIMES-Ireland Model (TIM), an energy systems optimisation model. ILED represents a scenario where ESDs are decoupled from economic growth by shifting travel, increasing end-use efficiency, urban densification, restructuring economic sectors, and changing social infrastructure. Compared to a scenario where ESDs follow 'Business-as-usual' growth, ILED enables the achievement of steep decarbonisation targets with a less rapid energy system transformation, lower capital and marginal abatement costs, and with lower reliance on the deployment of novel technologies.

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Keywords: Climate change mitigation, Decarbonization, Lifestyle change, Low energy

demand, Net-zero, TIMES, Macro Energy Systems Optimization Models

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Abbreviations

ASI	Avoid Shift Improve
BAU	Business as Usual
BECCS	Bioenergy with Carbon Capture and Storage
BER	Building Energy Rating
CAP	Climate Action Plan
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CREDS	Centre for Research into Energy Demand Solutions
EKC	Environmental Kuznets Curve
ESD	Energy Service Demand
ESOM	Energy System Optimisation Model
ETS	Emission Trading Scheme
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse gas
IAM	Integrated Assessment Model
ICE	Internal Combustion Engine
ILED	Ireland's Low Energy Demand
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
MAC	Marginal Abatement Cost
MEDEAS	Modelling the Energy Development under Environmental and Social constraints

*Corresponding Author. Tel: +353 (021) 4901931. Address: Environmental Research Institute, Lee Rd, Cork, Ireland , T23 XE10.

Email addresses: agaur@ucc.ie (Ankita Gaur), olexandr.balyk@ucc.ie (Olexandr Balyk), jg4434@columbia.edu (James Glynn), john.curtis@esri.ie (John Curtis), h.daly@ucc.ie (Hannah Daly)

MESOM	Macro Energy System Optimisation Model
NET	Negative Emissions Technology
PKMS	Passenger kilometres
PSV	Public Service Vehicle
RECC	Resource Efficiency and Climate Change
RES	Reference Energy System
SDG	Sustainable Development Goal
SEAI	Sustainable Energy Authority of Ireland
STS	Societal Transformation Scenario
TIAM	TIMES Integrated Assessment Model
TIM	TIMES Ireland Model
TIMES	The Integrated MARKAL-EFOM System

1. Introduction

The IPCC's Special Report on global warming of 1.5°C (SR1.5) published in 2018 had a profound impact on international and national climate policy discussions [1]. It emphasised the need to reduce global annual CO_2 emissions by half by 2030, relative to 2010, and to net-zero by 2050, to limit global temperature rise. The report prominently features climate mitigation scenarios and development pathways that inform the techno-economic feasibility of measures adopted to curb emissions. Pathways that limit global warming to 1.5°C this century require rapid and deep transformations in the energy and industrial systems, land use and urban infrastructure.

Energy consumption has always been strongly coupled with economic growth and if this correlation exists in the future, meeting climate goals will require unprecedented changes in most technologies, fuels and infrastructure, innovations and large-scale negative emission technologies. A pathway that occupies a notable position in the climate change policy discourse is the 'green growth' theory that asserts economic growth (measured in terms of GDP) can be decoupled from resource use and CO_2 emissions. However, some studies argue that existing empirical evidence does not fully support this theory, partly due to the economy-wide rebound effect [2–4]. Another approach that addresses economy-environment interactions is called the Environmental Kuznets Curve (EKC) that postulates CO_2 emissions increase at the early stages of economic development and automatically start to decline at a later stage when economic growth is high and green technologies can be implanted as shown in Figure 1 [5]. This decoupling between environmental degradation and economic growth is also achieved by outsourcing environmentally intensive production on a national basis but this does not work on a closed-loop global system [6]. Hence, harmonising unabated economic growth and ambitious climate goals within the time-frame available to limit global warming is challenging [7].

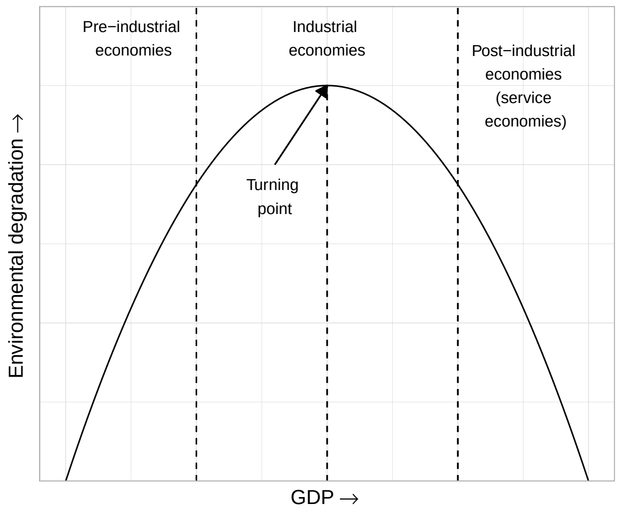


Figure 1: Environmental Kuznets Curve (own adaptation)

With some exceptions, energy system decarbonisation scenarios tend to conform to the 'green-growth' paradigm: assuming that the drivers of energy demands will follow historical patterns, they demonstrate how mitigation targets can be met with technology and fuel switches alone.

One of the major features of the scenarios reviewed in the IPCC's SR1.5 is the role of carbon dioxide removal (CDR) through the use of negative emissions technologies (NETs) to meet the end-of-century climate goals [1]. Most of the scenarios modelled for this report feature a temporary overshoot in the increase of the global temperature of 1.5°C above preindustrial levels, and use NETs to reduce atmospheric concentrations of GHGs and return to the the temperature target. However, there is a real risk that these technologies might not be able to deliver CDR at the scale promised and a CDR-depe[8–13]. Some NETs can have adverse impacts on ecosystem and questions about their feasibility in terms of cost, land availability and competition for food production, feedstock resource potential, social acceptance, and safety are yet to be addressed along with other geophysical and institutional barriers [8, 12, 14]. Hence, there is a need to explore alternate mitigation pathways that limit or do not use NETs [15].

Figure 2 shows the CO_2 emissions in the four 1.5 °C consistent illustrative pathways featured in SR 1.5 [1, 16–18]. It can be clearly seen that the LED pathway has the lowest negative emissions among other featured scenarios.

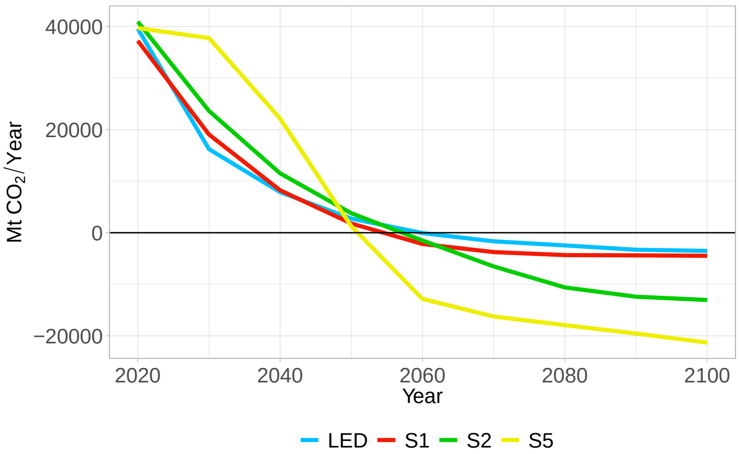


Figure 2: Evolution of CO_2 emissions in the illustrative pathways featured in SR 1.5 where S1, S2 and S5 are shared socioeconomic pathways [16–18]

Alternate deep mitigation pathways include the impact of technological changes, structural changes in the economy, and societal transformations on the drivers of energy demand [19, 20]. Mitigation scenarios have traditionally focused on the supply side of the energy system while behavioural and end-use demands have received less attention [21]. This is because the present generation of Integrated Assessment Models (IAMs) or Energy System Optimisation Models (ESOMs), which underpin global and national climate mitigation planning, typically has limited capabilities for endogenously representing new behavioural changes or social structures that can affect energy demand, whereas, representing technology and fuel switches are straightforward [22, 23]. Most models produce future energy mixes based on exogenous energy service demand projections driven by historical relationship between population and economic growth. Though efficiency improvements are often included such as building retrofits, electrification and fuel switch, and technology upgrades, other solutions that could either lower energy demand or shift to cleaner modes of provision such as mode shift, lowering heating temperature set-point and material recycling are relatively new that can limit climate change but are often missing [24–27].

The purpose of this paper is threefold: First, we argue for broadening mitigation scenarios to include Low Energy Demand (LED) pathways, which include changes in both the structure and trajectory of energy service demands[1] (ESDs) as a mitigation option. We begin by discussing the importance of considering LED pathways in climate mitigation scenarios and the role they might play in achieving the Paris Agreement temperature targets (Section 1.1). Then, we explore the measures through which demand could be modified along with their interdependencies (Section 1.2). Second, we review the LED-type scenarios available in the energy system modelling literature including scenario narratives and corresponding parameters (Section 2). Third, we present a case study for Ireland using the newly-developed TIMES Ireland Model (TIM) (Section 3). Ireland has recently committed to a legally-binding target of reducing GHG emissions by 51% by 2030 relative to 2018 and a net-zero GHG target by 2050. We develop a new Irish LED scenario (ILED) and demonstrate the impacts this has in achieving energy system decarbonisation targets. The discussion and conclusion are presented in Sections 5 and 6 respectively

1.1. Rationale for low energy demand pathway

"Low energy demand" (LED) pathways are mitigation scenarios in the literature based on reducing energy service demands through changes in behaviour, increasing end-use efficiency, brought about by, for example, denser urban development, economic restructuring, consumer practices and changing social infrastructure [7, 26, 28]. Most of the climate mitigation scenarios are technology optimistic and assume novel fuels and technologies to be economically feasible in the future and that existing fuels and technologies are to undergo efficiency improvements. On the contrary, in LED scenarios the absolute levels of energy service demands are reduced relative to a baseline or "business as usual" (BAU) case, and enables faster GHG reductions and/or lowers the need for novel fuel and technologies [26].

A lower level of energy demand services implies downsizing of the entire energy system, compared to a BAU growth in ESDs, making it easier to decarbonise the supply side [26, 29]. Along with enabling a clean energy transformation, the LED pathway requires lower deployment of CDR and biofuels [29]. The most widely-modelled NET is bioenergy with carbon capture and storage (BECCS), which requires large areas of land that raises concerns about biodiversity loss, which can be avoided in the LED pathways [7, 8, 26].

Long-term decarbonisation pathways are dependent on short-term policies, and feasible only if actions are taken sooner rather than later [30–32]. However, achieving the near-term (2030) steep decarbonisation targets necessary to meet the Paris Agreement goals is challenging given the slow turnover of fossil fuel technologies, leading to high mitigation costs,

[1] Energy Service Demands (ESDs) include demand for activities that drive the demand for final energy consumption, such as space and water heating, cooking, washing, mobility, materials production etc.

heavy reliance on often novel technology deployment, and increases likelihood of overshooting the carbon budgets and targets [33, 34]. In such a scenario, the LED can play a crucial role in overcoming the impacts of delayed response and making near-term targets feasible (see Section 4).

An important point to note is that the LED pathway proposes a reduction in energy demand without compromising quality of life [7, 26]. Other possible co-benefits of the LED pathway include reduced air pollution, better indoor environment, healthier lifestyles, a decent standard of living for all and smaller energy bills [7, 26].

1.2. Reducing energy service demand: options and modelling

'Reducing' energy service demands is a viable option for helping to meet decarbonisation targets, especially for developed countries. However, there is a lack of detailed discussion on how this can be practically achieved [35]. Energy demand can be reduced in several ways:

- By improving device efficiency, where the same level of energy service demand is met with less energy consumed through more efficient devices, such as more efficient cars or heating systems;
- Through structural shifts in energy service demands towards more efficient processes, for example through mode switching in private transport towards public transport or active modes, or switching construction materials from carbon-intensive products such as cement to timber, or
- Through reducing energy service demands, such as reducing travel demand through compact urban development and teleworking, or reducing the size of residential homes, thus reducing the floor area of dwellings to be heated [36].

If we assume car kilometres are fixed, then decarbonisation may only be delivered through changing vehicles or fuels. However, a broader perspective on mobility that includes the possibility of mode shit, ride sharing or telecommunication expands the mitigation options space. Although LED scenarios consider efficiency improvements in their narratives, it is necessary to distinguish between energy demand (kWh, MJ, litres of petrol) and energy service demands (practices and economic products, like mobility, passenger bus, tonnes of cement, value added in services, thermal comfort in buildings, materials production, etc). Efficiency improvements and technology uptakes reduce the energy demand levels, while in the LED we emphasize decreasing the ESD levels or changing their structure. Nevertheless, modifying ESDs will need technical and social innovations such as investments in public transport infrastructure, encouraging work-from-home scheme, building retrofit grants, planning dense urban development [37].

The enablers of modifying ESDs can be broadly classified into four categories, namely: Technological, economic system transition, behavioural and lifestyle changes, and policy interventions (Figure 3). The enablers are methods or changes through which end-use service demands can be reduced directly or indirectly. For instance, remote working and online shopping directly reduce passenger kilometres whereas public transport infrastructure has an indirect impact on passenger kilometres through mode shift. We acknowledge that the interactions shown in the figure are not exhaustive.

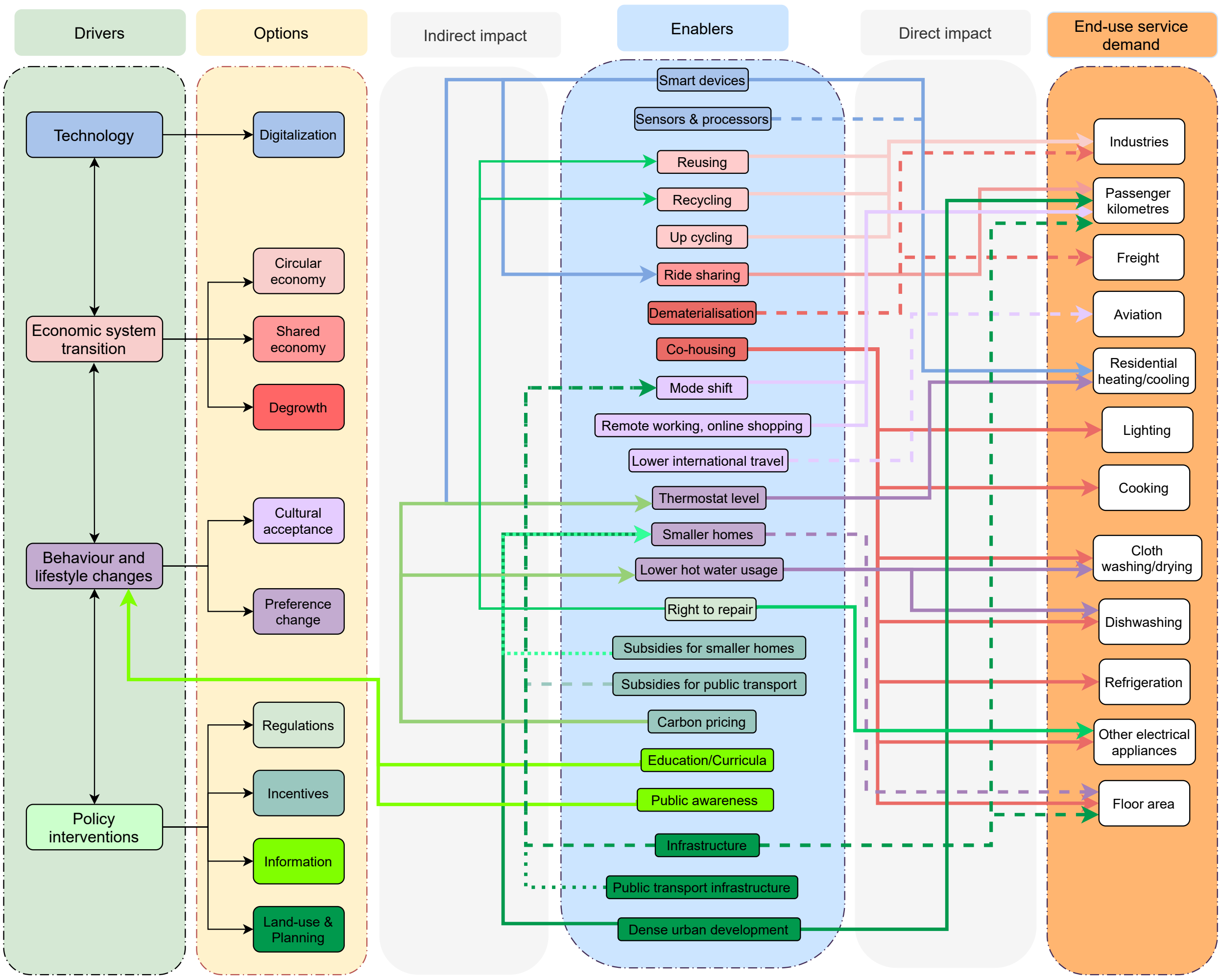


Figure 3: Options to reduce energy demand

Among the options described in Figure 3, IAMs and ESOMs often endogenously represent efficiency improvements (same energy service output, lower energy input e.g. more efficient boiler) and technological substitution (same energy service output, different technology input e.g. heat pump vs oil boiler) while lifestyle changes (different energy input and energy service output e.g. lower internal temperature setting) are usually exogenous and in a stylised form in such models [38]. Apart from efficiency and technology, demand reduction can be analysed endogenously in ESOMs like TIMES through cross-price elasticities as shown by Kesicki and Anandarajah [25].

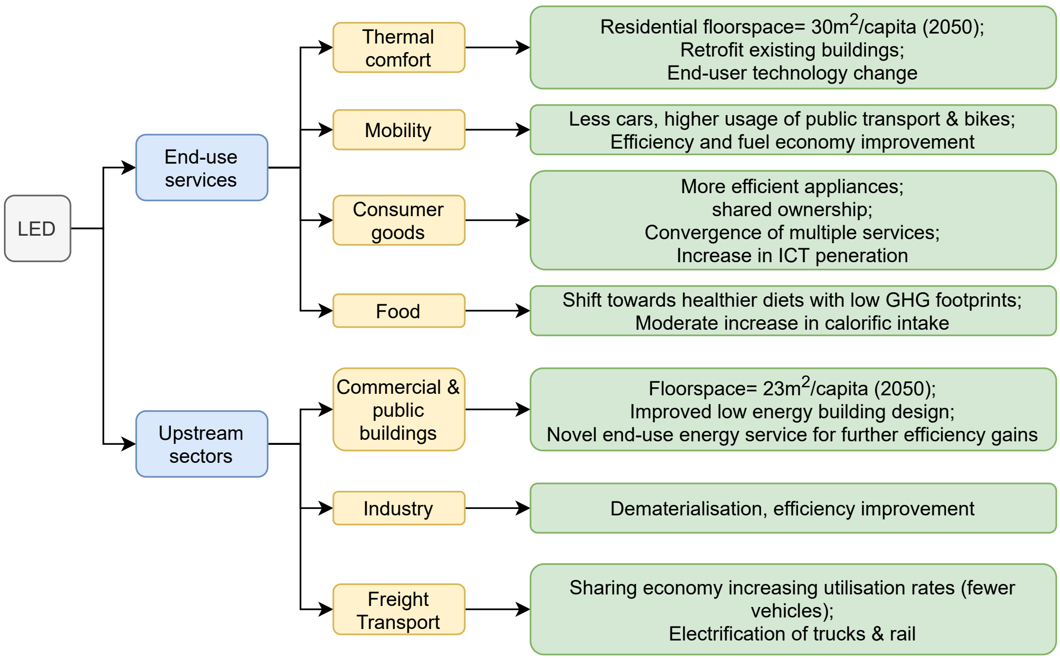
Some studies have also incorporated behavioural constraints in IAMs and ESOMs to endogenously represent behavioural measures. For example, McCollum et al. [39] show the benefits of incorporating behavioural features in connection with vehicle choice in an IAM framework. Their scenarios indicate that including behavioural aspects allows a more 'realistic' assessment of non-price based policies [39]. Daly et al. [40] use the travel time budget concept and a public transport investment factor (travel time investment parameter) to enable endogenous modal choice within the TIMES framework. This concept is further extended by Pye and Daly [41] to include the rate of modal shift and maximum modal shift potential. Both these studies demonstrate that behavioural measures are an important mitigation strategy for decarbonising passenger transport. Tattini et al. [42] further elaborate the previous two studies and assess modal shift dynamics in an integrated energy system in TIMES for the whole country. This studies shows that modal shift enables the energy and transport sectors to reach carbon-neutrality at a faster pace and at lower costs compared to the case when modal shift is not included [42]. Tattini et al. [43] further improve representation of endogenous modal choice in a TIMES framework by including demand-side heterogeneity and intangible costs that vary with class of transport users. Cayla and Maïzi [44] develop a modelling approach to include household behaviour in terms of energy consumption and equipment purchase, and household heterogeneity in TIMES-Households model. The results indicate that unrealistic technology diffusion can be avoided if sufficient heterogeneity is considered. These studies demonstrate the value of endogenising consumer decisions within IAMs or ESOMs and how behavioural measures are an important part of decarbonisation strategies. However, a number of gaps still remain: options to 'reduce' energy service demand are missing from these studies, costs of bringing about behaviour change are typically not captured and these studies focus on sectors in isolation, rather than taking a whole-systems approach.

2. Low energy demand scenarios

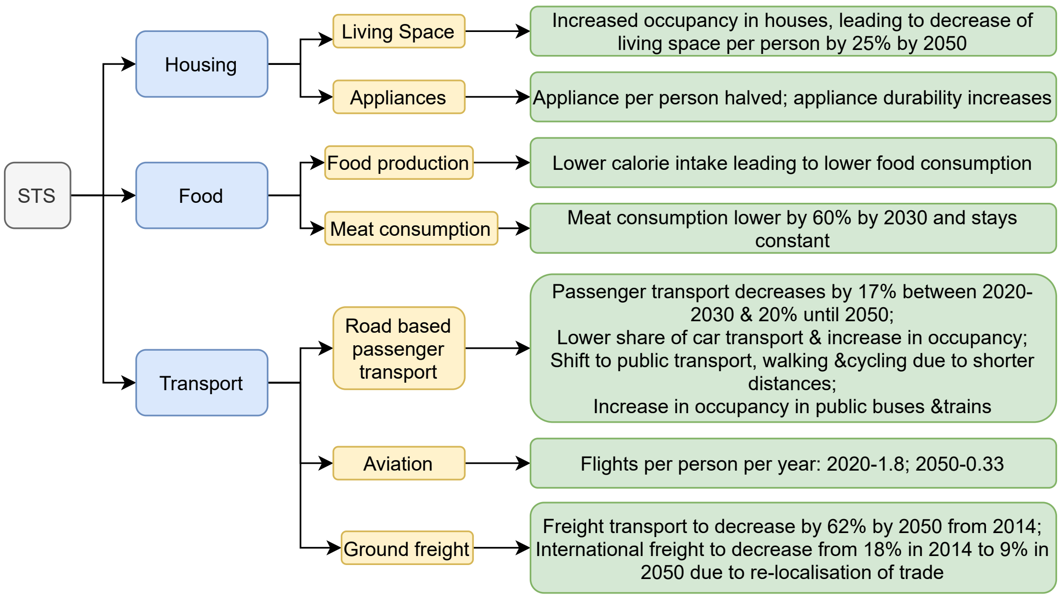
This section reviews low energy demand scenarios identified in the literature. The previous section covered studies that focus on a single sector while the LED scenarios reviewed here encompass narratives covering multiple ESDs. We found two studies that consider the global energy system and exclusively focus on the potential for lower demand scenarios and their implications for the energy system, called 'Low Energy Demand' (LED) by Grubler et al. [26] and 'Societal Transformation Scenario' STS by Kuhnhenn et al. [7]. Figure 4 shows the layout of narratives in the LED and STS scenarios. Both scenarios broadly rely on a combination of technological innovations, economic transitions, behavioural and lifestyle changes to bring about major reductions in energy service demands. The key premise in both scenarios is to maintain energy consumption at sufficiency levels for a decent standard of living for all. The studies also evaluate their impact on the United Nation's Sustainable Development Goals (SDGs). These scenarios convert behavioural and lifestyle change narratives into relevant parameters and calculate demand reductions exogenously. However, there are several key differences to note. Firstly, the LED scenario is simulated using MESSAGEix-GLOBIOM (optimisation), an integrated assessment modelling framework while the STS uses Global Calculator (simulation) that is an open source model of the world's energy, land and food system. Secondly, in the LED, changing energy service demands have impacts on upstream sectors, covering a greater part of the energy and economic system while the STS is solely focused on end-use services. And finally, the LED includes nuclear power whereas STS omits this option.

The LED and STS scenarios each cover only two world regions: the Global North and Global South in the former, and Annex I and Non-Annex I countries in the latter. More regional resolution would allow consideration of socioeconomic trends and technology uptake rates [45]. As an application of the Grubler et al. [26] LED scenario, Fishman et al. [45] develop detailed scenario parameters for the residential buildings and private transport sectors, covering 20 global regions. Dwelling area is assumed to converge to 30m^2/capita by 2060 globally and passenger kilometres to reduce to 8434 person-km per capita in developed nations in the LED scenario. The changes are to occur through denser urbanisation, multi-family homes, modal shift, and lifetime extensions of buildings and vehicles. The material efficiency improvement potentials are determined for each of the sectors using the Resource Efficiency and Climate Change (RECC) framework and implementation strategies include end-of-life recovery, material substitution, reuse, downsizing among others.

Several other global studies have modelled low energy demand-type scenarios for particu-



(a) Low Energy Demand scenario by Grubler et al. [26]



(b) Societal Transformation Scenario by Kuhnhenn et al. [7]

Figure 4: Comparison of narratives of two global low energy demand scenarios

lar sectors. Sharmina et al. [46] focus on difficult-to-decarbonise sectors: aviation, shipping, road freight, and industry using IMAGE. Demand reduction options for the various sectors are as follows: Aviation:- large scale modal shifts to high-speed trains and carbon tax to discourage flying; Shipping and road freight:- carbon tax which will provide incentives for distributed manufacturing and local storage to reduce need for freight; Industry:- recycling of iron and steel. This study concludes that demand-side opportunities exist and need better representation in IAMs. They argue that without any demand reduction in these sectors, decarbonisation will depend on the deployment of CDR technologies.

Napp et al. [47] use the TIMES Integrated Assessment Model-Grantham (TIAM-Grantham) to explore the role that advanced technologies and energy demand reductions through behavioral changes can have for the global industry and transport sectors. The demand reduction potential of each sector is obtained from the literature. Their results indicate that advanced technologies along with demand reduction can bring about deep and rapid decarbonisation of the energy system and reduce the reliance on BECCS by approximately 18% [47].

At the national level, two studies were found that present LED scenarios using an energy system model with exogenous energy service demand projections [48, 49]. Barrett et al. [48] present a comprehensive analysis of the role energy service demand reduction can play in meeting UK's 2050 net-zero goal undertaken by the Centre for Research into Energy Demand Solutions (CREDS). Their 'Transform Demand' LED scenario considers a transformative change in technologies, practices and infrastructure that bring about reduction in energy service demands along with co-benefits such as improved health and local environment, lower investment needs and lower cumulative GHG emissions. This report concludes that LED scenario has several advantages in achieving the net-zero target which include reducing fossil-based energy production, overcoming technical challenges associated with transforming a large energy supply system, reduces overall investment and reliance on risky CDR technologies. The LED scenario does not compromise quality of life even with a halving of energy demand in UK.

Oshiro et al. [49] present a LED scenario for Japan called 'LoDem' scenario that considers energy service demand reduction measures such as dematerialisation, material efficiency improvement, reducing hot water usage, adjusting thermostat level, shifting to non-motorised and public transport, reducing passenger trip frequency, and lower freight demand. Implementing energy service demand reduction measures along with energy-efficient technologies could reduce final energy demand up to 37% by 2050 [49]. These measures could also reduce dependency on CCS by 50% in 2050. Sectoral analysis indicates that industry is the largest contributor to reducing system costs through demand reduction followed by buildings and transport.

The industrial sector, a major energy consumer, can be difficult to decarbonise, especially due to rebound effects following efficiency improvements [50]. We found two studies that present LED pathways exclusively for the industrial sector, one at the global level and the other at the national level for Japan [50, 51]. Globally, industrial sector consumes 24% lower energy in 2050 in the LED scenario relative to a BAU scenario when energy efficiency improvement measures and increased recycling are considered alongside lower material demand [50]. On the other hand, Ju et al. [51] present climate mitigation scenarios for Japan's industries using four energy-economic models and IAMs. They present two low energy demand scenarios. In the first scenario, lower GDP growth rates are used while in the second, energy service demands are reduced by 50% by 2050 along with lower GDP growth rates. The underlying narrative for the second scenario includes improvements in material efficiency, shift to smart devices and low carbon products, natural disasters, financial crisis, etc. The multi-model analysis shows that a low industry demand scenario reports the largest emission reduction and also reduces production and marginal abatement costs.

Passenger transport demand is driven by infrastructure, spatial settlement patterns and, socioeconomic and technological transitions. Behavioural and lifestyle changes have huge impacts on transport energy consumption enabled by public and active transport infrastructure and, planning and policy signals that favour these modes over private cars [52]. Four studies are found, three at the national level and one at the global level, that analyse a low energy demand pathway for passenger transport. de Blas et al. [53] use MEDEAS-World IAM to analyse global transport decarbonisation strategies for 2050. Among the simulated scenarios, the 'Degrowth' scenario accounts for demand reduction through behavioural and cultural change that leads to change in mobility patterns. This scenario is based on the assumption that serious efforts will cause a shift from the present growth-oriented economy towards one which ensures sufficiency without excessive growth in energy demand. These include modal shift in passenger and freight transport, demand reduction and decrease in economic activity. The recycling rate is assumed to double between 2020 and 2050. Results show that only the degrowth scenario meets decarbonisation targets while maintaining minimum mineral reserves for critical materials.

Two studies describing passenger transport decarbonisation scenarios for Japan are found [54, 55]. Both these studies assume that teleworking, online shopping, better public transport, carpooling and ride sharing, and efficient urban planning are factors that will lead to a decrease in passenger kilometres [54, 55]. Besides a decline in individual mobility, an ageing society leads to a decrease in total passenger kilometres despite economic growth [55]. Although both studies have similar narratives, Gi et al. [54] present a very detailed scenario, they capture daily life behaviour as well as megatrends such as population aging, gender equality, tertiary industrialization, and transport technology innovation, as compared to Kainuma et al. [55].

Brand et al. [52] present contrasting futures using a simulation model and quantitative scenarios that consider transport-related lifestyle change along with techno-economic transition for Scotland. They found that carbon budgets are achievable only in the 'Combined lifestyle and EV' (radical change in travel patterns, mode choice, high electrification and phasing out of conventional petrol and diesel road vehicles) scenario, in which the average number of trips decrease by 55/person/year and distance travelled decreases by 1653 kms/person/year by 2050 relative to 2012 [52]. In this scenario, lower demand is met by a different modal shift (less private cars, more public transport, higher occupancy, ride-sharing), higher fuel efficiency, and new low carbon technologies [52].

For the residential sector, Levesque et al. [56] explore the potential of low energy consuming practices that include new behaviours and uptake of green technologies. Their analysis revealed that these practices could reduce energy demand from the residential sector by 61% by 2100. Some of the behavioural measures include low demand for floor space, shorter and lesser showers, adjusting thermostat levels according to the outdoor temperature, wearing the same clothes more often, using dishwashers at full load only, and reduced hot water usage.

As a slight variation of the LED scenarios, Millward-Hopkins et al. [28] present a global energy scenario using a bottom-up modelling approach that combines activity levels and energy intensities for each end-use service and then calculate total final energy consumption maintaining 'Decent Living Standard' globally. They estimate that global energy use could be reduced to 1960 levels despite population growth, provided energy demand is reduced to sufficiency levels.

Figure 5 summarises all the options discussed in the literature presented above. We use the "Avoid-Shift-Improve" (ASI) framework to categorise all the options. Although generally used for the transport sector, this framework is now being extended to include other demand-side sectors as well [57]. This ASI framework is associated with a modified 'Kaya identity', which helps to identify how each option has the potential to reduce emissions [58]. In this form of the identity, carbon emissions are decomposed into four parts namely activity, structural change, energy intensity, and fuel mix (carbon intensity). Lower activity implies lower service demand which is equivalent to energy demand 'avoided'. Any structural change in energy consumption leads to a 'shift' in energy demand e.g. mode shift, material substitution. And finally, decreasing energy intensity and reducing the carbon intensity of the fuel mix is an 'improvement' in efficiency. The 'improve' category is endogenous in IAMs and ESMs while the 'avoid' and 'shift' categories are generally exogenous.

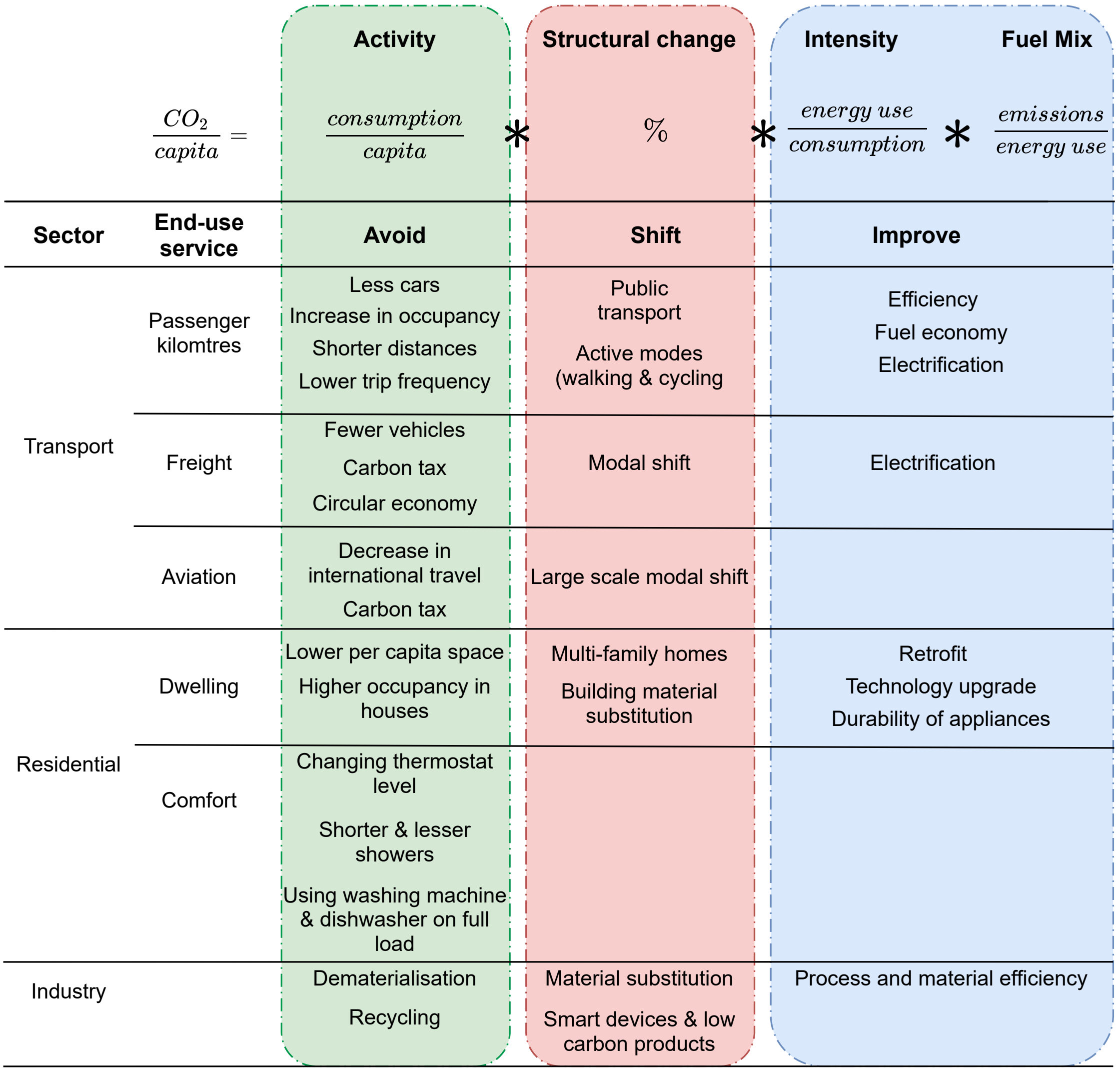


Figure 5: Categorisation of options in LED pathways (adopted from [58])

The literature above suggests that LED scenarios can play an important role in mapping energy system pathways consistent with limiting global warming to 1.5-2°C. The studies above demonstrate additional mitigation measures which enable more feasible technical transition and can bring co-benefits are needed to achieve ambitious GHG reduction targets. They demonstrate the importance of diversifying and expanding the mitigation space. Without considering demand sector mitigation options, the burden of decarbonising the energy sector is on NETs, which has uncertainty in its deployment.

The mitigation options above cannot be achieved through responsible behaviour alone and should be brought about by a planned socio-economic transformation. Policies must include behavioural and lifestyle changes and not just technology-dependent solutions. More research and development is needed to promote such changes through effective policy designs.

However, there are very limited national studies that demonstrate a mitigation pathway including an LED scenario. Although global studies provide good examples of what the energy service demand reduction options are, the feasibility of these mitigation options can be very regionally specific. Further, the economic, social and political feasibility of these pathways and the 'cost' of demand reduction is not discussed in the literature, and are important research questions. Although demand reduction has been a topic of discussion for a long time, its analysis and implementation have not been discussed sufficiently in the energy systems modelling literature. This study seeks to fill that gap.

3. A Low Energy Demand pathway for Ireland (ILED)

This study develops an Irish Low Energy Demand scenario (ILED) to demonstrate how modifying energy service demands can contribute to meeting very ambitious decarbonisation goals. Broadly, ILED encompasses a scenario with densification of settlement patterns, very significant investment in public transport and walking and cycling infrastructure, and dematerialisation of the economy, which enables large-scale modal shifts in transport, lower heat demand in buildings, and lower demands for materials such as cement. This study then applies both a business-as-usual energy demand scenario and ILED to different climate mitigation targets, including very steep near-term ambition as well as a 'net-zero' target for 2050.

3.1. Background

Ireland's energy system accounted for 58% of the total GHG emissions in 2019 of which the transport (20.4%), energy industries (15.8%) and residential (10.9%) sectors had the highest shares [59]. Further, the CO_2 intensity of energy supply in Ireland is 20% higher than the European average, which makes long-term decarbonisation goals a challenge [60]. The Irish Government has enacted the Climate Action and Low Carbon Development (Amendment) Act 2021 which sets in place a framework for legally-binding carbon budget ceilings consistent with reducing GHG emissions by 51% by 2030 relative to 2018, and to reach net-zero CO_2 by 2050 [61].

However, there are several challenges that Ireland must overcome to achieve these targets. Firstly, 35% of GHG emissions arise in the agriculture sector, which is dominated by beef and dairy production. The emissions from agriculture are considered more difficult to abate than energy sectors, and therefore the energy sector is likely to be required to decarbonise faster than 51% to meet the overall target. The most recent Climate Action Plan published in 2021 by the government sets out a sectoral decarbonisation ranges for 20-30% for the agriculture sector to 2030, which would require CO_2 emissions from the energy system to reduce by 60-70% this decade. Secondly, fossil fuels represent more than 90% of the share of energy in the transport and heating sector demands. Dispersed settlement patterns and an inefficient building stock make decarbonisation particularly challenging [62]. Finally, decarbonising electricity is a challenge given that nuclear energy is not adopted, and as the electricity grid is relatively isolated from mainland Europe, integrating high shares of renewables is technically challenging though, the wind resource is substantial [63].

To demonstrate how very steep decarbonisation of the energy system may be achieved, both to 2030 and 2050, this paper presents a case study on the evolution of the Irish energy system with energy service demand reduction as a mitigation pathway.

3.2. TIMES-Ireland Model and ILED Scenario Description

This study models the ILED scenario in an energy system optimisation model (ESOM). For our purpose, we have used the TIMES Ireland Model (TIM), a successor to the Irish TIMES model, which has provided inputs to Irish energy policies for over a decade [64–67]. This new model has been recently finalised and accounts for the changing energy system, advances in modelling methodology, and the ambitious mitigation targets for Ireland [64].

Figure 6 shows a simplified reference energy system (RES) in TIM. The RES consists of two main modules: Supply and Demand. The supply module consists of resources, fuel production and conversion technologies, and infrastructure. The demand module comprises the end-use sectors and their corresponding energy service demands. The base year is 2018 and all energy flows, emissions, and energy technology stocks are calibrated to SEAI's 2018 energy balance [68]. A social discount rate of 4% is applied. TIM is set up with flexible regional and timeslice definitions, ranging from a single region national model at one annual time slice, all the way to 26 counties at hourly resolution. We use the annual period definition, single region, and the 40 timeslice version of TIM in this study.

The business-as-usual (BAU) ESDs in end-use sectors are driven by growth in the population and the economy. The energy service demands are sufficiently disaggregated to allow for alternative scenarios for these drivers to feed into alternative energy service demand projections, namely ILED. Further information on BAU energy service demands can be found in Appendix A. Table 2 outlines the key assumptions for the ILED scenario.

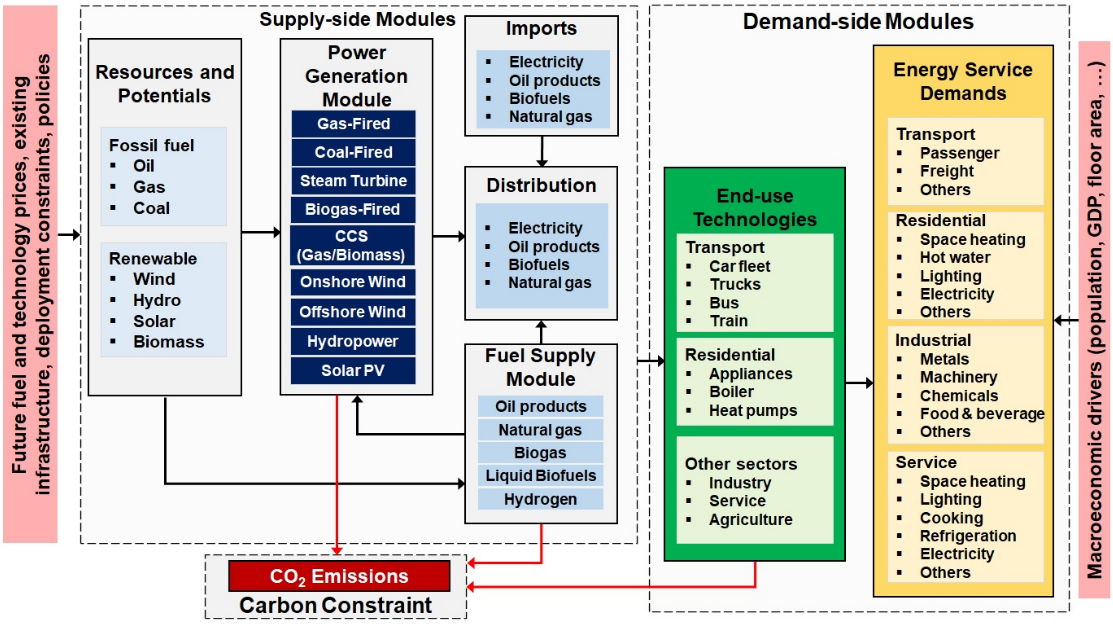


Figure 6: Reference energy system in TIM

The ILED pathway parameters are based on literature view, historical trends and comparison with other developed nations that lead to low energy demand. These parameters are not only based on technical details such as efficiencies but also on behavioural and societal transformations such as choosing more sustainable modes of transport or lowering internal heating temperatures in homes. The assumptions on parameter values are rather arbitrary and need additional scoping. The ILED is basically a "what-if" scenario that represents a future where ESDs are lower in comparison to BAU projections.

- Transport
  - Freight transport: The total road freight activity was approximately 11.5 billion tonne-kilometres (tkms) in 2018. Road-based freight transport increased by 110% between 1995 and 2018, with current projections foreseeing a further increase of 2.18 times between 2018 and 2050. Figure 7 shows the historical freight tkms in Ireland in comparison to Great Britain (GBR), United States (USA), Japan (JPN) and the EU average [69]. Freight activity in Ireland increased during the Celtic Tiger years (1994-2007) when the Irish economy grew rapidly. ILED assumes per-capita freight activity will return to the 1995 level - 1525 tkms/capita in 2050. This is a reduction of about 36% from the 2018 level of 2375 tkms/capita. The underlying narrative is that reviving local economies, better logistics and

reductions in consumer demands, particularly for heavy materials such as construction materials, enables this reduction. Total freight activity is then expected to be 9.45 billion tonne-kilometres in 2050, a total reduction of about 18% from that in 2018.

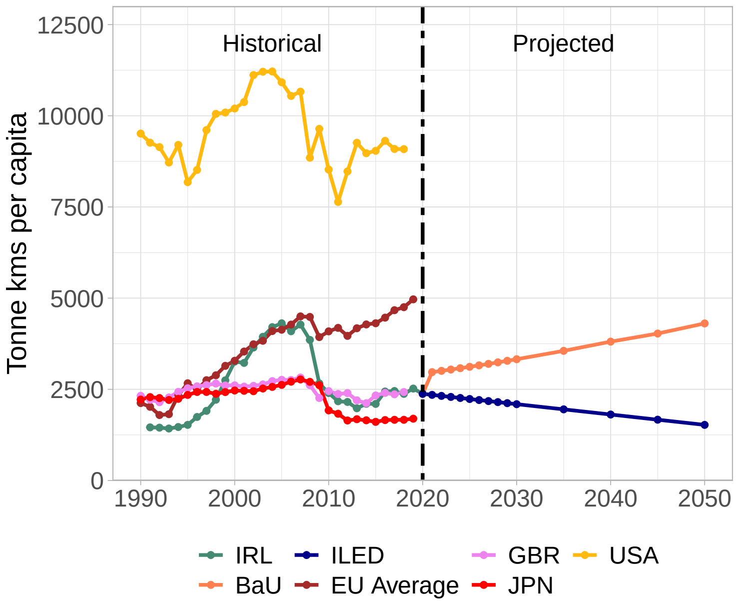


Figure 7: Comparison of tonne kilometres per capita

– Passenger transport: Road-based passenger transport activity (vehicle kilometres (vkms)) increased by about 36% between 2000 and 2018 [70]. The total passenger transport resulted in about 73.7 billion-passenger kilometres (bpkms) in 2018, which is about 15,342 passenger kilometres (pkms)/capita. In BAU projections, this increases to around 17,000 pkms/capita in 2050. In the ILED scenario, we assume that the pkms/capita will decrease to 12,000 owing to shorter travel distances, increased occupancy in vehicles, and a large share of the labour force working from home by 2050. This results in a total of 74.3 billion pkms in 2050. The long-term development strategy of the Irish government is to ensure compact growth of cities such as to reduce travel distances which is to be enabled through infrastructure and supporting amenities [71]. In this context, we assume short distance travel (< 5kms) to increase by 5% in 2050 whereas medium (5-30 kms) and long-distance (>30kms) journeys to decrease by 2.5% each. The historical modal share of passenger transport is shown in Figure 9. Private cars make up about 80% of total passenger transport in Ireland. In the ILED scenario we assume a change in travel pattern that encourages more of active modes and public services, and less of private cars as shown in Table 1. Active modes such as walking, and cycling have a much greater share in the ILED scenario as compared to 2018. The share of private cars decrease by 21% and that of large PSVs increase by 9%.

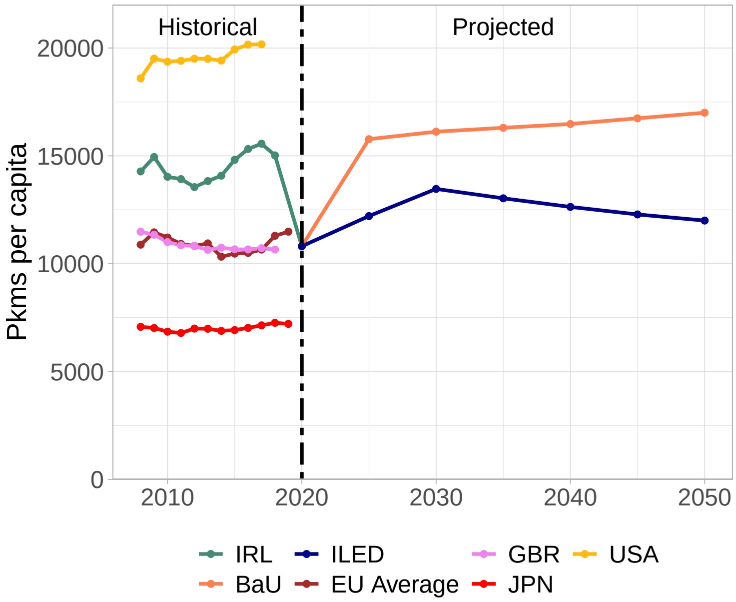


Figure 8: Comparison of passenger kilometres per capita

Table 1: Passenger transport modal share

Mode	Short distance (< 5km)		Medium distance (5-30 km)		Long distance (> 30 km)		Total	
	2018	2050_ILED	2018	2050_ILED	2018	2050_ILED	2018	2050_ILED
Private cars	51%	20%	83%	65%	74%	62%	73%	52%
Motorcycles	0%	0%	0%	0%	0%	0%	0%	0%
Small PSVs	2%	2%	2%	1%	1%	1%	2%	2%
Large PSVs	8%	13%	13%	27%	16%	24%	14%	23%
LUAS	1%	3%	1%	4%	0%	0%	0%	2%
Train	0%	0%	0%	2%	8%	13%	3%	5%
Walking	32%	49%	0%	0%	0%	0%	6%	12%
Cycling	5%	14%	0%	1%	0%	0%	1%	4%

- Residential sector: The residential sector accounted for 24% of final energy consumption and about 10% of CO_2 emissions in 2018. A total 1.7 million houses and apartments were occupied by residents of Ireland according to the 2016 Census, of which 12.2% were apartments, 45.1% were attached and 42.7% were detached houses. The

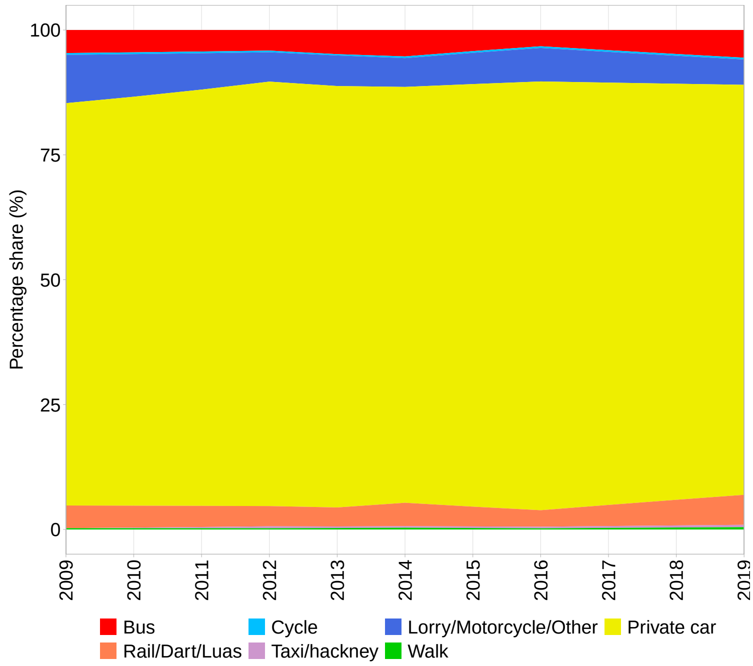


Figure 9: Historical mode share of passenger kilometres in Ireland

total housing stock is projected to grow to 2.57 million by 2050, with 24.4% apartments, 41.1% attached and 34.5% detached dwellings in the BAU case. The planned urbanisation in [71] talks about 50% of new dwellings will be in built-up footprint of 4 larger cities. And for most other urban areas it is 30%. The ILED assumes that new detached houses are upgrading and replacing existing ones, and of the new houses required, 60% will be apartments and 40% attached dwellings due to planned urbanisation [71]. Figure 10 shows the comparison of dwelling types for the BAU projection and ILED. Further, behavioural and efficiency improvements reduce the energy service demands within households. Space and water heating make up to 80% of residential energy demand. The ILED assumes that space heating demand per dwelling decreases by 20% by 2050, 10% of which is to be achieved by lowering heating temperature by 1°C [72, 73]. The other 10% can be achieved by encouraging boiler servicing every year. A further 4% saving in space heating is assumed for attached and detached dwellings, to be attained by using radiator valves to turn off heating in unoccupied areas. Domestic water heating demand is assumed to decrease by 30% owing to shorter showers, lower heating temperatures, insulating tanks and installing immersion timers. Energy demand for lighting and, pumps and fans are assumed to decrease by 10% each.

The ILED assumes that all refrigerators and cooking appliances will be of maximum

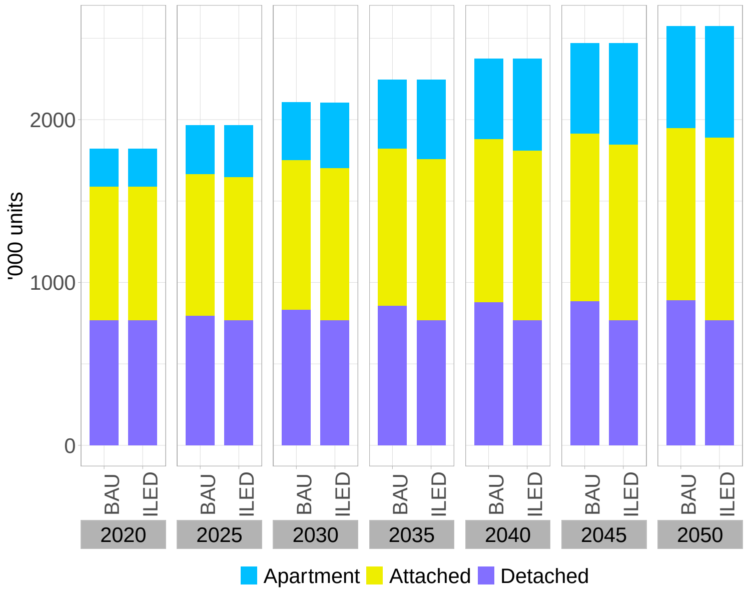


Figure 10: Comparison of type of residential dwellings in BAU and ILED scenarios

efficiency (85%) by 2050. Clothes washing and drying, and dish washing demand is assumed to decrease by 20% relative to BAU ESD projections, the narrative being, wearing same clothes more often, line drying, and using machines on full load. Electrical appliances also reduce consumption by 20% relative to BAU ESD projections due to efficiency improvements and unplugging devices to avoid stand-by mode power consumption.

- Industry: The industrial sector was responsible for about 18% of the final energy consumption and about 7.7% of the total GHG emissions in 2018. The average energy intensity (energy/GDP) of industrial activity is expected to decline by 30% in the next decade, mentioned in the World Energy Outlook 2020 [74]. A further decrease by 15% to 2050 is considered in the ILED scenario (in total a 45% decrease in energy intensity from current level). This can be achieved by increasing production efficiency and better usage of materials (e.g., recycling, circular economy). A 50% reduction in energy demand from the cement industry is expected by 2050, which is to be replaced by other building materials. In total, the industrial energy demand declines by 25% in 2050 as compared to 2018.

- Commercial and public services accounted for 14% of the total energy demand in Ireland in 2018. At current level, commercial and public service buildings amount to 6m^2/capita and 12m^2/capita respectively, with current projections foreseeing an increase to 7.65m^2/capita and 15.39m^2/capita. In the ILED scenario, we assume indeed that space reduces to 5.3m^2/capita and 10.7m^2/capita for the commercial and public buildings. This results in a decrease of energy demand by 37% in 2050 as compared to the 2018 level. This reduction is energy demand is to be achieved through promoting work from home (less number of offices needed) and dense urban development (smaller office space). Public lighting units are assumed to remain constant at the 2040 level, in line with government plans to expand major cities up to 50% from current levels. In the ILED scenario, we assume that no further expansion takes place and lighting units remain constant at 540,000.

4. Results

In this case study, we explore a total of three mitigation scenarios along with two demand variations for each which are enumerated below. The scenario names describe the percentage of emission reduction from the energy system by 2030 relative to 2018: E51 and E61 correspond to scenarios where energy-system CO_2 emissions fall by 51% and 61% respectively between 2018 and 2030. Both scenarios achieve net-zero emissions by 2050. These are consistent with the national climate target of reducing economy-wide emissions by 51% and require the agriculture sector to meet emissions reductions targets of 51% and 33% respectively. Whereas, the E32 mitigation scenario does not meet the national mitigation target but is consistent with the Climate Action Plan 2019 targets whereby Non-ETS GHG emissions are to be reduced by 30% in 2030 relative to 2005 and by 80% in 2050 relative to 1990. Figure 11 shows the CO_2 emission pathways modelled in this case study.

Each mitigation pathway is modelled with two different energy system demand scenarios: BAU (described in Appendix A) and ILED, described in the previous section.

4.1. Impact on costs

Figure 12 shows the average marginal abatement cost (MAC) for subsequent 5-year periods between 2025 and 2050. The MAC represents the cost of mitigating the most expensive tonne of CO_2 in each scenario for the energy sector. The E61 scenario has the highest MAC between 2055 and 2030 since this is the most ambitious decarbonisation scenario among those explored in this study. The E51 scenario also has a very high MAC relative to others, implying that achieving near term ambitious climate goals will be challenging. On the other hand, scenarios meeting these mitigation targets with ILED pathways have much lower MACs as compared to their BAU ESD projection counterparts.

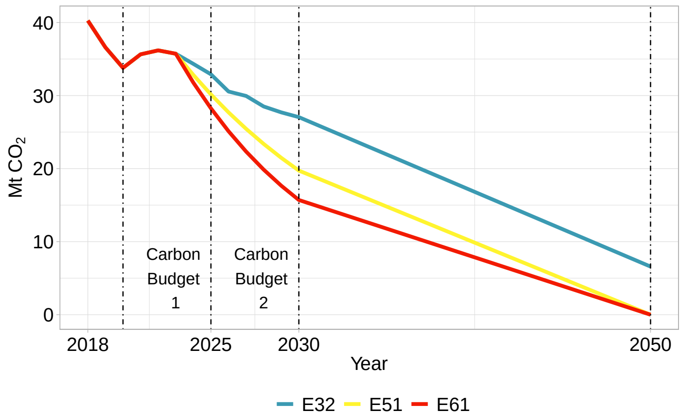


Figure 11: Decarbonisation trajectories modelled in TIM and carbon budget outcomes (Scenario EX- CO_2 Emission reduction by X% in 2030 relative to 2018 where X= 32, 51 and 61)

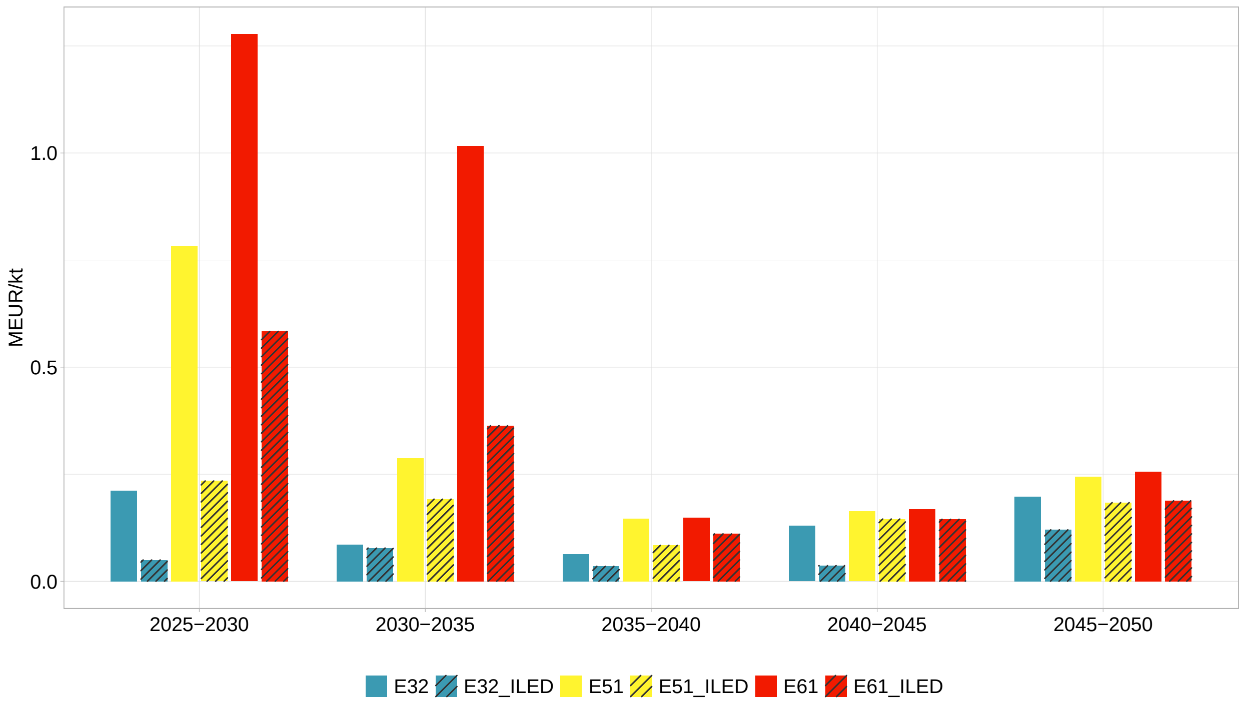


Figure 12: Average marginal abatement cost for every 5 years between 2025-2050

The total undiscounted annual system cost is shown in Figure 13. As discussed previously, the final energy demand determines the size of the energy system. In the scenarios with BAU ESD projection, the size of the energy system is large compared to that in the ILED pathway. Hence much higher investments are needed in these scenarios. E61 incurs the highest investments because of the extra work the energy system has to do to meet the targets of the climate bill. Figure 14 shows the total savings in fixed, investment and

Table 2: Comparison of energy service demand values in BAU and ILED scenario

Sector	Parameter		Unit	Value: 2018		Value: 2050_BAU		Value: 2050_ILED	
Transport	Freight		tonne kilometres (tkms)	2375 tkms/capita		4307 tkms/capita		1525 tkms/capita	
	Passenger transport		passenger kilometres (pkms)	15342 pkms/capita		17000 pkms/capita		12000 pkms/capita	
Residential	Dwellings	Apartments	'000 units	206.799		628.932		686.467	
		Attached	'000 units	766.352		1056.500		1120.427	
		Detached	'000 units	724.430		889.756		768.294	
				Old	New	Old	New	Old	New
	Space heating	Apartments	MWh/dwelling	3.85	1.23	3.85	1.23	3.08	0.98
		Attached	MWh/dwelling	7.85	2.85	7.85	2.85	5.81	2.11
		Detached	MWh/dwelling	14.41	6.74	14.41	6.74	10.66	4.99
	Water heating	Apartments	MWh/dwelling	3.41	2.20	3.41	2.20	2.39	1.54
		Attached	MWh/dwelling	3.01	2.35	3.01	2.35	2.11	1.65
		Detached	MWh/dwelling	3.81	2.49	3.81	2.49	2.66	1.75
	Lighing/Pumps & fans	Apartments	MWh/dwelling	0.54	0.69	0.54	0.69	0.49	0.62
		Attached	MWh/dwelling	0.81	0.92	0.81	0.92	0.73	0.83
		Detached	MWh/dwelling	1.26	1.49	1.26	1.49	1.14	1.34
	Refrigeration		PJ	1.13		1.71		1.61	
	Cooking		PJ	2.00		3.03		2.86	
	Cloth washing		PJ	0.77		1.20		0.96	
	cloth drying		PJ	1.03		2.41		1.93	
	Dish washing		PJ	0.83		1.95		1.56	
	Electrical appliances		PJ	9.22		13.98		11.19	
Industry	Energy intensity		PJ/MEUR					45% decrease from current level	
	Cement		PJ	17.8		24.82		8.9	
Services	Commercial buildings		m^2/capita	5.95		7.65		5.3	
	Public buildings		m^2/capita	11.97		15.39		10.7	
	Public lighting units		million lamps	0.48		0.575		0.54	

variable cost between BAU demand and ILED demand pathways in 2030 and 2050. There are huge savings in the investment costs in the ILED pathways, reducing total system costs in turn, particularly in 2050.

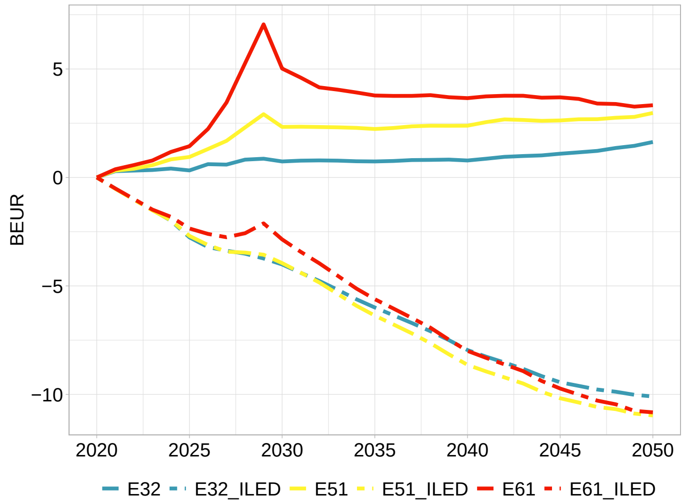


Figure 13: Total undiscounted annual energy system cost in addition to the No_mitigation scenario. Includes annual investments, fixed and variable costs, and excludes network and infrastructure costs

Figure 15 shows the personal investments per person needed in the housing and transport sectors. The cash flow needed in the ILED pathways for meeting climate goals is much less than the BAU ESD pathways.

The ILED pathways bring down the MAC considerably which shows their importance, particularly for meeting near-term decarbonisation targets. Further, the ILED pathways significantly reduce the total system costs, bringing down the costs of transforming the energy sector. They follow a low investment trajectory to deliver the energy needs and meet climate goals. And finally, per-capita personal investments are also lower in the ILED pathways. These results imply that the total cost of decarbonising the energy sector is significantly lower in the ILED pathways.

4.2. Impact on energy consumption and technology uptake

Figures 16 shows the per-capita final energy consumption and the percentage share of fuels in the fuel mix. In 2030, the share of electricity and other renewables is lower in the ILED pathways while that of oil and natural gas is high as compared to the scenarios with BAU ESD projection. This means that pursuing the ILED pathway allows some fossil fuels in the energy mix and does not require very significant changes in the supply-side of the energy system. Progressing towards the mid-century, hydrogen is increasing in the

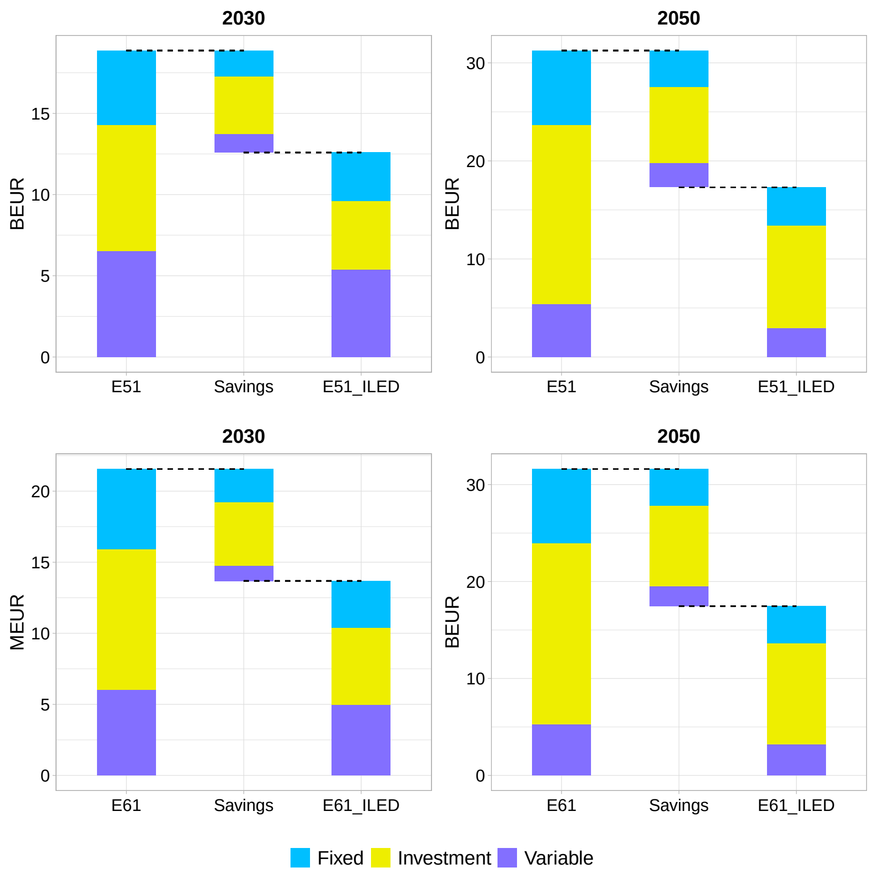


Figure 14: Difference in energy system costs (fixed, investment and variable) between BAU ESD and ILED pathways in 2030 and 2050

E32, E51 and E61 scenarios while for the ILED pathways the share is very small. In the E32_ILED scenario, the share of renewables is very small, while in the E51_ILED and E61_ILED scenarios share of biofuels is lower than BAU scenarios. The ILED pathways still have higher share of natural gas and oil in 2050.

Figure 17 shows the uptake of novel technologies in various sectors. The generation from offshore wind is double in 2050 in the BAU ESD projection scenarios as compared to their ILED equivalents. This result is especially important for 2030 (near-term) where offshore wind capacity needed is about 7.5 GW in the BAU ESD projections, which would be challenging to install from planning permission point of view, while it is 3.7 GW in the ILED pathways.

New private EV sales are much lower in the ILED pathways, particularly in E61_ILED. Around 4,000 EVs were sold in Ireland in 2020 and about 8,000 in 2021 till October [75]. In E61 and E51 pathways, on an average, approximately 130,000 and 49,000 respectively, must

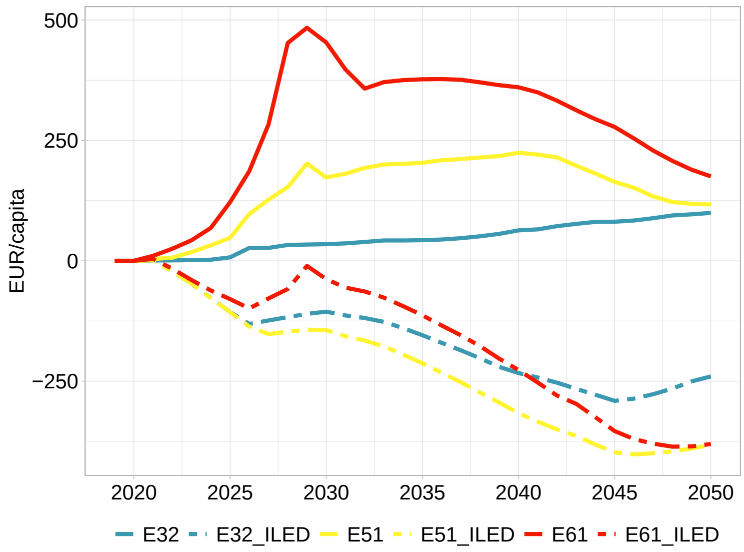


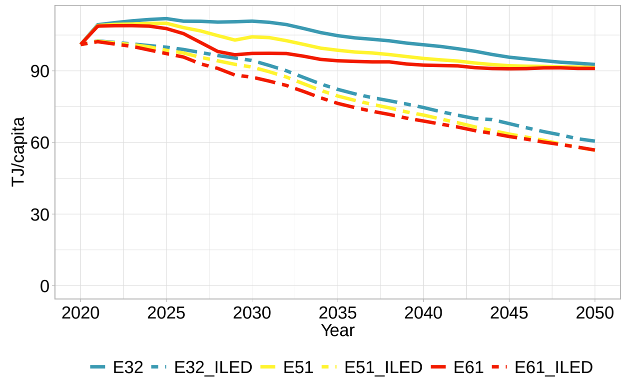
Figure 15: Annual per capita personal investments in residential (retrofits) and transport sectors (new private car) in addition to the No_mitigation scenario

be sold per year till 2030 to meet the emission reduction targets. However, in the ILED pathways, about 8,700 EVs must be sold each year till 2030, which is more in line with the current trends.

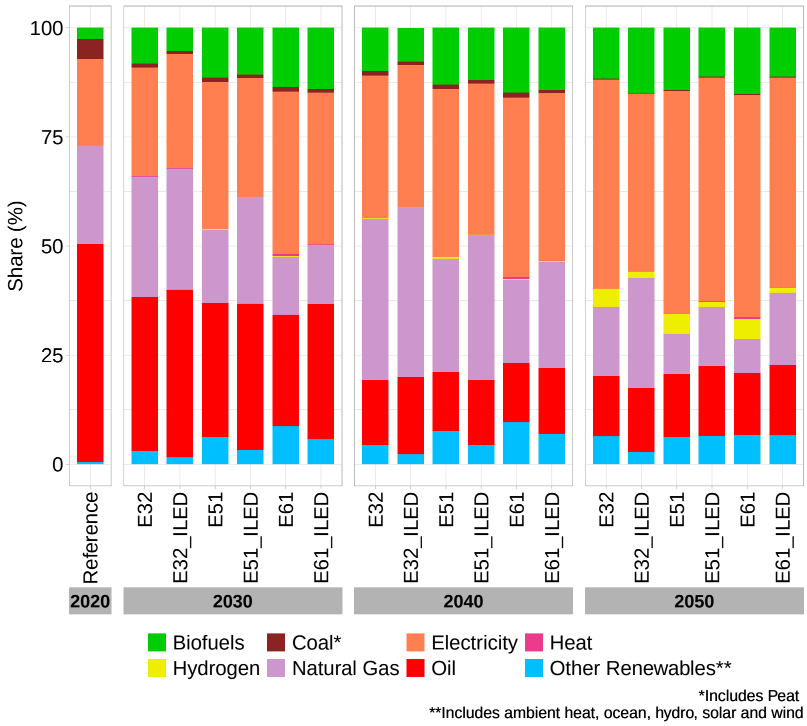
New EV and fuel cell vehicle sales for freight are also lower in ILED pathways. In 2021 (till October) around 1,000 such freight vehicles were sold in Ireland [75]. However, in E32, E51 and E61 pathways, about 10,000, 23,000 and 37,000 EV and fuel cell vehicles respectively are needed every till 2030. In the ILED pathways, 4,000-11,000 EV and fuel cell vehicles for freight are needed each year till 2030. These numbers are still higher than current trends but much lower than the BAU ESD projection scenarios.

The Irish Government has set a target of upgrading about 0.5 million residential dwellings to B2 Building Energy Rating (BER). In 2The E51 and E61 pathways foresee 39,000 and 60,000 retrofits per year till 2030. On the other hand, about 10,000 and 39,000 retrofits per year are needed in the E51_ILED and E61_ILED pathways respectively. Lowering ESDs in residential dwellings reduces the need for upgrades. Further, quiet a few retrofits are pushed beyond 2040 in the ILED pathways.

These results indicate that the ILED pathways decrease the requirement of novel fuels and technologies. They allow fossils to remain in the fuel mix for a longer time period, while still complying with the emission constraints. The ILED pathways also foresee much lower technological transformations in power generation, decreasing the technical challenges of integrating large amounts of renewables in the grid. The pace and scale of transformation



(a) Final energy consumption per capita



(b) Fuel mix

Figure 16: Final energy consumption per capita and resultant fuel mix

needed in the supply side of the energy system is much lower in the ILED pathways.

The ILED pathways require less rapid technology replacement. These pathways foresee lower ESDs which can be met through sustainable modes and behavioural change instead of depending on technology uptake, which is expensive. Secondly, the ILED pathways postpone the need for technology uptake, allowing greater timeframe to achieve climate goals.

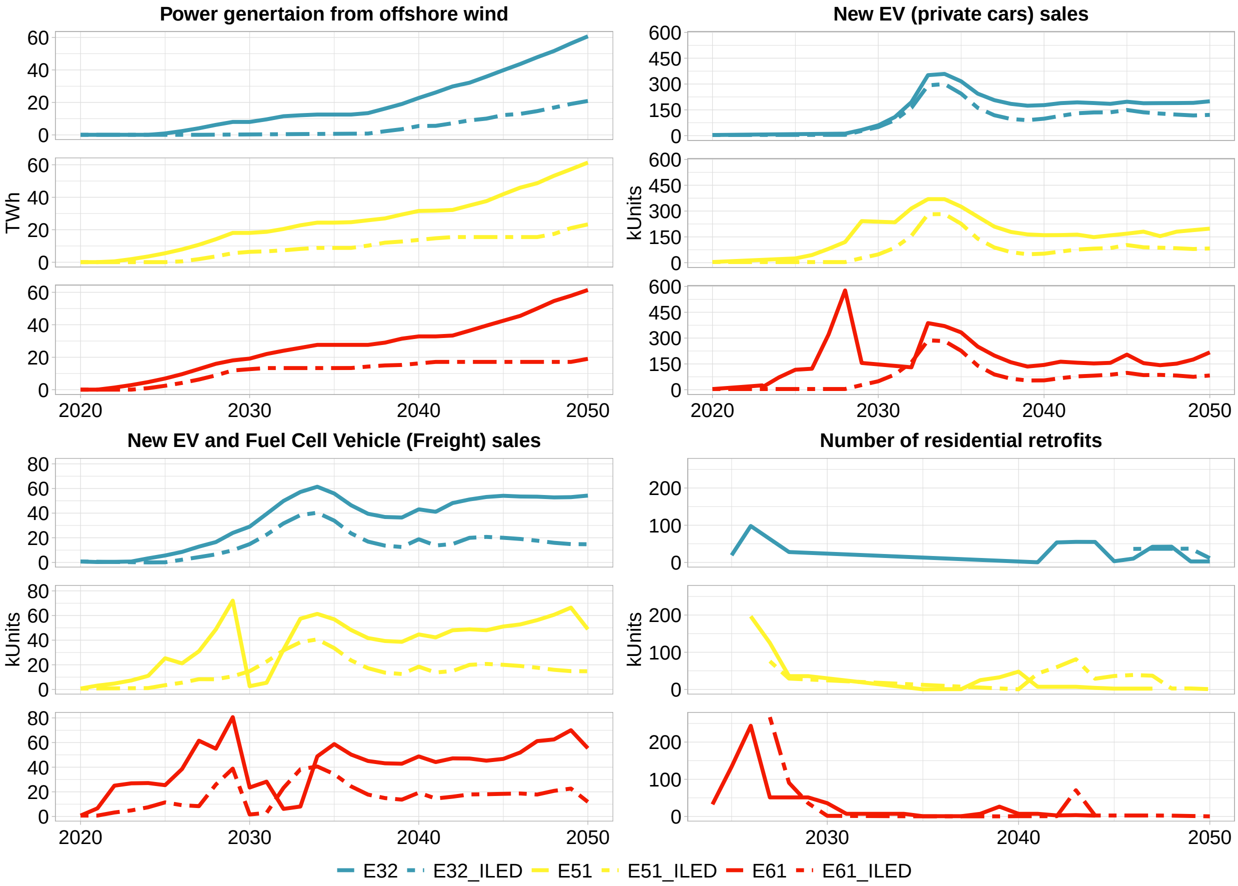


Figure 17: Novel technology uptake

4.3. Impact on CO_2 emissions

Figure 18 shows the cumulative CO_2 emissions of every sector between 2020 and 2050. The total cumulative emissions are the same in BAU ESD projection and ILED pathways, however there are some differences in individual sectors. For instance, emissions in the residential and power generation are higher in the ILED pathways as compared to BAU ESD projection pathways. Lower retrofits in the residential sector and greater fossil-fuel based generation in the power sector cause a lack of fuel switching which leads to slightly higher emissions in these sectors in the ILED pathways.

Figure 19 shows the cumulative amount of CO_2 capture from BECCS needed between 2020 and 2050. E31 foresees the lowest amount of BECCS while E51 requires greatest amount. E51 needs higher BECCS than E61 because the latter does more work in terms of decarbonisation by 2030 than the former. E32_ILED pathway needs no BECCS at all, while E51_ILED and E61_ILED pathways need 38% and 23% lower BECCS as compared to E51

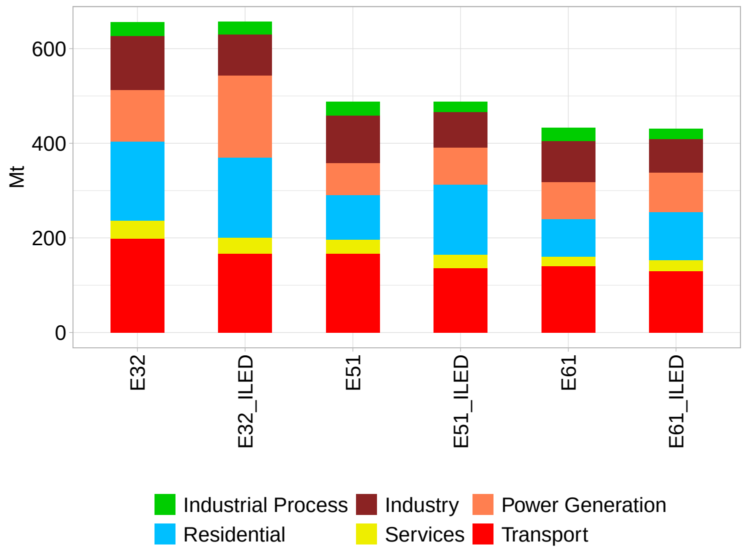


Figure 18: Cumulative CO_2 emissions between 2020 and 2050

and E61 respectively.

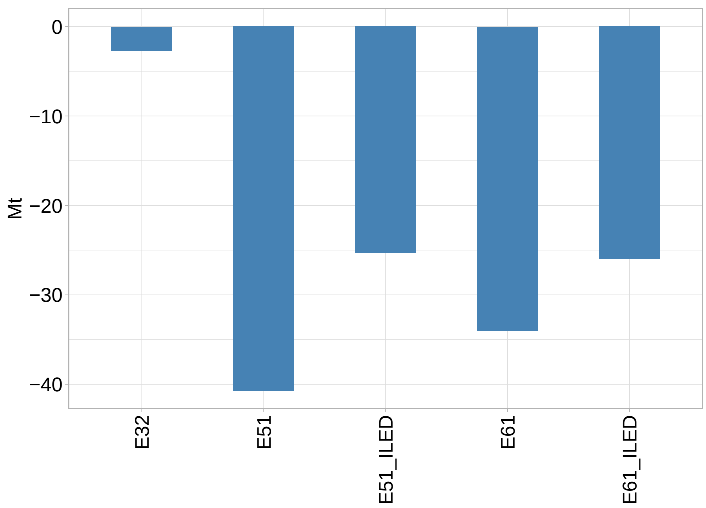


Figure 19: Cumulative BECCS needed between 2020 and 2050

The ILED pathways result in similar cumulative emissions as BAU ESD projection pathways, however, some sectoral differences exist. The ILED pathways reduce dependency of the energy system on uncertain and risky technologies like BECCS.

5. Discussion

There is a consensus that modelling social, economic, and political disruptions that could change the way energy is consumed is important to understand possible future levels of energy service demands [76–79]. Better representation of demand-side policies and integrating multidisciplinary insights from social sciences, economics, and engineering could help policymakers devise effective plans for future changes [76, 78]. This is further confirmed by two recent reports at the global level from the International Energy Agency, World Energy Outlook 2020 [74] and Net Zero by 2050 [27]. They emphasise that behavioural change will be an integral part of decarbonisation pathways. These reports estimate that about 1.7-2 GT of CO_2 emissions can be avoided by 2030 if behavioural changes are implemented quickly, and about half of these emissions savings are associated with the transport sector.

The ILED pathway considers a number of demand-side mitigation options, often missing in mainstream energy scenarios. The ILED pathway is modelled exogenously to demonstrate the impact of reducing energy service demands on the whole energy system. Although we do not describe in detail how these reductions are to be brought about, or quantify the costs required, this scenario presents a possible future energy system evolution pathway which is often ignored in energy policy discussions. The methodology used to design the ILED pathway is based on literature review, historical trends and a comparison with other developed nations.

Our results show the benefits that the ILED pathway could bring for Ireland to meet its climate goals. Firstly, marginal abatement costs and investments are much lower in the ILED pathway due to smaller system size. Secondly, technology uptake rate is smaller in the ILED pathway. The share of novel fuels and technologies like hydrogen and electric vehicles is lower in the ILED pathways, while fossil fuels and ICE's are present in the system for a longer time. The residential sector foresees fewer number of retrofits in the ILED pathways, with some retrofits postponed to beyond 2040. Further, power generation from offshore wind is much smaller in the ILED pathways, especially in the near term. These results imply that rapid deep technological transformation in the energy system will not be necessary if pursuing the ILED pathway.

There are many financial and non-financial barriers to achieving climate targets. Both, BAU and ILED pathways are successful in achieving carbon constraints set in the model, but they indicate completely different energy system transitions. The BAU demand scenarios are reliant on quick technology adoption and deep supply-side transformation, whereas in the ILED pathways these changes are much slower. It can be said that the ILED pathways are more coherent with political cycles and the likely delays in system transition.

On the other hand, the ILED pathways are only achievable through active policy designs. However, failures in implementing previous policies raises questions about the attainability of the ILED pathways which are heavily dependent on social and economic transformations. The ILED pathways require dense urban planning and smart investments in infrastructure to bring about the reductions in ESDs but the current silo mentality in city and state governance is still a big barrier in implementing these plans. Better cooperation between different government departments is needed. For example, housing permissions in areas having access to public transport infrastructure.

Energy service demand reduction has not been on the government's agenda while formulating climate mitigation policies. Government should meaningfully engage with the public and use public awareness to their advantage. Lifestyle changes that permit demand reduction must be promoted. It should be noted that behavioural change is not independent of the infrastructure and energy system. To bring about changes in behaviour, changes in the system are needed. For example, to promote active of modes of travel, footpaths and cycling lanes are needed. The government needs to look for opportunities to create new industries and services that are sustainable in the long-term. Reducing energy service demands have several co-benefits such as lower energy bills, higher fairness, and costs of technologies going down. Sector specific policies must be designed and implemented, keeping planning and investment needs in mind.

6. Conclusion

While the importance of limiting global warming to 1.5 °C is being recognised, the literature fails to acknowledge that unless we move away from the energy consumption growth imperative, attaining climate goals will be problematic. By presenting a case study for Ireland, this study established that the LED pathway is especially valuable to meet the near-term targets, where technology alone cannot bring about the necessary reductions in CO_2 emissions. Our main results find that the LED pathway reduces dependency on capital-intensive fuels and technologies, and also reduces overall system costs and the size of the energy system.

The LED is a fast, cost-efficient and secure pathway to mitigate climate change. It would also bring many societal benefits, less congestion, more compact and "liveable" cities and towns, health benefits, and a better standard of living from active travel and more comfortable homes. The LED helps in meeting climate goals along with United Nation's other SDGs. “Low hanging fruit” of energy demand reduction may allow for steeper action while increasing quality of life.

However, the LED pathway cannot be achieved by assuming voluntary behaviour changes from people and companies but must be enabled through sector-specific and targeted policies. Large-scale investment into sustainable mobility, better planning to allow densification, and public education to shift in values towards lower consumption also is needed. The cost of these required investments is difficult to quantify and is a priority for future developments in this study. The overall impact of reducing energy consumption on the economy and rebound effects have not been quantified. However, energy efficiency improvements are not paramount in our scenario assumptions and some rebound effects could be absorbed.

Acknowledgement

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Appendix A. Summary of energy service demand projections in TIM

The full methodology used to project each ESD is outlined in [64]. This section provides an overview of the drivers of all ESDs in TIM and their corresponding values for 2018 and 2050.

Appendix A.1. Drivers

Appendix A.1.1. Population

Historical population estimates and future projections are obtained from the Central Statistics Office (CSO), Ireland [80]. We use the M2F1 scenario since it represents medium growth in population and is in line with population projections used in other national sources [81].

Appendix A.1.2. Economic growth

- Historical Gross Value Added (GVA) for the required NACE categories in the Services and Industry sectors is obtained from EUROSTAT database. Projections for GVA are outputs of the Ireland Environment, Energy and Economy (I3E) model [81].

Table A.3: Population add citation

Year	Population (millions)
2018	4.85
2020	4.98
2030	5.40
2040	5.82
2050	6.19

- Gross Domestic Product (GDP) - Historical and future projections for GDP is obtained from Organisation for Economic Co-operation and Development (OECD) [82].
- Income - Historical values of total incomes are taken from CSO's database [83]. Assumption about income growth in the future are that from the National Transport Model [84].
- Modified Gross National Income (GNI*)- Derived from CSO's labour force scenario combined with a forecast for output per person [85].

Appendix A.1.3. Energy service demands

Table A.4 lists the energy service demands in TIM along with their corresponding drivers and values for 2018 and 2050. The Nomenclature of Economic Activities (NACE) code is mentioned for all the industries.

Table A.4: Energy service demands in TIM

Energy Service Demand	Unit	Driver	Value	
			2018	2050
Non-Energy Mining [05-09]	PJ	GVA per capita, Population	2.07	0.13
Food and beverages [10-11]	PJ	GVA per capita, Population	22.25	34.00
Textiles and textile products [13-14]	PJ	GVA per capita, Population	1.20	4.97
Wood and wood products [16]	PJ	GVA per capita, Population	6.69	7.65
Pulp, paper, publishing and printing [17-18]	PJ	GVA per capita, Population	0.67	2.31
Chemicals and man-made fibres [20-21]	PJ	GVA per capita, Population	10.60	13.11
Rubber and plastic products [22]	PJ	GVA per capita, Population	1.14	0.89
Other non-metallic mineral products [23]	PJ	Modified investment, GNI*	17.77	24.82
Basic metals and fabricated metal products [24-25]	PJ	GVA per capita, Population	19.54	21.73
Machinery and equipment n.e.c. [28]	PJ	GVA per capita, Population	1.29	1.69

Electrical and optical equipment demand [26-27]	PJ	GVA per capita, Population	4.27	16.37
Transport equipment manufacture [29-30]	PJ	GVA per capita, Population	0.17	0.04
Other manufacturing [31-33,12 & 15]	PJ	GVA per capita, Population	4.25	6.12
Construction [41-43]	PJ	GVA per capita, Population	4.02	5.90
Short-range passenger travels	BPKMS	Income, population	14.56	21.07
Medium-range passenger travels	BPKMS	Income, population	31.28	45.29
Long-range passenger travels	BPKMS	Income, population	27.13	38.97
Goods vehicle for freight	BTKMS	Growth rate from [84]	11.54	25.14
Tourism fuel	PJ		7.72	0.00
Navigation fuel	PJ	GDP	3.51	10.04
Unspecified fuel	PJ		21.78	0.00
Aviation domestic	PJ		0.23	0.23
Aviation international	PJ	International Aviation Passengers	45.94	62.63
Residential Apartment Demand	000'	Population	206.80	628.93
Residential Attached Demand	000'	Population	766.35	1056.50
Residential Detached Demand	000'	Population	724.43	889.76
Residential Refrigeration Demand	PJ	Residential dwelling growth (total)	1.13	1.71
Residential Cooking Demand	PJ	Residential dwelling growth (total)	2.00	3.03
Residential Cloth Washing Demand	PJ	Residential dwelling growth (total)	0.77	1.17
Residential Cloth Drying Demand	PJ	Residential dwelling growth (total)	1.03	1.56
Residential Dish Washing Demand	PJ	Residential dwelling growth (total)	0.83	1.26
Residential ELC Appliances Demand	PJ	Residential dwelling growth (total)	9.22	13.98
Residential Other Applications Demand	PJ	Residential dwelling growth (total)	0.00	0.00
Services - Commercial Services	Mm^2	GNI*	28.90	47.39
Services - Public Services	Mm^2	GNI*	58.15	95.35
SRV-Commercial Services: Data centers	PJ	From EirGrid	5.63	40.30
SRV-Public Services: Public lighting	Mlamps	From [86]	0.48	0.58

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