ENVIRONMENTAL RESEARCH
ENERGY

PURPOSE-LED PUBLISHING™

Part of the ENVIRONMENTAL RESEARCH SERIES

**ACCEPTED MANUSCRIPT • OPEN ACCESS**

# Evaluating the consistency between Ireland's carbon budget-aligned energy system pathways and EU energy and climate targets

To cite this article before publication: Ciara Doherty *et al* 2026 *Environ. Res.: Energy* in press https://doi.org/10.1088/2753-3751/ae4a2b

# Evaluating the consistency between Ireland's carbon budget-aligned energy system pathways and EU energy and climate targets

Ciara Doherty[a,b,*], Vahid Aryanpur[a,b], Hannah Daly[a,b]

[a] MaREI Centre for Energy, Climate and Marine, Sustainability Institute, University College Cork, Cork, Ireland

[b] School of Engineering and Architecture, University College Cork, Co. Cork, Ireland

*Corresponding author details: ciaradoher@gmail.com

## Abstract

Ireland's climate legislation mandates greenhouse gas (GHG) reductions consistent with the Paris Agreement, implemented through legally binding carbon budgets (CBs) targeting a 51% reduction by 2030, relative to 2018, and climate neutrality by 2050. As an EU Member State, Ireland must also meet obligations under European climate and energy legislation, including the Emissions Trading Scheme (ETS), the Energy Efficiency Directive (EED), and the Effort Sharing Regulation (ESR). The extent to which national policy frameworks, such as Ireland's domestic CBs, align with EU obligations is underexplored.

This study assesses the alignment of Ireland's energy system decarbonisation pathways – developed using the TIMES-Ireland Model (TIM) and aligned with approved and adopted national CBs - with EU climate and energy targets for 2030 and 2040. The analysis focuses on a composite "*TIM-CBaligned*" pathway, representing the weighted average of scenarios underpinning Ireland's third and fourth CB proposals, alongside current and planned policy scenarios.

Results show that *TIM-CBaligned* outperforms the 2030 EU ETS target in power and industry sectors by 24% and exceeds the indicative EU-2040 benchmark for energy emissions by 68%. ESR compliance is achievable only with significant agricultural mitigation; otherwise, non-compliance persists even with use of flexibilities. Final energy consumption in 2030 falls 6% short of the EED target, although low energy demand scenarios help to close the gap.

These findings confirm that ambitious, CB-aligned energy pathways can deliver strong coherence between national and EU climate goals, in line with literature on multilevel climate governance. However, they also highlight the persistent risk that underperformance in non-energy sectors undermines overall compliance, which is particularly pertinent for countries with a high share of emissions from agriculture. Policy coherence requires sustained investment, accelerated demand reduction, and integrated planning across all sectors. This study contributes a novel, quantitative example of national–EU target alignment, addressing a recognised gap in the literature and providing evidence to inform both domestic and EU policy debates.

**Keywords**

Carbon budgets; Policy coherence; Energy systems modelling; European Union climate policy; Multilevel climate governance

**Abbreviations**

AEA, Annual Emissions Allocation; BAU, Business-as-Usual; BECCS, Bioenergy with Carbon Capture and Storage; CB, Carbon Budget; CCS, Carbon Capture and Storage; $CO_2$ / $CO_2e$, Carbon Dioxide / Carbon Dioxide Equivalent; EED, Energy Efficiency Directive; EPA, Environmental Protection Agency; ESR, Effort Sharing Regulation; ETS, Emissions Trading Scheme; EU, European Union; EV, Electric Vehicle; GAMS, General Algebraic Modelling System; GDP, Gross Domestic Product; GHG, Greenhouse Gas; IPCC, Intergovernmental Panel on Climate Change; LED, Low Energy Demand (scenario); LowBio, Low Biomass Import (scenario); LULUCF, Land Use, Land-Use Change and Forestry; Mt, Million tonnes; $MtCO_2$ / $MtCO_2e$, Million tonnes of $CO_2$ / $CO_2$ equivalent; MW, Megawatt; TIM, TIMES-Ireland Model; TIMES, The Integrated MARKAL-EFOM System; WAM, With Additional Measures; WEM, With Existing Measures

## 1.0 Introduction

Achieving climate neutrality requires coherent action across governance levels. The European Union (EU) has legislated a net-zero greenhouse gas (GHG) target for 2050, with an intermediate reduction of at least 55% by 2030 relative to 1990 [1], [2]. These goals are operationalised through multiple policy instruments within the European Green Deal [3], the EU's overarching strategy for addressing climate change, and the "Fit for 55" legislative package. Key measures for 2030 include the EU Emissions Trading Scheme (ETS), a cap and trade system for large emitters; the Effort Sharing Regulation (ESR), which sets binding national annual emissions allocations (AEAs) for Member States for non-ETS sectors (excluding land use, land use change and forestry (LULUCF)); and the Energy Efficiency Directive (EED), which requires reductions in final energy consumption [4], [5], [6]. The European Climate Law also mandates the delivery of an intermediate climate target for 2040, for which a 90% net GHG emissions reduction relative to 1990 has been proposed [7].

While these frameworks operate at the EU level, compliance ultimately depends on Member States meeting their binding ESR and EED targets and participating in the ETS and long-term decarbonisation goals. Ireland provides a relevant case for examining this multi-level governance challenge. Ireland is a small, highly open economy with a significant multinational presence, which inflates conventional GDP measures relative to domestic income. Its emissions profile is distinct within the EU, where agriculture accounts for over one third of emissions, while heavy industry represents a comparatively small component of the economy.

The Irish energy system is characterised by high dependence on imported fossil fuels, and a reliance on natural gas in electricity supply. The transport sector is characterised by high reliance on private car ownership, dispersed settlement patterns, and an emerging growth in EV sales. Heat is highly fossil fuel dependent, with kerosene and solid fuels playing a significant role. These features shape both the scale of the compliance challenge and the mitigation options available.

The Climate Action and Low Carbon Development (Amendment) Act (2021) [8] establishes a national framework for climate action, underpinned by legally binding five-year carbon budgets (CBs), and sectoral emissions ceilings aligned with a 51% GHG reduction by 2030 (relative to 2018) and climate neutrality by 2050 at the latest. CB1 and CB2 (2021-2030) were approved in 2022 [9], and the Irish Climate Council has since delivered proposed budgets CB3 and CB4 covering 2031-2040 [10][1]. These domestic commitments must be implemented alongside EU obligations.

However, current projections indicate that Ireland is significantly off track. Under both "With Existing Measures" (WEM) and "With Additional Measures" (WAM) scenarios, reflecting implemented and planned policies, Ireland is projected to exceed national CBs, fall short of ESR obligations and miss its EED target [11], [12]. Non-compliance of EU targets carries both legal and substantial financial risks: Recent estimates suggest that due to non-compliance under WEM, Ireland may face compliance costs of between €8 and €26 billion, by paying other EU Member States to compensate for not meeting its agreed climate targets [13]. Ireland risks becoming a significant outlier, with compliance costs potentially up to five times higher as a share of national income compared to larger EU economies [14]. It also records the highest per capita emissions gap in the EU. This disproportionate shortfall indicates that Ireland may face higher relative costs and greater challenges in meeting its climate targets. Beyond the financial implications, misalignment between EU and national targets may undermine the broader co-benefits of decarbonisation, including economic growth, enhanced energy security, and improved public health [15].

Existing literature has explored Ireland's energy transition and decarbonisation pathways [16], [17], [18], while official reports highlight gaps between Ireland's emissions and energy projections and EU objectives [11], [12]. However, a key gap remains: the extent to which nationally focused pathways are consistent with the pace and scale of decarbonisation required under specific EU legislation. CB1 and CB2 were broadly consistent with EU ETS and ESR targets [19], but evaluating whether subsequent CBs remain sufficient to ensure compliance with evolving EU frameworks is essential. Moreover, no studies exist that propose energy system pathways that help bridge the projected compliance gap between Ireland's projected emissions trajectory and EU targets.

More broadly, comparative analyses have assessed Member States' progress towards EU 2030 targets [20], examined the robustness of national climate plans relative to long-term EU commitments [21], and evaluated the alignment of EU ambition and national pledges [22]. These studies reveal that while Member States have clearly defined EU targets, the policy actions and instruments required to deliver them often remain underdeveloped,

[1] At the time of writing (October 2025), these proposed carbon budgets for CB3 and CB4 are under consideration by the Government.

limiting progress towards overall EU objectives. Such comparative analyses typically remain at the level of declared targets as defined in National Energy and Climate Plans, rather than testing whether national policy frameworks can quantitatively deliver compliance with EU obligations.

This highlights wider risks of implementation shortfalls and policy incoherence - where measures at one governance level undermine those at another - and reinforces the need to assess the interaction between pathways aligned with both national and EU targets. Research on multi-level climate governance similarly highlights the risks of policy incoherence, and underscores the need for empirical case studies to demonstrate how national and supranational targets can be mutually reinforcing [23].

A number of studies have also explored mitigation policies at sub-national levels, including regions and provinces [24] and cities [25], [26], [27]. However, while sub-national analyses provide valuable insights into local implementation and governance challenges, they are less relevant for assessing overall national compliance with EU-level climate and energy targets.

This study addresses these gaps by assessing whether Ireland's energy-sector pathways, consistent with approved and proposed national CBs, are aligned with EU climate and energy targets for 2030 and 2040. Specifically, we ask: *To what extent does a carbon budget–aligned (CBaligned) energy pathway ensure compliance with EU obligations under the ETS, ESR, and EED, and position Ireland to meet the proposed 2040 target?* We also evaluate how closely these national pathways, developed using the TIMES-Ireland Model (TIM), an energy systems optimisation model, converge or diverge from EU policy. We evaluate a composite "*TIM-CBaligned*" scenario, which underpins Ireland's recommended third and fourth CBs, to identify specific mitigation measures and investment necessary to achieve this pathway, comparing it against Ireland's current policy projections, WEM and WAM.

The remainder of the study is structured as follows: Section 2.0 describes the methodology and scenario framework. Section 3.0 presents the results on target alignment, including a sectoral analysis and details on system costs. Section 4.0 discusses the key findings and policy implications. Section 5.0 provides conclusions, limitations and suggestions for future research.

## 2.0 Methods

This study uses scenarios developed with the TIMES-Ireland model (TIM), an established energy systems optimisation model. The analysis also develops a composite *CB-aligned* scenario to represent an energy trajectory consistent with national CBs. Modelled pathways are benchmarked against targets under the ETS, ESR, EED and the proposed 2040 target. To enable ESR benchmarking, a methodology is introduced to estimate the share of national annual emissions allocations (AEAs) that can be attributed to the energy sector.

### 2.1 Model description

The TIMES-Ireland Model (TIM), built within the TIMES (The Integrated MARKAL-EFOM System) framework is a technology-rich, bottom-up, linear optimisation model that represents the Irish energy landscape and models future potential energy system pathways across energy supply, electricity, transport, buildings and industry sectors [16]. It generates cost-optimal energy system configurations to meet energy system demands while ensuring decarbonisation under CBs and other user-defined techno-economic or policy constraints, and offers outputs including optimal technology deployment, emissions trajectories, sectoral energy flows, and costs (investments, variable, operational and maintenance). The objective function minimises total discounted energy system cost over a specified time horizon. The TIMES code is written in General Algebraic Modelling Software (GAMS) language, and the source code, comprehensive model description and methodology are available in [28], [29], [30], [31].

TIM comprises three main parts: (i) the supply module covers resources, fuel production and conversions, and transmission and distribution infrastructure; (ii) the demand module captures end-use sectors and energy service demands; and (iii) the emissions control module tracks $CO_2$ emissions within the system (Figure 1).

Decarbonisation is driven through explicit carbon budget constraints rather than exogenous carbon price trajectories or policy assumptions; the resulting shadow carbon prices therefore represent the marginal cost of meeting emissions limits. A global social discount rate of 4% is applied; technology- and sector-specific discount rates are not applied. The results can be interpreted as socially optimal pathways (minimised total discounted system costs) to meet both energy service demands and carbon budget constraints, subject to resource and technology deployment constraints, rather than a simulation of energy system outcomes in response to market forces or policy levers, such as exogenous carbon price trajectories. Resulting shadow prices therefore represent the marginal cost of meeting emissions targets rather than market-clearing ETS prices or optimal carbon taxes.

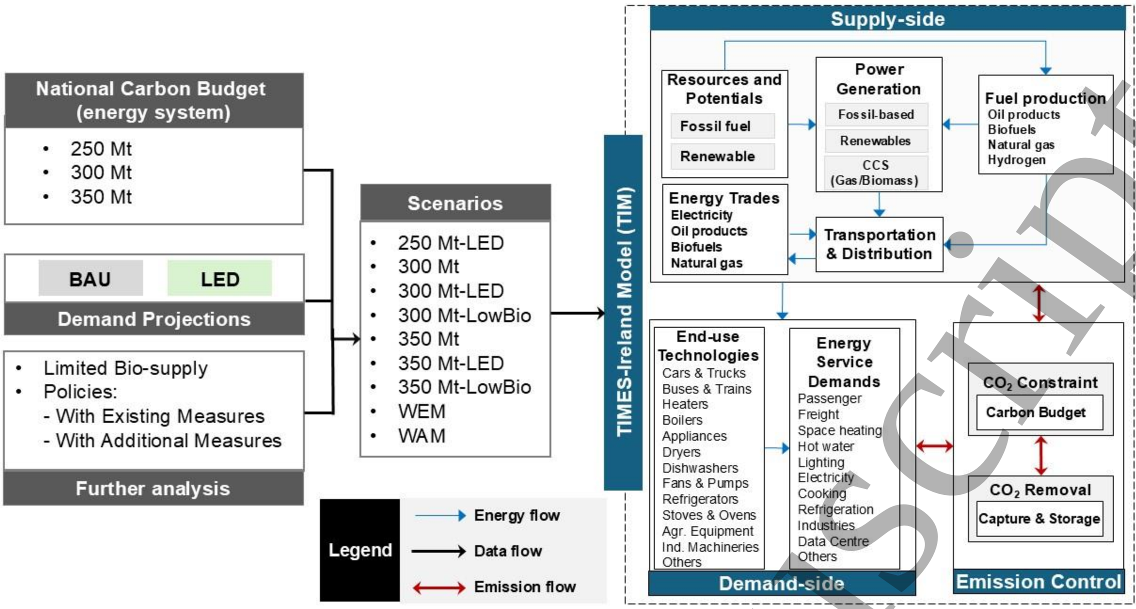


*Figure 1 Methodological framework illustrating the national energy system carbon budgets, scenarios, and simplified TIM model structure.*

## 2.2 Carbon budget scenarios

CB scenarios for 2021-2050 constrain total energy sector GHG emissions (Figure 1). Budgets of 250, 300 and 350 million tonnes of $CO_2e$ (Mt) are derived by downscaling the global remaining carbon budget reported by the IPCC [32], allocating to Ireland on a per-capita basis, with 70% of the CB allocated to the energy system to account for emissions not captured in TIM from LULUCF, and international aviation and shipping. This is detailed further in Daly et al. [33]. These budgets were used to inform the proposed CB3 and CB4.

Approved sectoral emissions ceilings for CB1 and CB2, which specify the legally binding maximum emissions permitted for each sector of the economy within the limits of the overall CBs [34], total 269 Mt for 2021-2030. To account for these mandated sectoral emissions ceilings and allow for some flexibility, we apply an additional 275 Mt constraint for 2021-2030 in each CB scenario. The residual CB is allocated to 2031-2050. For example, the 250 Mt CB scenario implies a deficit of -25 Mt for 2031-2050, while 350 Mt leaves 75 Mt.

Scenario energy demand is modelled using a business-as-usual (BAU) projection, driven by population and economic growth. Several sensitivities explore different assumptions within TIM. A *Low Energy Demand (LED)* scenario lowers energy demand by applying different energy service demand rates across sectors, relative to BAU, with full assumptions documented in Gaur et al. [17]. An additional sensitivity, *LowBio*, limits biomass imports to current levels. These scenarios are applied to the CBs and are denoted with *LED* or *LowBio*: *350Mt-LED* represents a total CB of 350 $MtCO_2$ for 2021-2050, with low energy demand projections.

The scenarios included in this analysis and implemented in TIM are as follows: *250Mt-LED*, *300Mt, 300Mt-LED, 300Mt-LowBio, 350Mt, 350Mt-LED, 350Mt-LowBio*. WEM and WAM scenarios are also modelled within TIM to represent current and proposed policies, using emissions projections from the Environmental Protection Agency (EPA) as the lower bound for emissions [11].

### 2.3 Carbon budget aligned composite scenario

The national carbon budget proposal was informed by a set of shortlisted scenarios, each comprising a combination of energy, agriculture and LULUCF sector pathways [10]. The energy pathways included 300 Mt and 350 Mt scenarios and their *LED*/*LowBio* sensitivities. To represent an energy sector pathway aligned with approved and proposed CBs, a composite scenario - *TIM-CBaligned* - is developed from these scenarios. It is constructed as a weighted average of the TIM outputs from the scenario runs. This weighting reflects how frequently each scenario appears within the shortlist, thereby capturing an energy emissions pathway representative of the CB recommendation.

### 2.4 Benchmarking against EU targets and ESR energy allocations

Compliance is assessed by comparing scenario outcomes against Ireland's obligations under EU targets. Under the ETS, the EU-wide target is non-binding at the Member State level, but is applied at the Irish level, to provide a benchmark for comparison. The ETS covers power, large industry and intra-EU aviation, but our analysis focuses on industry and power only. EED compliance is assessed by comparing projected final energy consumption to Ireland's 2030 target. Under the EED, final energy excludes ambient energy (heat pumps) but includes final energy in international aviation. While Ireland's national target under the proposed EU 2040 target is not yet defined, nor the specific treatment of each sector, we apply the EU-level target to Ireland's energy emissions to provide a benchmark for assessing compliance.

The ESR sets an overall emissions reduction target by 2030, but it is the Annual Emissions Allocations (AEAs) that are binding. The AEAs are defined for 2021-2025, and estimated for 2026-2030 as per the methodology in the ESR [11], [35]. Since the allocations are not defined by sector, we estimate the share available to the energy sector by deducting projected non-energy ESR emissions (agriculture, f-gases and waste) from the overall allowance. As agriculture accounts for around 50% of Ireland's ESR emissions, energy AEAs are highly sensitive to agricultural projections. Four projections are assessed, with resulting energy AEAs shown cumulatively in Figure 2:

- **Agri-2018:** Assumes a 50/50 split in ESR emissions between energy and non-energy, based on Ireland's 2018 emissions.
- **Agri-WEM / Agri-WAM:** Uses non-energy ESR emissions from WEM and WAM projections [11].
- **Agri-CBaligned:** Uses non-energy ESR emissions from the CB proposal agriculture scenario [10]. Like *TIM-CBaligned*, this is based on the weighted average of agriculture, waste, and f-gas emissions across the shortlisted scenarios.

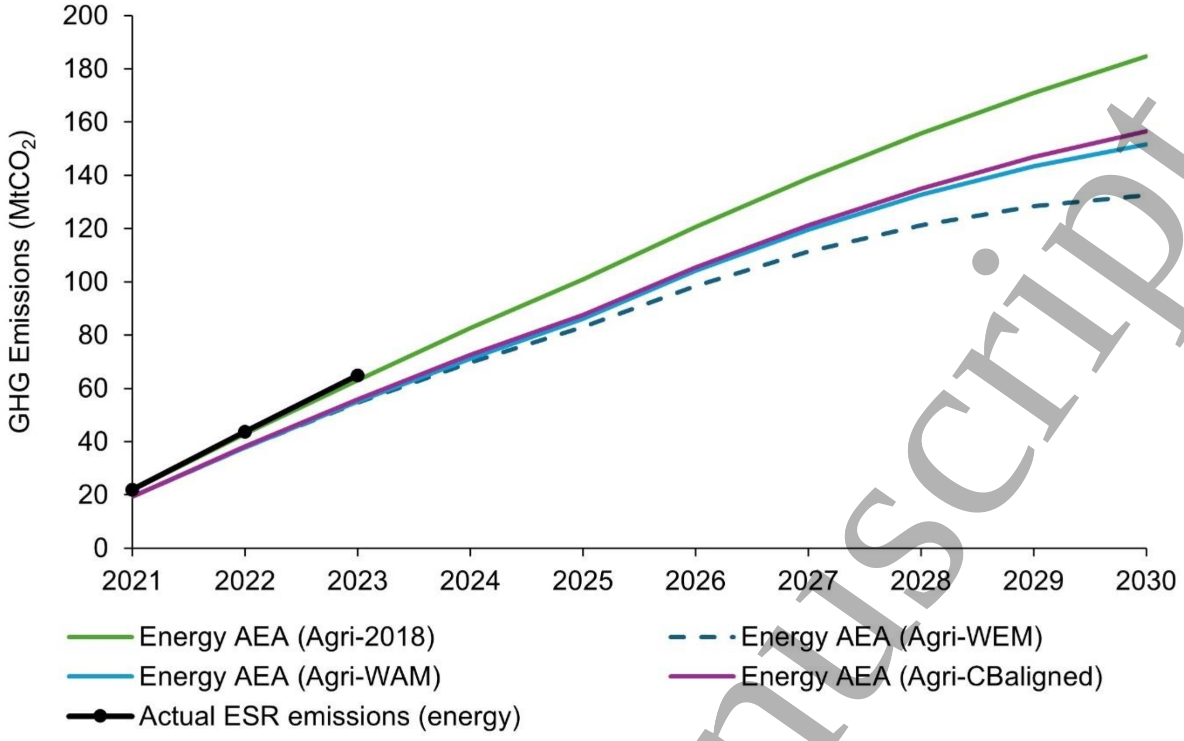


*Figure 2 Estimated cumulative energy system AEAs under the ESR, assuming different agricultural emissions pathways.*

Under the ESR, Ireland has access to two flexibilities to help bridge the gap between ESR emissions and the AEAs. The ETS flexibility allows ETS credits, equivalent to 4% of 2005 ESR emissions (1.91 Mt each year from 2021-2030), to be transferred to an equivalent amount of AEAs, which would otherwise be auctioned [36]. A LULUCF flexibility of 2.68 Mt is estimated to be available each year for 2021-2025 only [11].

## 3.0 Results

This section evaluates how CB pathways perform against EU climate and energy targets, focusing mainly on *TIM-CBaligned*. Comparison with the EPA's WEM and WAM projections highlights the gap between current policies and compliance pathways.

### 3.1 Alignment with the EU ETS

Applying the EU-wide ETS target (-62% relative to 2005) to Ireland implies an equivalent benchmark of 8.3 $MtCO_2$ in 2030 (power and industry sectors only). All CB scenarios surpass this threshold (Figure 3), following a similar trajectory to 2030. *TIM-CBaligned* achieves a 77% decrease relative to 2005, mainly due to power sector decarbonisation and industrial fuel switching. Existing policies (WEM) already put Ireland close to the benchmark, and additional measures (WAM) would result in overachievement.

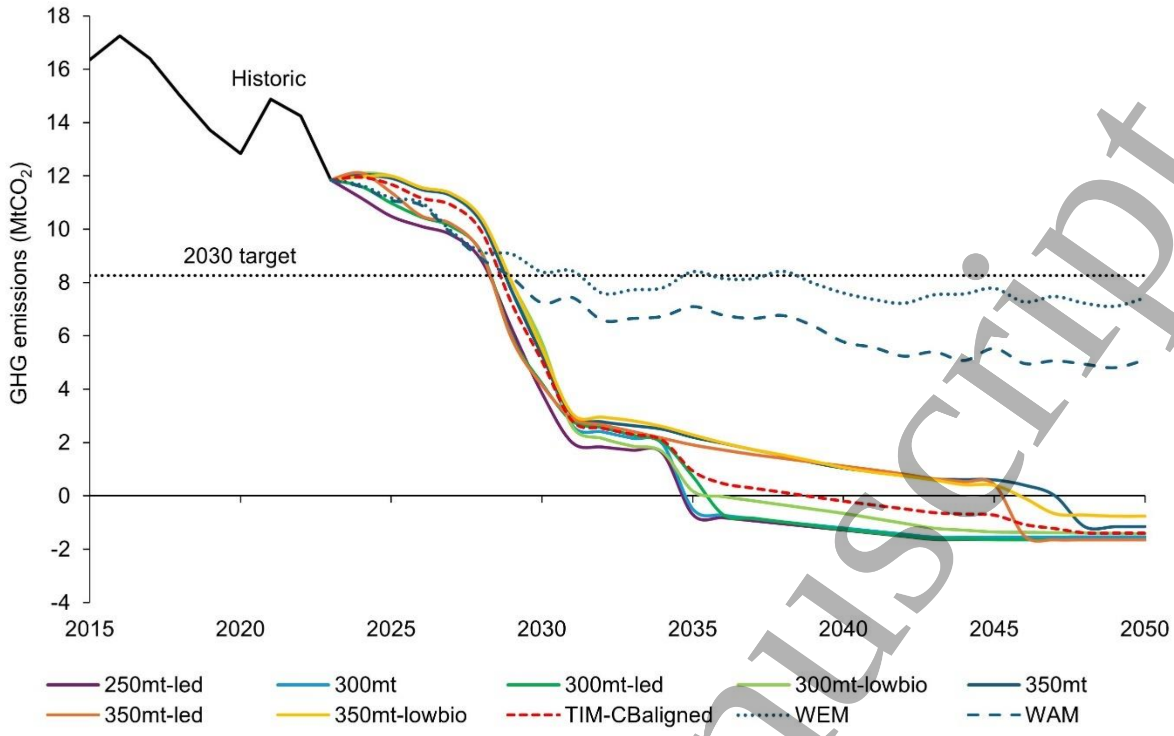


*Figure 3 Ireland's ETS emissions pathways under different scenarios against a 62% ETS emissions reduction target for 2030. Includes power and industry emissions only, and excludes emissions from international aviation.*

### 3.2 Alignment with the ESR

The picture is very different under the ESR. While all CB scenarios reduce energy ESR emissions far beyond Ireland's 2030 target (-42% relative to 2005), staying within the binding AEAs is challenging.

Results highlight that compliance strongly depends on agricultural emissions (Figure 4). Under *Agri-2018*, which maintains a 50:50 split between energy and non-energy ESR emissions, all CB scenarios remain comfortably within AEA limits. If agriculture follows WEM and WAM projections, every scenario exceeds AEAs, even with substantial energy reductions. Only in the case of the most ambitious *250Mt-LED* pathway, combined with an agriculture pathway aligned to the CB proposal (*Agri-CBaligned)*, is compliance achieved.

In *TIM-CBaligned*, energy ESR emissions fall by 63% relative to 2005, but cumulative emissions still exceed AEAs under all pathways except *Agri-2018*. Flexibilities could partially close the gap: Ireland can access 32.5 $MtCO_2$, which could close the gap under *Agri-WAM* and *TIM-CBaligned*, but not under *Agri-WEM*. By contrast, current policy projections are much weaker. WEM and WAM achieve ESR reductions of only 23% and 38% by 2030, exceeding AEAs under all agricultural pathways but *Agri-2018*, even with full use of flexibilities.


*Figure 4 ESR compliance: Cumulative scenario overshoot or undershoot of total AEAs for the energy sector (2021-2030) based on energy AEAs with different agricultural emissions pathways. Figures exclude the use of flexibilities.*

### 3.3 Alignment with the EED

Ireland's binding target under the EED is to limit 2030 final energy consumption to 10.45 Mtoe. Only *250Mt-LED* achieves full compliance by 2030 (9.9 Mtoe). Other *LED* scenarios fall just short of the target (within 0.5 Mtoe) and reach compliance by 2032 (Figure 5). In the remaining CB scenarios (where energy service demands follow a BAU pathway), final energy consumption falls by 5-9% in 2030, leaving a gap of approximately 1 Mtoe. *TIM-CBaligned* reaches compliance after a three-year delay. Across both *BAU* and *LED* energy demand pathways (including *LowBio*), stricter CBs deliver deeper reductions in final energy. WEM and WAM overshoot the target by 2.8 Mtoe and 2 Mtoe, respectively; energy demand increases between 2022 and 2030.

Beyond 2030, final energy consumption in *LED* scenarios converge by 2040 and continues to decline, reaching 8 Mtoe by 2050. *BAU* demand stabilises post-2035, achieving the 2030 target by 2040, and remains steady to 2050. This suggests that sustained demand reduction delivers a more robust long-term route to compliance with the EED.

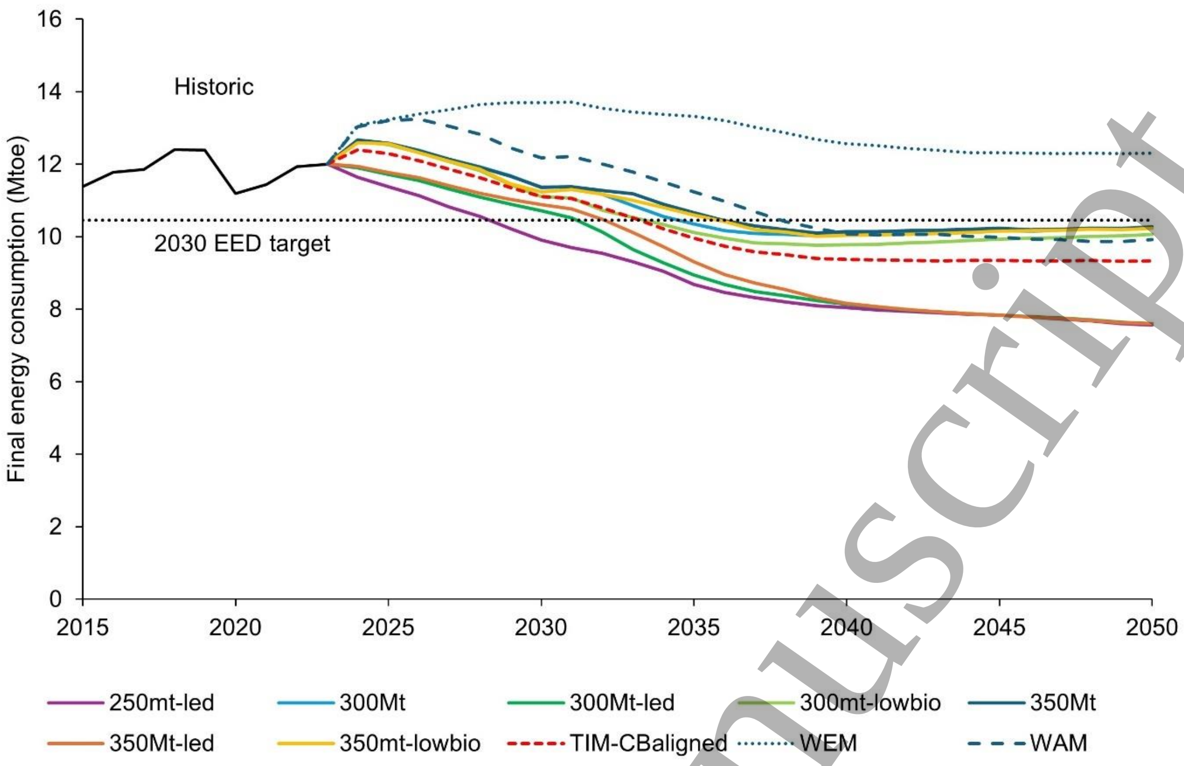


*Figure 5 Final energy consumption for each scenario for 2020-2050, compared to the 2030 EED target for Ireland. Figures include international aviation and exclude ambient energy, as per the EED.*

### 3.4 Alignment with the EU 2040 target

The proposed 2040 target of a 90% reduction in GHG emissions relative to 1990 translates to approximately 3.4 $MtCO_2$ for Ireland. All CB scenarios meet this benchmark (Figure 6). *TIM-CBaligned* achieves the target as early as 2036 and reduces energy emissions by 97% by 2040, reaching net-zero in the early 2040s and net-negative thereafter. *250Mt-LED* achieves net-negative emissions as early as 2037, eight years earlier than *TIM-CBaligned* (Figure 6).

In contrast, WEM and WAM fall far short: they deliver a reduction of only 39% and 57% by 2040, respectively, and fail to meet net-zero emissions by 2050. The divergence between CB pathways and WEM/WAM trajectories becomes apparent immediately after 2023, with CB scenarios exhibiting a sharp decline in emissions to 2030.

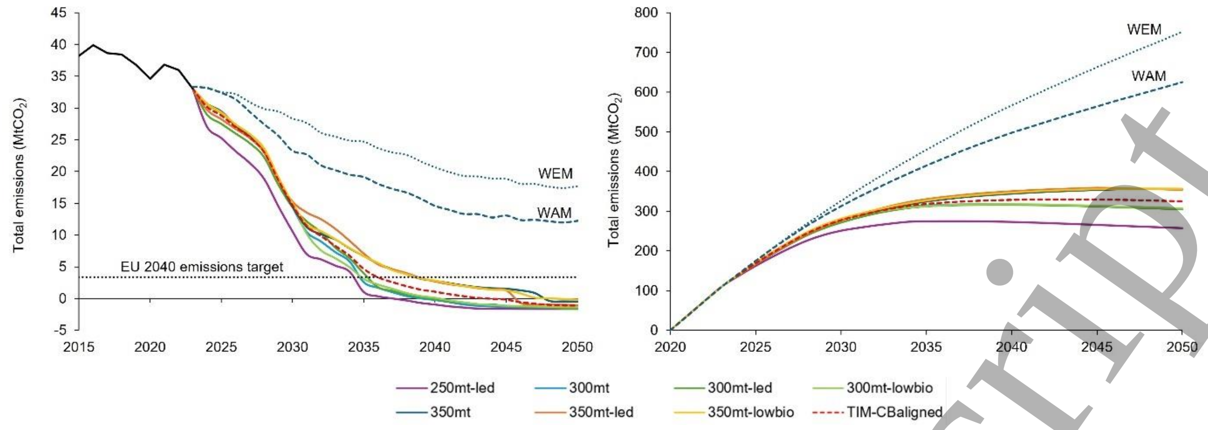


*Figure 6 Scenario emissions pathways, benchmarked against the EU 2040 target of 90% reduction (relative to 1990), applied to Ireland's energy system emissions (left panel) and cumulative emissions pathways (right panel).*

## 3.5 Sectoral transformation

*TIM-CBaligned* distributes emissions reductions across sectors in line with national CBs and EU trajectories. For CB1 (2021-2025) and CB2 (2026-2030), cumulative emissions amount to 274 Mt$CO_2$, in line with the SEC constraints. Emissions for energy sectors are 41 Mt$CO_2$ in CB3 (2031-2035) and 10 Mt$CO_2$ for CB4 (2036-2040).

Figure 7 outlines the key mitigation measures in each sector for 2030 and 2040 under *TIM-CBaligned* and compares them with the policy measures assumed in 2030 for WEM and WAM [12].

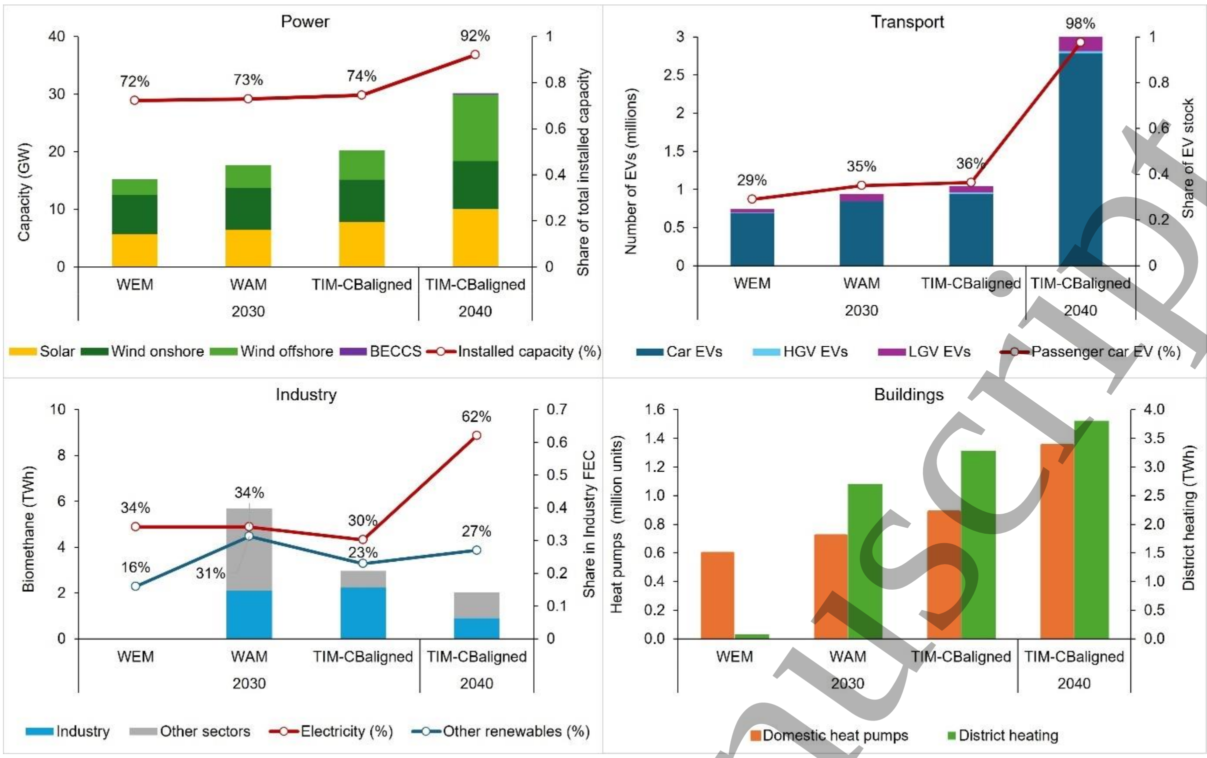


*Figure 7 Comparison of key sectoral technology deployment in TIM-CBaligned, WEM and WAM. For the transport sector, LGV refers to light goods vehicles and HGV refers to heavy goods vehicles.*

A net-negative emissions *power* system is achieved by 2035 with the implementation of 200 MW of Bioenergy with Carbon Capture and Storage (BECCS), which increases to 300 MW by 2040, generating 2% of the total electricity and removal of up to 0.8 $MtCO_2$ annually. By 2040, power sector emissions fall by 108%, relative to 1990. *TIM-CBaligned* achieves earlier and deeper renewable deployment than WEM and WAM.

*Industry* emissions fall by around 40% by 2030 and 90% by 2040 through the electrification of most heat levels, fuel switching from solid fuels to solid biomass and natural gas to biogas, and the deployment of carbon capture and storage (CCS) in cement manufacturing. Biomethane is a transitional measure in the short to medium term. WEM and WAM show slightly higher electrification by 2030, along with higher renewable penetration in WAM. However, overall final energy in *TIM-CBaligned* is 12% lower, reflecting stronger efficiency gains and structural changes in energy use.

*Transport* emissions halve by 2030 and decline by 97% by 2040, relative to 2018, outperforming WEM and WAM, despite substantially higher activity levels. By 2030, private car travel increases by 43% in *TIM-CBaligned*, compared to 2019, while WAM projects a modest decline (-12%) and WEM a moderate increase (+12%). Decarbonisation is primarily driven by accelerated EV uptake (Figure 7) and the cessation of internal combustion engine car sales by 2025, which is 5 years earlier than WAM and 10 years earlier than WEM.

*Building* sector emissions fall by 70% by 2030, and 97% by 2040, relative to 2018, achieved through increased electrification, heat pump deployment, and the introduction of district heating. Heat pump deployment is 23% higher than WAM in 2030, with a slightly higher level of district heating.

This sectoral breakdown highlights how accelerated electrification, efficiency improvements, and fuel switching drive EU compliance under CB-aligned pathways, while WEM and WAM systematically fall short across most sectors (Figure 7).

### 3.6 System costs

Delivering *TIM-CBaligned* requires a significant upfront cumulative investment of €100 billion by 2030 and a further €125 billion by 2040, approximately 9% higher than WEM and 2% higher than WAM. However, this higher upfront capital spending is offset by lower fuel and operating costs.

By 2040, annualised energy system costs in *TIM-CBaligned* amount to 2% of 2020 GDP, compared to 2.2% in WEM and WAM (Figure 8), which continue to rely on fossil fuels. This confirms a key finding of international studies: ambitious decarbonisation pathways require substantial early investment, which are largely or wholly paid back in the long-term from fuel savings [37].

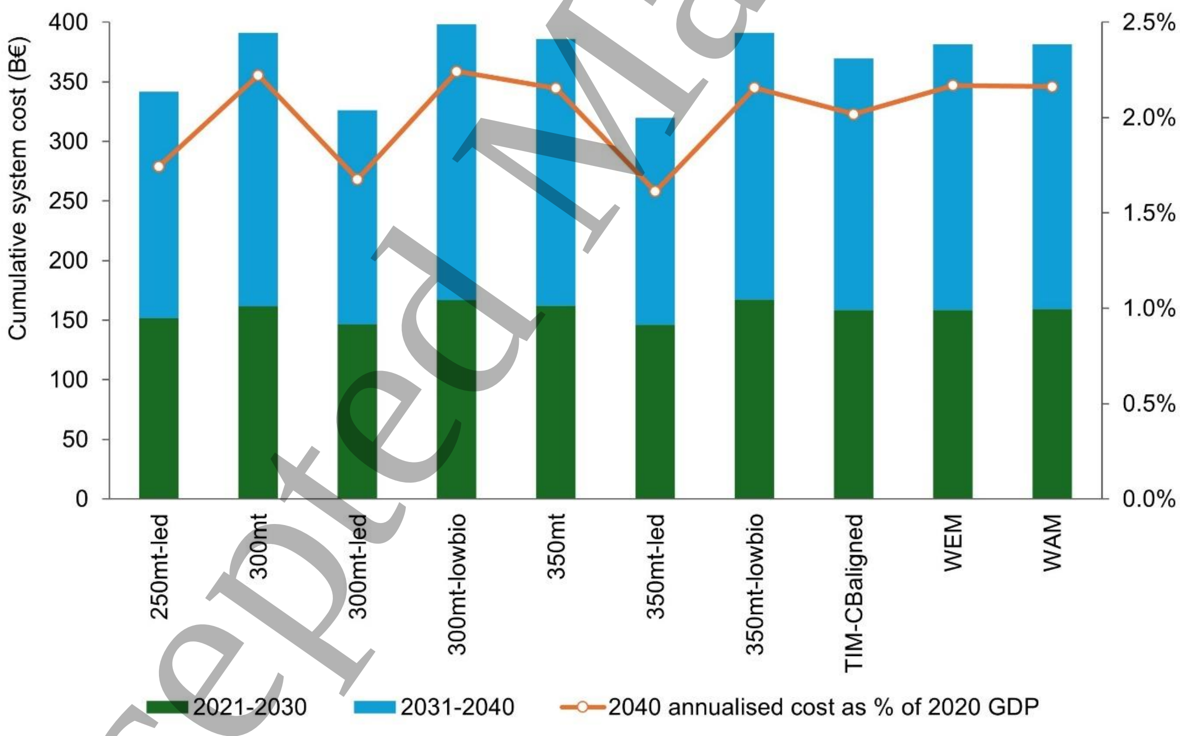


*Figure 8 Cumulative energy system operating costs (2021-2040) and annualised cost in 2040 as a percentage of 2020 GDP.*

## 4.0 Discussion

This study examined whether Ireland's energy-sector pathways, consistent with legally binding carbon budgets to 2030 and those proposed in the period to 2040, are aligned with

EU climate and energy targets. Results show strong alignment with the ETS and 2040 benchmark, partial alignment with the EED, and persistent challenges in the ESR (Figure 9). By contrast, current Irish policies (WEM and WAM) underperform across most dimensions, particularly the ESR and 2040 targets.

The message is unambiguous: if Irish policy is successful in delivering these energy transition scenarios required under domestic climate policy, compliance with EU targets will follow, while current pathways are insufficient. However, the analysis also exposes vulnerabilities, particularly under the ESR.

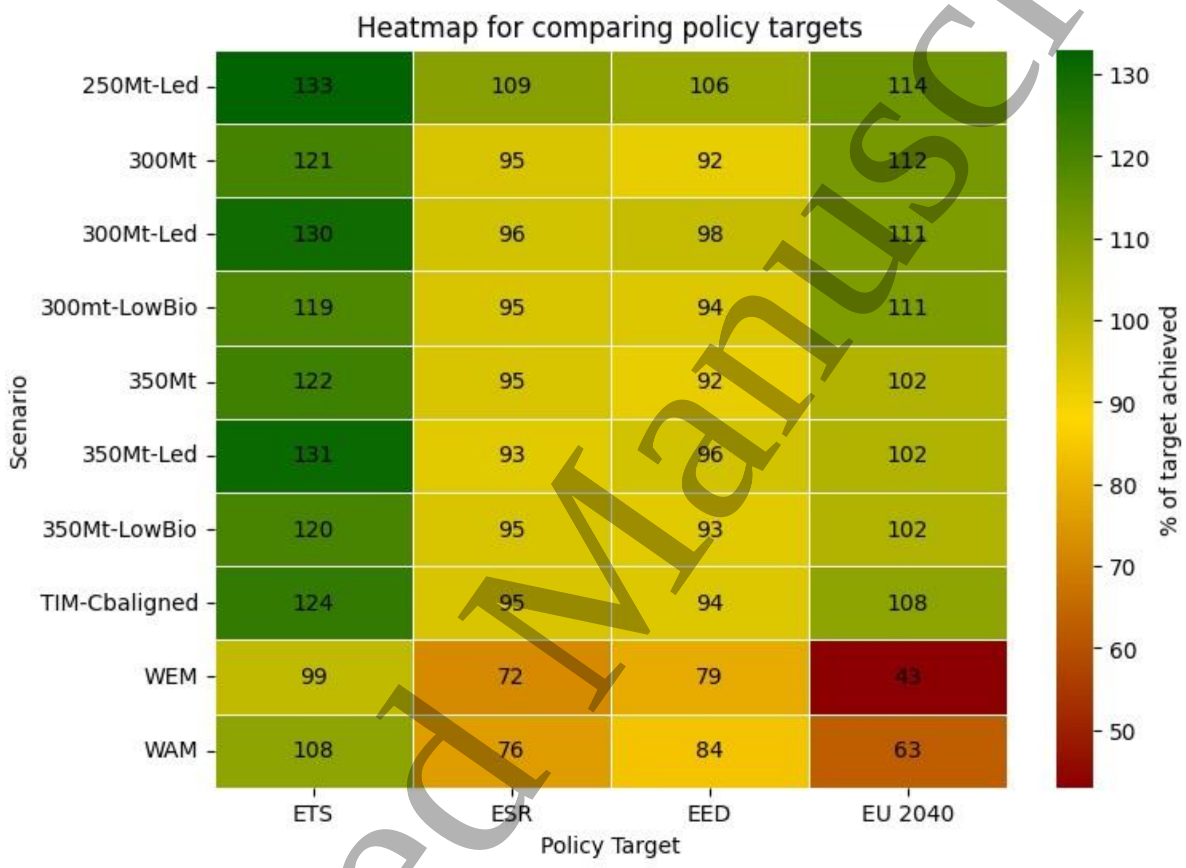


*Figure 9 Compliance of Irish energy system scenarios with EU climate and energy targets, expressed as a percentage of the target achieved. ESR figures shown use Agri-WAM energy AEA allocation.*

### 4.1 How national ambition supports EU compliance

**Alignment with the EU-ETS** is strong. An energy pathway compliant with meeting domestic CBs would place Ireland in a very strong position to cut ETS emissions in the power and industry sectors beyond the 2030 EU-wide target of -62%, relative to 2005. The Irish State is not mandated to achieve this EU-wide target, which is to be delivered through the ETS market mechanism. Consequently, this does not imply “overcompliance” against an EU target. However, Ireland can benefit through the ETS ESR flexibility, allowing transfer of ETS allowances towards ESR compliance.

**Compliance with the ESR** remains a challenge. *TIM-CBaligned* cuts energy-related ESR emissions by 63% relative to 2005, surpassing the 42% requirement, but compliance requires cumulative emissions to remain below the AEAs. This hinges on mitigation in the agriculture sector, Ireland's dominant non-ETS sector. While this study focuses on energy-related emissions and pathways, a key finding is that even in the strongest energy decarbonisation scenario, overall ESR compliance requires stronger mitigation in domestic agriculture policy and/or heavy reliance on ESR flexibilities.

This finding aligns with previous Irish assessments [11] and supports international evidence that hard-to-abate sectors can dictate overall compliance trajectories [38]. It also reflects broader EU-level concerns that agricultural emissions are not being sufficiently addressed [39], [40]. As a result, the European Scientific Advisory Board on Climate Change recommends better aligning the EU's common agricultural policy with EU climate ambitions, including shifting support away from emission-intensive agricultural practices, such as livestock production, and towards lower-emitting products and activities [41]. The implication is clear: ESR alignment requires integrated, mitigation strategies spanning agriculture, land use, and energy, not siloed sectoral planning.

While focused on Ireland, these findings have broader relevance for other Member States with a high share of non-$CO_2$ agricultural emissions, including Denmark and parts of Central and Eastern Europe. In such contexts, strong decarbonisation of the energy system alone may be insufficient to ensure compliance with effort-sharing obligations, and cross-sectoral mitigation strategies are therefore likely to be a prerequisite for achieving multi-level policy coherence.

Ireland's target under the **EED** – to reduce final energy consumption to 10.45 Mtoe by 2030 – is narrowly missed in *TIM-CBaligned* (11.1 Mtoe), which represents a significant gain but falls short of the target. *Low energy demand* pathways are most closely aligned with the target. This suggests that relying on device-level efficiency gains and fuel switching alone is unlikely to deliver the required outcome without a broader shift to reduce overall energy demand, consistent with findings in Gaur et al. [17] that deep demand reduction is a prerequisite for feasible and cost-effective decarbonisation. This also aligns with recent EU discourse on energy security, where lowering absolute demand is seen as both a compliance and resilience measure [42], [43]. Ireland's Energy Security Package similarly emphasises demand reduction as a core strategy to enhance energy security [44]. The transition towards a renewable-based power system and electrification could also reduce dependence on oil and gas imports, lowering exposure to volatile global fuel markets and supply disruptions, thereby enhancing energy security.

Over the longer term, the CB-aligned pathway outperforms the EU's **indicative 2040 target**, highlighting its potential as a robust pathway for national compliance. This is particularly relevant given Ireland's high share of agricultural emissions, where mitigation options are more limited and decarbonisation is inherently more challenging. The early divergence between CB pathways and WEM/WAM trajectories underscores the current compliance gap, the inadequacy of existing and planned measures, and the necessity of immediate actions to meet both near- and long-term emissions targets.

### 4.2 Implementation gap and policy implications

WEM and WAM scenarios show that Ireland's current policies are insufficient to meet national CBs and EU targets. Ireland has already exceeded its ESR emissions allocation for 2021-2023, increasing future compliance pressures. This aligns with EU-wide analyses showing that, without accelerated measures, most Member States will fail to meet Fit for 55 commitments [14]. Ireland's position is particularly exposed because of its high ESR share and limited flexibilities. This underscores calls in the governance literature for early, decisive action to reduce the risk of costly last-minute compliance purchases [45], [46].

However, this analysis shows strong coherence between the measures required to align the energy system with domestic CBs and to meet EU targets. The modelling underpinning these scenarios also demonstrates the cost-effectiveness of realising CB-compliant energy transition. Deep and early GHG reductions in power, transport, buildings, and industry are required, driven by electrification, renewable deployment, efficiency, and fuel switching. Although enormously technically challenging – for example, net-zero or negative emissions are achieved in the power sector by 2035 – investment needs are manageable. Costs are lower than WEM/WAM over the long term due to reduced fossil fuel imports and energy system operating costs; however, the political economy literature warns that even cost-effective transitions can face resistance when upfront costs are high, especially for distributed technologies like heat pumps and EVs. Overcoming this requires not only financial mechanisms but also coordinated delivery in infrastructure, skills, and public engagement, factors underlined in Daly et al. [33] as critical to Ireland's net-zero transition.

At the time of writing, the Oireachtas (Irish Parliament) Committee on Climate, Environment and Energy is holding hearings on the proposed CBs, and the Government is due to accept or amend CB proposals shortly. This gives the findings direct policy relevance: the scenarios presented here provide evidence that delivering ambitious CB pathways is necessary not only for domestic law but also for compliance with EU targets.

The findings also highlight the importance of early emissions reductions, clear planning for sectoral contributions, and timely implementation of existing policy commitments. Demand-side measures and sustained investment are also likely to play a central role in enabling compliance and avoiding long-term cost and feasibility risks [38], [47], [48], [49].

## 5.0 Conclusion

This study provides the first quantitative assessment of the alignment between Ireland's legally binding national carbon budgets and its EU climate and energy obligations for the energy system. Using the TIMES-Ireland Model, we find that:

- ETS compliance is exceeded: a 77% reduction in power and industry emissions by 2030 vs an EU-wide target of 62%.
- ESR compliance is conditional and achievable for energy-sector emissions only if agriculture delivers substantial reductions above current policy pathways. Otherwise, non-compliance is likely, even with flexibilities and the most ambitious energy-related decarbonisation pathways.
- EED compliance is narrowly missed, and demand reduction through structural shifts in transport, heat and the economy is required.
- The 2040 benchmark is surpassed, achieving a 97% reduction in energy-related emissions relative to an indicative EU-wide target of 90% for all GHGs.

No published studies explicitly test the coherence of a national CB pathway against multiple EU targets using quantitative modelling. This analysis addresses that gap by integrating energy system decarbonisation scenarios with ESR allocation methods and EU compliance metrics, providing a replicable approach for other Member States. It strengthens the empirical foundation of multi-level climate governance and coherence research, offering concrete evidence that domestic ambition can underpin, and in some cases exceed, supranational compliance, while also highlighting the sectoral vulnerabilities that can still cause failure. Future research should expand this integrated modelling to include agriculture, LULUCF, international aviation and shipping, and additional EU frameworks such as the Renewable Energy Directive.

Policy implications are clear. First, ambitious domestic targets aligned with carbon budgets can deliver strong multi-level policy coherence, ensuring EU compliance in major sectors. Second, partial alignment is insufficient: underperformance in agriculture can negate energy-sector gains, increasing compliance risk. Third, demand-side measures are indispensable for meeting energy efficiency goals and minimising compliance costs.

Ultimately, Ireland's experience demonstrates that a strategy of pursuing national decarbonisation at or beyond EU ambition can simultaneously strengthen domestic climate credibility, minimise compliance risk, and contribute to collective European targets. In a decade when climate action will be judged on delivery rather than ambition, ensuring such alignment is not optional but essential.

### 5.1 Limitations and future work

This analysis is subject to limitations and caveats. First, while the *TIM-CBaligned* scenario captures a range of decarbonisation pathways, it does not fully represent uncertainties in technology costs, behavioural change, or macroeconomic conditions that may influence future emissions and energy demand. It does not include a range of financial and non-financial costs and benefits, such as some infrastructure (energy and transport networks), and sustainability and health benefits. The composite nature of *TIM-CBaligned* may also limit the internal consistency of the results. This study adopts a system planner approach to decarbonisation, in which emissions are constrained directly through carbon budgets rather than induced via exogenous carbon price assumptions. While this approach is appropriate for evaluating target coherence, it does not capture allowance price formation within the EU ETS or ETS-2 markets.

Second, compliance estimates carry some uncertainty: ESR annual emissions limits for 2026-2030 remain provisional; accounting rules for LULUCF flexibilities post-2026 are uncertain; and the EED does not have a binding compliance framework which penalises non-compliance.

Third, given the focus on energy decarbonisation, simplified sectoral allocation methods and fixed assumptions on agricultural mitigation are undertaken; alternative allocation rules or more granular agricultural abatement modelling could yield different outcomes. Moreover, international aviation, LULUCF, waste and F-gases are not covered – these require further analysis.

Future work should undertake uncertainty and sensitivity analysis to test the robustness of findings. Moreover, linking energy system modelling more directly with detailed agricultural and land-use modelling would improve ESR compliance estimates and inform cross-sectoral strategies. Comparative application of this framework to other EU Member States could build a broader evidence base on national–EU target alignment.

## Acknowledgments

This paper is based on research that was commissioned by the Climate Change Advisory Council. Development of the TIMES-Ireland Model is supported by the Department of Climate, Energy and the Environment through the Climate and Energy Modelling Services to the Climate Action Modelling Group (CAMG) (grant No. RFT2022/S 164-466018), and supported by MaREI, the Research Ireland Centre for Energy, Climate and Marine (grant No. 12/RC/2302_P2). Vahid Aryanpur also acknowledges support from the Environmental Protection Agency Research Programme 2021–2030 via the SHIELD project (2024-CE-1261).

The authors wish to thank members of the Energy Policy and Modelling Group, particularly Dr. Paul Deane and Mr. Bakytzhan Suleimenov for reviewing and providing technical support, Zahra Hajighasemi for assistance in preparing several figures, and members of the CCAC secretariat and EPA for reviewing drafts.

## Author contributions: CRediT

**Ciara Doherty:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Vahid Aryanpur**: Writing – review & editing, Visualization, Validation. **Hannah Daly:** Writing, review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization.

## Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Additional information

### Code and data availability

The TIMES code is open source and has been archived on Zenodo [31] The files and input data for the TIMES-Ireland model used in this study can be accessed on GitHub and archived on Zenodo [50]. Detailed modelling results across all CB scenarios are available on an online portal: https://epmg.netlify.app/TIM-Carbon-Budget-August_2024.

## References


[1] European Parliament & Council, ‘Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (“European Climate Law”)’, *Off. J. Eur. Union*, vol. L 243, pp. 1–17, Sep. 2021.

[2] UNFCCC, *Paris Agreement*. 2015, p. 16. Accessed: Mar. 17, 2025. [Online]. Available: https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

[3] European Commission, ‘The European Green Deal’, vol. COM/2019/640 final, 2019, Accessed: Sep. 17, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640

[4] European Parliament & Council, ‘Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system’, *Off. J. Eur. Union*, vol. L 130, pp. 134–202, May 2023.

[5] European Parliament & Council, ‘Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast)’, *Off. J. Eur. Union*, vol. L 231, no. 1–111, Sep. 2023, Accessed: Sep. 17, 2025. [Online]. Available: http://data.europa.eu/eli/dir/2023/1791/oj

[6] European Parliament & Council, ‘Regulation (EU) 2023/857 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement, and Regulation (EU) 2018/1999’, *Off. J. Eur. Union*, vol. L 111, pp. 1–14, Apr. 2023.

[7] European Commission, ‘Europe’s 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society’, 2024. Accessed: Mar. 17, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A63%3AFIN

[8] 'Climate Action and Low Carbon Development (Amendment) Act 2021', *Ir. Statute Book*, vol. No. 32 of 2021, 2021, Accessed: Jan. 31, 2024. [Online]. Available: https://www.irishstatutebook.ie/eli/2021/act/32/enacted/en/html
[9] DECC, 'Carbon Budgets 2022', 2022. Accessed: Mar. 17, 2025. [Online]. Available: https://www.gov.ie/en/publication/9af1b-carbon-budgets/
[10] CCAC, 'Carbon Budget Proposal Report 2024', 2024. Accessed: Mar. 17, 2025. [Online]. Available: https://www.climatecouncil.ie/councilpublications/
[11] EPA, 'Ireland's Greenhouse Gas Emissions Projections 2023-2050', 2024. Accessed: Mar. 14, 2025. [Online]. Available: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/irelands-greenhouse-gas-emissions-projections-2023-2050.php
[12] SEAI, 'National Energy Projections 2024', 2024. Accessed: Mar. 14, 2025. [Online]. Available: https://www.seai.ie/sites/default/files/publications/National-Energy-Projections-Report-2024.pdf
[13] IFAC and CCAC, 'A colossal missed opportunity: Ireland's climate action and the potential costs of missing targets', 2025. Accessed: Mar. 14, 2025. [Online]. Available: https://www.fiscalcouncil.ie/wp-content/uploads/2025/03/Irelands-climate-action-and-the-potential-costs-of-missing-targets.pdf
[14] European Commission, *Climate action Progress Report 2024*. LU: Publications Office, 2024. Accessed: Mar. 18, 2025. [Online]. Available: https://data.europa.eu/doi/10.2834/8000893
[15] IEA, 'Net Zero by 2050', Paris, 2021. [Online]. Available: https://www.iea.org/reports/net-zero-by-2050
[16] O. Balyk *et al.*, 'TIM: Modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1.0)', *Geosci. Model Dev.*, vol. 15, no. 12, pp. 4991–5019, Jun. 2022, doi: 10.5194/gmd-15-4991-2022.
[17] A. Gaur, O. Balyk, J. Glynn, J. Curtis, and H. Daly, 'Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland', *Renew. Sustain. Energy Transit.*, vol. 2, p. 100024, Aug. 2022, doi: 10.1016/j.rset.2022.100024.
[18] V. Aryanpur, O. Balyk, J. Glynn, A. Gaur, J. McGuire, and H. Daly, 'Implications of accelerated and delayed climate action for Ireland's energy transition under carbon budgets', *Npj Clim. Action*, vol. 3, no. 1, p. 97, Nov. 2024, doi: 10.1038/s44168-024-00181-7.
[19] CCAC, 'Carbon Budget Technical Report', Oct. 2021. [Online]. Available: https://assets.gov.ie/static/documents/climate-change-advisory-councils-carbon-budget-technical-report-ccac-report.pdf
[20] G. Verhaeghe and V. Mauerhofer, 'National progress towards supranational climate & energy goals due to policies & their mixes? Insights from Northern & Western Europe', *J. Environ. Manage.*, vol. 348, p. 119304, Dec. 2023, doi: 10.1016/j.jenvman.2023.119304.
[21] I. Perissi and A. Jones, 'Investigating European Union Decarbonization Strategies: Evaluating the Pathway to Carbon Neutrality by 2050', *Sustainability*, vol. 14, no. 8, p. 4728, Apr. 2022, doi: 10.3390/su14084728.
[22] J. Poschmann, V. Bach, and M. Finkbeiner, 'Are the EU climate ambitions reflected on member-state level for greenhouse gas reductions and renewable energy consumption shares?', *Energy Strategy Rev.*, vol. 43, p. 100936, Sep. 2022, doi: 10.1016/j.esr.2022.100936.

[23] M. Bellanca, 'What, how and where: an assessment of multi-level European climate mitigation policies', *Npj Clim. Action*, vol. 3, no. 1, p. 119, Dec. 2024, doi: 10.1038/s44168-024-00200-7.
[24] G. Melica, P. Bertoldi, A. Kona, A. Iancu, S. Rivas, and P. Zancanella, 'Multilevel governance of sustainable energy policies: The role of regions and provinces to support the participation of small local authorities in the Covenant of Mayors', *Sustain. Cities Soc.*, vol. 39, pp. 729–739, May 2018, doi: 10.1016/j.scs.2018.01.013.
[25] A. Gouldson *et al.*, 'Exploring the economic case for climate action in cities', *Glob. Environ. Change*, vol. 35, pp. 93–105, Nov. 2015, doi: 10.1016/j.gloenvcha.2015.07.009.
[26] E. Croci, B. Lucchitta, and T. Molteni, 'Low carbon urban strategies: An investigation of 124 European cities', *Urban Clim.*, vol. 40, p. 101022, Dec. 2021, doi: 10.1016/j.uclim.2021.101022.
[27] A. Olsson, E. Rodriguez, A. Hansson, S. Jansson, and M. Fridahl, 'Forerunner city or net-zero opportunist? Carbon dioxide removal in Stockholm, residual emissions and risks of mitigation deterrence', *Energy Res. Soc. Sci.*, vol. 113, p. 103567, Jul. 2024, doi: 10.1016/j.erss.2024.103567.
[28] R. Loulou, G. Goldstein, A. Kanudia, A. Lettila, and U. Remme, 'Energy Technology Systems Analysis Programme: Documentation for the TIMES Model Part I: TIMES concept and theory', Jul. 2016.
[29] G. Goldstein, A. Kanudia, A. Lehtilä, U. Remme, and E. Wright, 'Energy Technology Systems Analysis Programme: Documentation for the TIMES Model Part III: The operation of the TIMES code', 2016. Accessed: Mar. 13, 2024. [Online]. Available: https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-PartIII.pdf
[30] R. Loulou, A. Lehtilä, A. Kanudia, U. Remme, and G. Goldstein, 'Energy Technology Systems Analysis Programme: Documentation for the TIMES Model Part II: Comprehensive reference manual', 2016, Accessed: Mar. 13, 2024. [Online]. Available: https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-PartII.pdf
[31] IEA-ETSAP, Antti-L, and Ggiannakidis, 'etsap-TIMES/TIMES_model: TIMES Version 4.5.3', Zenodo, Apr. 2021. doi: 10.5281/ZENODO.4660551.
[32] IPCC, 'Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change', Intergovernmental Panel on Climate Change, Geneva, Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647.001.
[33] H. Daly, Aryanpur, Vahid, B. Suleimenov, and Deane, Paul, 'Pathways for Ireland's energy system to 2050 - Modelling analysis to support the Climate Change Advisory Council on the Second Carbon Budget Programme', 2024. doi: 10.5281/ZENODO.17192991.
[34] DECC, 'Sectoral Emissions Ceilings', 2022. Accessed: Mar. 17, 2025. [Online]. Available: https://www.gov.ie/en/publication/76864-sectoral-emissions-ceilings/
[35] European Commission, 'Commission Implementing Decision (EU) 2023/1319 of 28 June 2023 amending Implementing Decision (EU) 2020/2126 to revise Member States' annual emission allocations for the period from 2023 to 2030', *Off. J. Eur. Union*, vol. L 163/9, pp. 9–11, Jun. 2023.
[36] European Commission, 'Commission Implementing Decision (EU) 2020/2126 of 16 December 2020 on setting out the annual emission allocations of the Member States for the period from 2021 to 2030 pursuant to Regulation (EU) 2018/842 of the European Parliament and of the Council', *Off. J. Eur. Union*, vol. L 426, pp. 58–64, Dec. 2020.

[37] IEA, 'Strategies for Affordable and Fair Clean Energy Transitions', IEA, Paris, 2024. [Online]. Available: https://www.iea.org/reports/strategies-for-affordable-and-fair-clean-energy-transitions

[38] O. Y. Edelenbosch *et al.*, 'Reducing sectoral hard-to-abate emissions to limit reliance on carbon dioxide removal', *Nat. Clim. Change*, vol. 14, no. 7, pp. 715–722, Jul. 2024, doi: 10.1038/s41558-024-02025-y.

[39] I. Cuadros-Casanova *et al.*, 'Opportunities and challenges for Common Agricultural Policy reform to support the European Green Deal', *Conserv. Biol.*, vol. 37, no. 3, p. e14052, Jun. 2023, doi: 10.1111/cobi.14052.

[40] ECA, 'Common Agricultural Policy Plans. Greener, but not matching the EU's ambitions for the climate and the environment', European COurt of Auditors, Luxembourg, Special Report No 20, 2024. [Online]. Available: https://www.eca.europa.eu/ECAPublications/SR-2024-20/SR-2024-20_EN.pdf

[41] ESABCC, *Towards EU climate neutrality: progress, policy gaps and opportunities : assessment report 2024.* LU: Publications Office, 2024. Accessed: Aug. 18, 2025. [Online]. Available: https://data.europa.eu/doi/10.2800/216446

[42] European Commission, 'COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS REPowerEU Plan (COM/2022/230 final)', May 2022, [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

[43] European Commission, 'COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU "Save Energy" (COM/2022/240 final)', May 2022, [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A240%3AFIN&qid=1653033053936

[44] DECC, 'Energy Security in Ireland to 2030. Energy Security Package', Nov. 2023. [Online]. Available: https://assets.gov.ie/static/documents/energy-security-in-ireland-to-2030-265afb44-cdff-4acc-b507-afe44a2462c8.pdf

[45] K. Calvin *et al.*, 'IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.', Intergovernmental Panel on Climate Change (IPCC), Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647.

[46] IEA, 'Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach', Paris, 2023. Accessed: Oct. 30, 2023. [Online]. Available: https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

[47] A. Grubler *et al.*, 'A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies', *Nat. Energy*, vol. 3, no. 6, pp. 515–527, Jun. 2018, doi: 10.1038/s41560-018-0172-6.

[48] IEA, 'World Energy Outlook 2021', 2021. [Online]. Available: https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf

[49] F. Creutzig *et al.*, 'Demand, services and social aspects of mitigation (Chapter 5). In: IPCC 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on

Climate Change. Eds. Shukla, A.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., et al.', Cambridge University Press, Cambridge, UK and New York, USA, 2022. Accessed: Aug. 26, 2025. [Online]. Available: 10.1017/9781009157926.007.

[50] O. Balyk *et al.*, *TIMES-Ireland Model*. (Aug. 29, 2024). Zenodo. doi: 10.5281/ZENODO.13497444.