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# Ireland's carbon emission trends and degrowth opportunities: Based on modified Tapio - LMDI model

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ABSTRACT

This study examines the complex interplay between economic growth and carbon emissions in Ireland from 1995 to 2023 at the national level, using the modified Tapio decoupling model and the Logarithmic Mean Divisia Index (LMDI) decomposition method from a degrowth perspective. It provides both a theoretical foundation and possible strategies for balancing Ireland's climate commitments with economic stability. The findings reveal distinct phase characteristics in Ireland's decoupling state, with the core tension arising from the dynamic interplay between technological effect (energy structure optimization, energy efficiency improvements, and material efficiency gains) and scale effects (per capita GNI* growth and population expansion). Furthermore, this study proposes the possible opportunity for degrowth at the national level, offering theoretical insights for small open economies seeking to reconcile carbon neutrality with economic growth.

## 1. Introduction

The urgency of the global climate change crisis and the imperative of achieving carbon neutrality are driving a profound transformation in economic growth paradigms toward decoupling from carbon emissions. As a legally binding climate accord (Kinley, 2017), the Paris Agreement mandates limiting this century's temperature rise to well below 2 °C and further seeks additional measures to restrict the increase to within 1.5 °C (Armstrong McKay et al., 2022). In this context, Ireland has continually introduced the Climate Action Plan 2024, outlining a revised pathway toward achieving climate neutrality, protecting biodiversity, and promoting an environmentally sustainable economic transition by 2050 (DECC, 2023).

As a typical small open economy, Ireland offers significant value for studying the relationship between energy structure and economic growth (Andreoni, 2020). It is necessary to analyze Ireland's decoupling and decomposition from a broader time span (O'Mahony et al., 2013) to better understand the correlation between Ireland's economic development and carbon emission decoupling (Wang et al., 2018).

Ireland's rapid growth has long attracted attention. From the 1990s to early 2000s, its rate exceeded the EU average, earning the "Celtic Tiger" nickname. Over the past decade, GDP rose from €219.7 billion in 2012 to €492.1 billion in 2023 (CSO, 2024), showing strong momentum. In 2022, it led EU countries with 9.4 % growth (CSO, 2023). Yet, this expansion has increased carbon emission pressures.

Between 1990 and 2001, Ireland's greenhouse gas (GHG) emissions steadily increased, peaking at 70.82 Mt $CO_2$ eq, and carbon dioxide ($CO_2$) is always the largest contributor to Ireland's greenhouse gas emissions (EPA, 2024). While emissions declined during the COVID-19 pandemic, the gradual lifting of restrictions in 2021, coupled with increased coal use and reduced renewable energy generation, resulted in 4.5 % emissions rebound that year. According to the latest figures from the Environmental Protection Agency (EPA) of Ireland, GHG emissions in 2023 were estimated at 55.01 Mt $CO_2$ eq, marking the first time in 33 years that emissions fell below the 1990 baseline, with a reduction of 1.2 % (EPA, 2024). Nevertheless, this trend highlights ongoing uncertainties about the extent and durability of decoupling between economic activity and $CO_2$ emissions in Ireland, underscoring the need for further investigation.

To tackle climate challenges, Ireland set bold targets. The 2021 Amendment Bill requires a 51 % GHG cut from 2018 levels by 2030 (DECC, 2021). Policies promote renewables, energy efficiency, and low-carbon transport. Projections aim for 70 % renewable electricity by 2030 (EPA, 2021). Yet, staying within carbon budgets is tough; the 2030

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goal needs 8.3 % annual cuts in 2024–2025.

Tapio's (2005) elasticity framework is widely used to classify decoupling and decompose drivers. For Ireland, evidence mostly comes from EU-wide or policy studies (Bianco et al., 2024; Perissi and Jones, 2023). Long-term, Ireland-specific analyses of drivers are rare (O'Mahony, 2013; O'Mahony et al., 2012). Research that integrates macro-level drivers with an analysis of Ireland's decoupling between emissions and economic growth remains underexplored. And previous research based on GDP may lead to incorrect analysis. Few compare GDP to Other national economic indicators or include material-flow metrics. Filling this gap clarifies Ireland's path and change mechanisms. Given growth-emission links and reduction targets, studying decoupling is key. This paper examines Ireland's long-term decoupling and quantifies technology-vs. scale-driver roles using modified GNI.

To evaluate the decoupling status, this study uses the classification framework proposed by Tapio (2005), a widely adopted approach in decoupling analysis. The Tapio method calculates a decoupling index, dividing the relationship between economic growth and emission pressure into eight states, thus providing a practical tool for analyzing the dynamic interplay between economic activity and carbon emissions. Because of the large number of foreign-owned companies in Ireland, GDP and even GNI are not good indicators of Ireland's overall economic activity. In order to suit with this special situation, this study uses modified GNI(GNI*) rather than GDP to reflect the real economic growth in Ireland. GNI*is designed specifically for Ireland's national income indicator that begins with Gross National Income, and then excludes globalization related components by subtracting depreciation on intellectual property and leased aircraft and the net factor income of redomiciled PLCs, yielding a measure that better reflects the domestic economy (CSO, n.d.). This approach is particularly suitable for this study, as it can measure trends in Ireland's carbon emissions during periods of economic growth and determine whether decoupling aligns with emission reduction goals. Furthermore, decoupling analysis can be integrated with the LMDI decomposition method to explore the factors influencing carbon emissions, a combination widely favored by researchers. Through modified LMDI analysis, macro-level drivers of Ireland's carbon emissions—such as energy structure or economic activity—can be pinpointed.

From the perspective of reducing carbon emissions, many studies have made a lot of progress in Ireland's decarbonisation measures and renewable energy technologies (Boyle and Littler, 2024; Gaur et al., 2022; Illahi et al., 2024; Martins and Carton, 2023; Mc Guire et al., 2023; Rourke et al., 2009; Xie et al., 2025; Zhu et al., 2023). According to data released by SEAI in 2023, Ireland's use of renewable energy reached a new high of 23.38 TWh. Despite the rapid development of renewable energy, fossil fuels still dominate Ireland's primary energy supply. Even in 2023, 82.6 % of energy consumption still comes from fossil fuels (SEAI, 2024). Ireland's rapid economic expansion has been accompanied by a rebound in greenhouse gas emissions, suggesting that strong decoupling is far from being achieved and that traditional pathways of technological progress can hardly balance the ranking pressures brought on by the expansion of economic scale.

Within this context, extensive analysis has been dedicated to examining the limitations of the green growth paradigm, as improvements in efficiency alone may hinder the achievement of carbon reduction targets. As an alternative, the degrowth paradigm has been proposed—advocating for a socio-economic structure that prioritizes sustainability over continuous economic expansion. Degrowth is an economic and social theory that advocates for a deliberate reduction in economic activity and resource consumption to achieve environmental sustainability and enhance social well-being (Kallis et al., 2012). Unlike traditional economic growth models, degrowth emphasizes sustainable development by optimizing consumption patterns, improving resource efficiency, and promoting social justice, without prioritizing continuous economic growth. For Ireland, degrowth fits the tension between expansion and emission cuts. It reduces high-carbon activities, cuts fossil reliance, and aids climate goals without harming welfare.

Integrating degrowth offers a new lens on Ireland's economy-environment ties. LMDI analyses focus on drivers like tech advances and efficiency. But they rarely question endless expansion's sustainability. Degrowth counters this by cutting unnecessary production and consumption to ease pressures. It complements LMDI: decomposition reveals causes, while degrowth guides scale adjustments for emission cuts. This integration deepens driver insights and broadens policy options.

Based on these considerations, this study aims to explore Ireland's decoupling dynamics by addressing the following research questions:

1. To what extent did Ireland achieve decoupling between economic development and decarbonisation from 1995 to 2023?
2. What role did key contributing factors play in influencing Ireland's decoupling status during this period?
3. Given the current state of decoupling, is it necessary for Ireland to adopt degrowth strategies, and if so, what specific strategies should be pursued?

This study makes contributions in three dimensions:

Theoretical Level: Reveals nonlinear decoupling traits in small economies; first applies degrowth to Ireland, filling a gap.

Methodological Level: Builds a "state-dynamics" framework using 1995–2023 data; pioneers GNI* and domestic material consumption in decomposition.

Strategy Level: Proposes selective degrowth to balance climate and growth; aids similar economies with empirical support.

This study uses a modified model to quantify each factor's contribution to Ireland's emissions reduction and decoupling, revealing why degrowth strategies should be part of its policy toolkit. It supports the Ireland's transformation to a low-carbon energy system and provides a clear small-country case that adds new evidence to global climate governance under the principle of common but differentiated responsibilities.

## 2. Literature review

### 2.1. EU and cross-country evidence

Since Tapio (2005) introduced the decoupling framework based on elasticity coefficients, this method has been widely applied in studies analyzing the degree of decoupling. To better understand the drivers of carbon emissions, many studies combine LMDI decomposition with Tapio analysis, as shown in (Bianco et al., 2024; González et al., 2014; Moutinho et al., 2015; O'Mahony, 2013; O'Mahony et al., 2012, 2013; Serrano-Puente, 2021). While LMDI relies on production-side accounting, using it alone may overstate the technical effect. By integrating Tapio analysis with consumption-based accounting, researchers can distinguish between 'apparent' and 'real' decoupling (Peters et al., 2011). Bianco et al. (2024) included seven indicators such as climate variables in their decomposition, though these are often intermediaries already reflected in energy-related drivers. Serrano-Puente (2021) applied input-output with LMDI to explore energy intensity and efficiency across EU countries, focusing on rebound effects in end-use sectors by tracing energy use and emissions. Study also identified population growth as the main driver of emissions in four EU regions, with cleaner energy mixes improving the energy effect (Moutinho et al., 2015). González et al. (2014) used a five-factor decomposition in the EU electricity sector, finding that energy intensity, fuel mix, and carbonization explained emissions reductions in some countries, including Ireland, though population growth still pushed up emissions. However, their study lacked decoupling elasticity coefficients, limiting the analysis of the link between economic growth and emissions. Notably, despite the key role of material use in shaping emissions, this factor is often left out in LMDI-based $CO_2$ analyses (Akdoğan et al., 2023).

### 2.2. Ireland-specific studies

Ireland has long been an important model for global development, with its rapid economic growth accompanied by rising energy demand and increasing carbon emissions (O'Mahony et al., 2012). Analyzing decoupling trends is essential for closely monitoring changes in the development process and achieving Ireland's ambitious emission reduction targets. Most studies on Ireland's decoupling process have been conducted at the EU level. A research analyzed carbon emissions across 27 EU countries using Tapio's decoupling coefficient and decomposition methods, finding that Ireland, along with six other countries, was in a weak decoupling state (Bianco et al., 2024). Additionally, there also exists study which explored decarbonisation strategies from the perspective of policy tools, such as carbon taxation (Perissi and Jones, 2023). However, there remains a lack of long-term, macro-level research specifically focused on Ireland's decoupling process over time.

Decomposition studies on Ireland have yet to deeply integrate the Tapio decoupling model for verification. Some studies have conducted sectoral decomposition for the period 1990–2007 (O'Mahony et al., 2012), examining carbon emission factors in economic and transportation sectors. These studies identified the transport sector as having the highest carbon intensity and highlighted the slow adoption of renewable energy in meeting demand, focusing on the high-carbon lock-in pathway of the transport sector. The same author later applied the Kaya identity to analyze Ireland's carbon emission decomposition from 1990 to 2010 (O'Mahony, 2013), but it based on GDP which in Ireland can be affected by multinational-related distortions, GDP-based measures may overstate scale effects in some periods. Using GNI* as the income metric provides a more domestically grounded lens and can yield more conservative decoupling classifications and different driver weights relative to GDP-based analyses. This study suggested that economic growth could not align with mitigation efforts, as emission reductions from energy substitution offset the emission increases driven by population growth. However, it only considered traditional factors such as energy structure, emission intensity, and scale effects. Moreover, it did not identify decoupling states, making it difficult to detect pseudo-decoupling effects driven by technological progress.

Studies on emissions reduction in Ireland have predominantly focused on technology-based mitigation frameworks, centering on energy consumption sectors and decarbonisation technologies (Boyle and Littler, 2024; Gaur et al., 2022; Illahi et al., 2024; Martins and Carton, 2023; Mc Guire et al., 2023; Rourke et al., 2009; Xie et al., 2025; Zhu et al., 2023). At the technological level, research can be categorized into two types. The first type concentrates on the expectation and promotion of renewable energy (Martins and Carton, 2023; McGeever et al., 2019; Rourke et al., 2009; Xie et al., 2025; Zhu et al., 2023), with hydrogen, bioenergy, carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), and negative emission technologies (NETs) as the main areas of development. However, current limitations in hydrogen production, storage, and transportation in Ireland prevent these technologies from fully meeting the substantial energy demand (Martins and Carton, 2023). Some studies indicate that cultivating crops for BECCS requires a considerable land area and may induce negative externalities in the use of agricultural land in Ireland (Aryanpur et al., 2024). Moreover, the marginal abatement cost (MAC) and long-term mitigation costs of these technologies are high, and an overreliance on them could lead to risks such as temperature overshoot and energy lock-in (Xie et al., 2025). The level of technological readiness remains to be further advanced. The second type of research discusses improvements in energy efficiency (Boyle and Littler, 2024; Mc Guire et al., 2023; Zhu et al., 2023), arguing that enhancing the efficiency of existing technologies and reducing energy consumption can improve energy use efficiency in specific industries.

From a policy perspective, measures include imposing vehicle taxes (Giblin and McNabola, 2009), carbon taxes (Conefrey et al., 2013; De Bruin and Yakut, 2024; Farrell, 2017), and providing subsidies for electric vehicles (Stefaniec et al., 2025) to encourage consumers to change their consumption patterns and reduce the consumption of products driven by unsustainable energy sources, thereby lowering residential energy demand. Gaur et al. (2022) applied the Irish Low Energy Demand (ILED) concept to the TIMES-Ireland energy system optimization model (TIM) and argued that decoupling energy demand from economic growth could be achieved by shifting travel patterns, enhancing end-use efficiency, emphasizing low energy-intensive economic activities, and altering social infrastructure. They stressed decomposing mitigation into demand, efficiency, and structure for savings quantification.

Technological mitigation benefits from the promotion of renewable energy technologies. Although significant progress has been made in related research, fossil fuels still dominate energy consumption (Bianco et al., 2024). While technological progress and efficiency improvements are frequently emphasized as key drivers of decoupling in Ireland's mitigation strategy (Boyle and Littler, 2024; Xie et al., 2025), the diffusion of renewable energy technologies is relatively slow in the short term (Chen and Lin, 2020), and the frequent occurrence of extreme weather events may pose potential threats to the green invention and iterative improvement of energy technologies (Chen et al., 2021; Okolo and Wen, 2022; Wen et al., 2023; Zhao et al., 2022). Relying solely on technological upgrading may be insufficient to achieve the deep decarbonisation required to meet Ireland's climate targets. Analysis using the TIMES-Ireland model by Daly et al. (2024) indicates that delaying mitigation efforts increases the risk of carbon lock-in in Ireland and heightens dependence on potentially expensive and unproven $CO_2$ removal technologies. Research shows that scenarios featuring low energy demand achieved through demand-side management strategies are crucial for reducing emissions and minimizing reliance on such technologies. Given that Ireland's current dependence on fossil fuels remains significant-for example, in 2023, over 80 % of energy consumption in Ireland was derived from fossil fuels (SEAI, 2024)-this situation underscores the necessity of exploring complementary degrowth strategies to effectively address the complex interplay between economic growth and carbon emissions.

### 2.3. Theoretical debates on degrowth

The debate surrounding the Jevons paradox highlights a fundamental tension between decoupling and degrowth perspectives. Although decoupling-especially in its "absolute" form-aims to reduce the environmental impact per unit of economic output, it often assumes that economic growth will continue or even accelerate (Jackson, 2009). However, as described by the Jevons paradox, the possibility of rebound effects indicates that improvements in efficiency may be offset by increased consumption, thereby undermining the anticipated environmental benefits (Polimeni, 2008; Sorrell, 2007). This is where degrowth offers a fundamentally different approach, challenging the inherent assumptions of a growth-oriented model that continually exceeds planetary boundaries (Hickel and Kallis, 2020). Degrowth explicitly calls for halting the growth of energy-related material flows while eliminating current resource waste (Kronenberg et al., 2024), rather than relying on the green growth theory derived from the Environmental Kuznets Curve (EKC), which often unrealistically presumes that technological progress and efficiency improvements can decouple economic growth from carbon emissions (Gill et al., 2018). Global material flow analyses provide empirical evidence that absolute decoupling of GDP growth from resource consumption is both rare and unsustainable (Ward et al., 2016), even leading some to contend that so-called "green" business initiatives are not genuinely green (Lux et al., 2023). An optimistic study argues that reducing the global energy system could greatly enhance the practicality of a low-carbon transition on the supply side. Their model suggests it's possible to meet the 1.5 °C climate target and multiple Sustainable Development Goals without depending on still-unreliable negative-emissions technologies (Grubler et al., 2018).

Suppressing growth may better hit IPCC targets. Warlenius (2023) claims 1.5 °C needs over 90 % Global North contraction, urging degrowth. Yang et al. (2021) show energy savings double productivity in decoupling, backing degrowth. Decoupling alone fails ambitious cuts; per capita material cuts needed in contraction (Haberl et al., 2020; Schandl et al., 2018; Wiedmann et al., 2015). From this viewpoint, decoupling is no longer about achieving more growth with less environmental impact, but rather about managing a smaller economy with minimal environmental consequences. The theoretical connection lies in recognizing that even if decoupling can be achieved through technological means in the short term, it may be inadequate to address the long-term ecological challenges posed by an ever-expanding economic system. Empirical evidence also shows that absolute decoupling—where resource consumption decreases as economic output increases—is rare and often unsustainable (Jackson, 2009; Ward et al., 2016).

Degrowth policies have already shown preliminary success in some countries, demonstrating their potential in reducing carbon emissions and resource consumption. In France, policies that shorten the workweek have not only enhanced social welfare but also decelerated energy-intensive production activities. Reduced working hours can lower energy consumption in industrial production, indirectly leading to a decrease in carbon emissions (Gough, 2017). The Netherlands has achieved remarkable results by circular economy initiatives in the construction and manufacturing industries, such as resource reuse and waste reduction which made material consumption decreased and carbon emissions improved (Circle Economy, 2020). These concrete data suggest that degrowth policies possess not only theoretical potential for emission reduction but have also yielded quantifiable results in practice, offering valuable insights for other countries. However, degrowth application and research are nascent globally. It lacks empirical base: only 4.8 % of publications use data, most without policy advice (Engler et al., 2024). Theory is growing, but practice or impact assessment lags, hindering adoption.

Consequently, empirical-based degrowth strategies are needed to test effectiveness across contexts. This study fills the gap by analyzing Ireland's 1995–2023 decoupling and drivers, supporting degrowth empirically.

This study contributes five ways: First, details Ireland's 1995–2023 decoupling and drivers with updated data. Second, modifies model via GNI* and Tapio-LMDI integration, avoiding tech overestimation and assessing real growth-emission elasticity. Third, first adds domestic material consumption to LMDI, expanding factors and addressing material neglect. Fourth, discusses degrowth to counter tech overemphasis in Ireland's pathways. Fifth, anchors degrowth in empirical decomposition, providing concrete recommendations.

## 3. Research method

### 3.1. Tapio decoupling status judgment

According to Tapio (2005), when analyzing the decoupling relationship between economic growth and carbon dioxide emissions, the dynamic association between the two can be quantified by constructing an elasticity coefficient indicator, as calculated in formula(1). Based on the classification intervals of the elasticity values (Table 1), differentiated states—such as expansive negative decoupling, weak decoupling, and strong decoupling—can be systematically identified (Table 2), thereby revealing the nonlinear characteristics of the relationship between economic scale expansion and changes in environmental pressure.

$$\varepsilon = \frac{\%\Delta CO_{2,t\text{-}1}}{\%\Delta GDP_{t\text{-}1}} = \frac{\frac{CO_{2,t}\text{-}CO_{2,t\text{-}1}}{CO_{2,t\text{-}1}}}{\frac{GDP_t\text{-}GDP_{t\text{-}1}}{GDP_{t\text{-}1}}} \tag{1}$$

The decoupling elasticity index can be calculated according to the above formula, and then the decoupling status of $CO_2$ and GDP changes is divided according to Tables 1 and 2 below:

**Table 1**
Tapio decoupling states (Aryanpur et al., 2024; Li and Jiang, 2020).

| Decoupling State | Specific Conditions | $\Delta CO_2$ | $\Delta GDP$ | E |
|---|---|---|---|---|
| Decoupling | Weak decoupling | >0 | >0 | 0< Ɛ< 0.8 |
| | Strong decoupling | <0 | >0 | Ɛ <0 |
| | Recessive decoupling | <0 | <0 | Ɛ >1.2 |
| Negative decoupling | Expansive negative decoupling | >0 | >0 | Ɛ >1.2 |
| | Weak negative decoupling | <0 | <0 | 0< Ɛ< 0.8 |
| | Strong negative decoupling | >0 | <0 | Ɛ <0 |
| Coupling | Expansive coupling | >0 | >0 | 0.8< Ɛ< 1.2 |
| | Recessive coupling | <0 | <0 | 0.8< Ɛ< 1.2 |

**Table 2**
Description of specific decoupling conditions (Pan et al., 2022).

| Specific conditions | Description |
|---|---|
| Weak decoupling (WD) | Carbon emissions and GDP are growing but the pace of growth of $CO_2$ is lower than that of GDP. |
| Strong decoupling (SD) | GDP is growing and carbon emissions are decreasing. A full decoupling is achieved |
| Recessive decoupling (RD) | Carbon emissions and GDP are decreasing but the pace of decrease of $CO_2$ is higher than that of GDP. |
| Expansive negative decoupling (END) | Carbon emissions increase with a higher pace with respect to GDP. |
| Weak negative decoupling (WND) | Carbon emissions and GDP are decreasing but the pace of decrease of GDP is higher than that of $CO_2$. |
| Strong negative decoupling (SND) | Carbon emissions increase while GDP decrease |
| Expansive coupling (EC) | Carbon emissions and GDP are growing with a similar pace. |
| Recessive coupling (RC) | Carbon emissions and GDP are declining with a similar pace. |

The specific conditions for reaching different decoupling states are described as follows:

Since this study focuses on Ireland, and as the CSO notes, Ireland's GDP has long been disturbed by profits earned here flowing to overseas parent companies and by high-depreciation assets whose costs are borne abroad. To strip out these factors that don't reflect real domestic economic activity, this study uses the modified gross national income (GNI*), which deducts the depreciation on two asset types—intellectual property and leased aircraft—from traditional GNI instead of relying on GDP data. GNI* comprises employee compensation, Ireland's companies' operating surplus and mixed income, and government revenue, all of which are available for local consumption and investment. Compared with GDP, GNI* provides a clearer picture of Ireland's true level of domestic output and residents' disposable income. The modified formula is formula(2):

$$\varepsilon = \frac{\%\Delta CO_{2,t\text{-}1}}{\%\Delta GNI^*_{t\text{-}1}} = \frac{\frac{CO_{2,t}\text{-}CO_{2,t\text{-}1}}{CO_{2,t\text{-}1}}}{\frac{GNI^*_t\text{-}GNI^*_{t\text{-}1}}{GNI^*_{t\text{-}1}}} \tag{2}$$

### 3.2. LMDI decomposition analysis

This study uses the Logarithmic Mean Divisia Index (LMDI) to construct a decomposition framework for the driving factors of carbon emissions. The LMDI method is widely recognized as a robust tool in energy and environmental policy analysis (Ang, 2005, 2015). Building on the traditional LMDI model, this study expands the decomposition dimensions by introducing a six-factor analysis framework, which systematically quantifies the technological and scale-driven mechanisms behind changes in Ireland's carbon emissions from 1995 to 2023. By distinguishing the interactive effects between technology and scale, this research aims to provide a theoretical basis for achieving deep decoupling in Ireland, particularly by assessing the necessity of limiting economic scale expansion from a degrowth perspective (Hickel and Kallis, 2020).

Specifically, this study selects and calculates the contribution of six influencing factors to $CO_2$ emissions, including Carbon Intensity (CI), Energy Structure (ES), Energy-Material Intensity (EMI), Material Intensity (MI), $GNI^*_{PC}$, and total population (Pop). By comparing the contribution degree and time series change trends between the factors horizontally and vertically, this study interprets the boundaries of low-carbon growth and the necessity of degrowth.

The six indicators and their units are described as follows:

— Carbon Intensity (CI)

The $CO_2$ to fossil energy ratio ($MtCO_2$/Mtoe) shows emissions per unit of fossil energy. CI reflects fuel carbon content and combustion efficiency. A rising CI suggests inefficient combustion or weak decarbonisation and continued fossil reliance. A falling CI indicates lower $CO_2$ per energy unit, marking progress in decarbonisation and cleaner energy adoption.

— Energy Structure (ES)

Measured as the proportion of fossil energy (Fos) within total energy consumption (Ene). ES ranges between 0 and 1; a higher value indicates greater dependence on fossil fuels and a higher carbon dioxide emission intensity with all other factors held constant. A lower ES value signifies a greater contribution from non-fossil energy sources, which supports decarbonisation goals.

— Energy-Material Intensity (EMI)

Measured as total energy consumption (Ene) per unit of material used (Dmc), (Mtoe/Mt), the EMI indicates resource efficiency. A lower EMI shows that less energy is needed per unit of material, reflecting advances like energy-saving processes or a shift toward low-energy service industries. By capturing both physical efficiency and the scale of material use, the EMI can guide policies on resource allocation, energy-saving technologies, industry taxation, and recycling.

— Material Intensity (MI)

It defined as domestic material consumption (Dmc) per unit of GNI* (Mt per million €), shows how material-intensive the economy is. A high MI means more materials are needed for growth, signaling low material-use efficiency and reliance on resource-heavy industries. A low MI indicates better decoupling of growth from material use and a leaner, sustainable structure.

— Per Capita GNI* ($GNI^*_{PC}$)

It shows average income per person and indicates development and living standards. Higher values reflect larger economic scale, often boosting energy use and $CO_2$ emissions. In decomposition, $GNI^*_{PC}$ measures this scale effect; if growth consistently raises emissions, degrowth policies warrant consideration.

— Total Population (Pop)

Population size (millions) drives energy use and $CO_2$ emissions: more people mean more consumption and production, raising emissions. Even with efficiency develops, population growth may still push total $CO_2$ increase.

The following formula represents the general form of the model:

$$CO_2 = CI \cdot ES \cdot EMI \cdot MI \cdot GNI^*_{PC} \cdot Pop \tag{3}$$

Formula(3) can be expressed more clearly based on definitions of each driver as follows:

$$CO_2 = \frac{CO_2}{Fos} \cdot \frac{Fos}{Ene} \cdot \frac{Ene}{Dmc} \cdot \frac{Dmc}{GNI^*} \cdot \frac{GNI^*}{Pop} \cdot Pop \tag{4}$$

Since formula(4) simplifies to an identity, our decomposition is valid. Using the additive LMDI method, the change in $CO_2$ emissions over the period can be broken down into the cumulative contributions of six drivers—CI, ES, EMI, MI, $GNI^*_{PC}$, and Pop—as follows:

$$\Delta CO_2 = \Delta CI + \Delta ES + \Delta EMI + \Delta MI + \Delta GNI^*_{PC} + \Delta Pop \tag{5}$$

The specific calculation method of the changes of each driver in formula(5) can be determined according to the following general expression (6):

$$\Delta A = L \cdot ln \frac{A_t}{A_{t-1}} \tag{6}$$

A is the general expression for the factors (CI, ES, EMI, MI, $GNI^*_{PC}$, Pop). L is a weighting factor, which is determined as formula(7):

$$L = \frac{CO_{2,t}\text{-}CO_{2,t-1}}{ln \frac{CO_{2,t}}{CO_{2,t-1}}} \tag{7}$$

t and t-1 represent the year after and the year before the study period. According to the above formula, the year-by-year data can be calculated directly through Excel. The process is simple and the results are direct. The advantage of LMDI decomposition without any difference is helpful for data result analysis.

Further, to quantify the influence of each driver on decoupling carbon, formula(5) can be substituted into formula(2), that is, the contribution of each driver A (i.e., CI, ES, EMI, MI, $GNI^*_{PC}$, Pop) to decoupling can be measured through the following general formula(8):

$$\varepsilon_A = \frac{\frac{\Delta A}{CO_{2,t-1}}}{\frac{\Delta GNI^*}{GNI^*_{t-1}}} \tag{8}$$

This results in the elasticity of $CO_2$ for each of these six drivers, revealing the decoupling status of the various factors which determine emission levels.

By summing the elasticities of the six factors obtained from formula (8), the total decoupling elasticity of carbon emissions relative to GNI* can be obtained as formula(9):

$$\varepsilon = \varepsilon_{CI} + \varepsilon_{ES} + \varepsilon_{EMI} + \varepsilon_{MI} + \varepsilon_{GNI^*_{pc}} + \varepsilon_{Pop} \tag{9}$$

## 4. Data analysis

The research sample of this study is Ireland during the period 1995–2023. The required original data sources are as follows: carbon emission data comes from EPA, domestic material consumption comes from Eurostat, energy-related consumption comes from SEAI, population and GDP are from World Bank, GNI*comes from CSO. All the above are from open sources, and links of them are shown in Table. A1.

Fig. 1(a) shows Ireland's $CO_2$ emissions from 1995 to 2023, which rose from 35.85 Mt in 1995 to a 47.66 Mt peak in 2007 before generally declining. Growth during the "Celtic Tiger" era reflected industrial expansion and heavy fossil use. The 2008–2012 financial crisis cut activity, energy demand, and emissions. Post-2015, emissions continued downward but high-energy sectors—transport and data centers—remain barriers to deeper cuts. From a degrowth standpoint, these industries hinder strong decoupling: technology helps but social change and industry restructuring are also needed. Targeted restrictions in energy-intensive sectors may be essential based on degrowth view.

Fig. 1(b) compares Ireland's constant-price GNI* and GDP from 1995

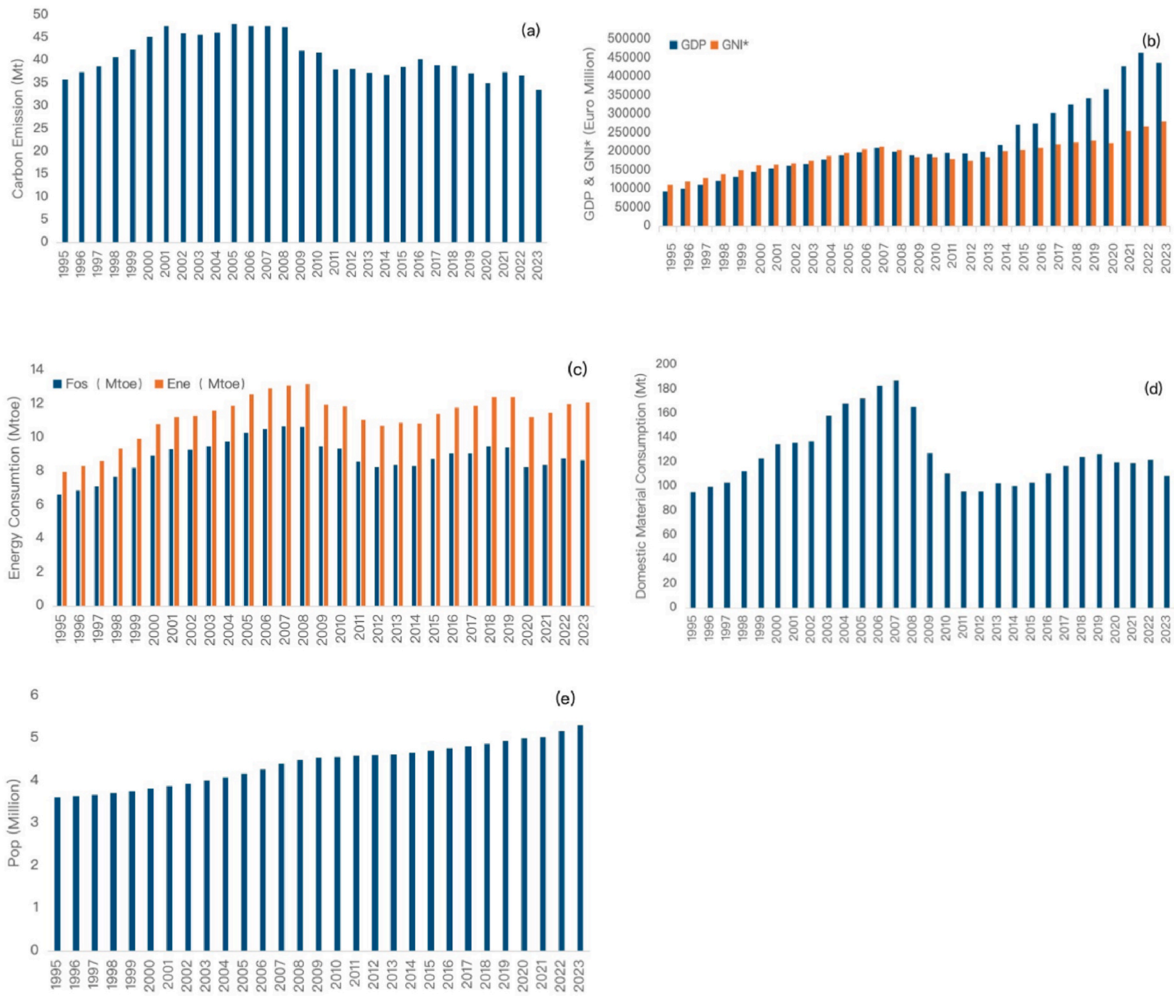


**Fig. 1.** The changing trend of (a) Carbon Emission; (b) GDP & GNI*; (c) Energy Consumption; (d) Domestic Material Consumption; (e) Pop during the study period. Emissions rise to a peak in 2007 and then decline; GNI* presents a smoother path than GDP; fossil reliance remains elevated; Dmc falls after the crisis and rises again from the mid-2010s; population increases steadily.

to 2023. GNI* rises smoothly from €111 035 million to €280 231 million, dipping only during 2008–2012 before recovering. GDP grows from €93 274 million to €438 417 million but shows sharp, misleading spikes from profit-transforming. By excluding intangible-asset depreciation and leased aircraft, GNI* better reflects Ireland' real income and spending power. For this reason, this study uses GNI* to assess economic growth and carbon decoupling, with GDP shown here only for comparison.

Fig. 1(c) traces Ireland's fossil and total energy consumption from 1995 to 2023. Both climbed steeply during the "Celtic Tiger" era, with fossil use rising from 6.60 Mtoe to 10.65 Mtoe and overall energy from 7.86 Mtoe to 13.19 Mtoe. The 2008–12 financial crisis then drove both down—to 8.26 Mtoe and 10.72 Mtoe—before a post-2015 rebound: by 2023, fossil use stood at 8.68 Mtoe and total energy at 12.01 Mtoe. This parallel movement underscores Ireland's enduring reliance on fossil fuels—even as renewables grow—and signals the challenge of displacing high-carbon sources in its low-carbon transition.

Fig. 1(d) shows Ireland's domestic material consumption (Dmc) from 1994 to 2023. Dmc rose from 95 Mt in 1995 to a 2007 peak of 187 Mt, then fell to 96 Mt during the 2008–2012 crisis. After 2015, it recovered to 109 Mt by 2023, despite a dip in 2019–2020 under COVID-19. This rebound underscores ongoing reliance on resource flows. While MI has improved, total consumption growth outpaces efficiency gains, highlighting the limits of current technologies. From a degrowth viewpoint, curbing resource-heavy industries and advancing a circular economy are essential to offset scale effects.

Fig. 1(e) shows the population trend over the same period, which has continued to grow.

## 5. Results discussion

The GNI*-based Tapio states and six-factor LMDI offer several contrasts with prior evidence. Relative to EU-wide assessments that often classify Ireland in weak decoupling (Bianco et al., 2024), our GNI*-based results identify WD and END episodes in 2014–2016 and more frequent SD in 2016–2019, suggesting that GDP-based classifications can understate scale pressures linked to multinational-driven expansions. Compared with O'Mahony (2013), which uses GDP per capita and a restricted factor set, the present six-factor framework attributes larger shares to material and carbon intensity pathways, aligning with findings that cleaner energy mixes and intensity improvements drive reductions but are partially offset by population and income scale (González et al., 2014; Moutinho et al., 2015). These differences are consistent with Ireland's open economy features and the GNI* lens, which better reflects domestic activity.

### 5.1. Tapio decoupling analysis

The Tapio elasticity framework combined with standard classification thresholds was employed to assess Ireland's decoupling status. The results shown as Table 3 below which summarizes the annual

**Table 3**
Ireland's total decoupling index and its decomposition based on GNI* and the total decoupling coefficient and status based on GDP, 1995–2023. Annual Tapio elasticity and decoupling state for Ireland under GNI* (main specification), with the GDP-based classification reported for comparison. State labels follow the standard taxonomy (strong, weak, coupling, negative).

| Year | ƐCI | ƐES | ƐMI | ƐEMI | ƐGNI*$_{PC}$ | ƐPop | Ɛ_GNI* | Decoupling State* | Ɛ_GDP | Decoupling State |
|---|---|---|---|---|---|---|---|---|---|---|
| 1995–1996 | 0.07 | −0.06 | −0.32 | −0.08 | 0.87 | 0.11 | 0.59 | WD | 0.61 | WD |
| 1996–1997 | 0.01 | −0.03 | −0.61 | 0.06 | 0.88 | 0.09 | 0.40 | WD | 0.32 | WD |
| 1997–1998 | −0.47 | 0.04 | 0.25 | −0.13 | 0.84 | 0.15 | 0.67 | WD | 0.56 | WD |
| 1998–1999 | −0.27 | 0.02 | 0.18 | −0.36 | 0.84 | 0.14 | 0.55 | WD | 0.40 | WD |
| 1999–2000 | −0.26 | 0.03 | 0.11 | −0.12 | 0.80 | 0.19 | 0.75 | WD | 0.70 | WD |
| 2000–2001 | 0.74 | 0.01 | −0.45 | 2.43 | −0.14 | 1.16 | 3.76 | END | 0.98 | EC |
| 2001–2002 | −1.42 | −0.28 | −0.58 | −0.20 | 0.26 | 0.71 | −1.50 | SD | −0.54 | SD |
| 2002–2003 | −0.76 | −0.12 | 2.47 | −2.77 | 0.55 | 0.43 | −0.21 | SD | −0.29 | SD |
| 2003–2004 | −0.24 | 0.04 | −0.09 | −0.52 | 0.71 | 0.26 | 0.16 | WD | 0.16 | WD |
| 2004–2005 | −0.25 | −0.05 | −0.44 | 0.60 | 0.55 | 0.45 | 0.86 | EC | 0.75 | WD |
| 2005–2006 | −0.65 | −0.16 | 0.25 | −0.66 | 0.42 | 0.55 | −0.25 | SD | −0.23 | SD |
| 2006–2007 | −0.42 | 0.04 | −0.28 | −0.29 | 0.11 | 0.88 | 0.04 | WD | 0.02 | WD |
| 2007–2008 | 0.05 | 0.19 | 1.82 | −2.94 | 1.49 | −0.47 | 0.14 | WND | 0.13 | WED |
| 2008–2009 | 0.03 | 0.16 | 1.56 | −1.61 | 1.10 | −0.11 | 1.13 | RC | 2.15 | RD |
| 2009–2010 | 1.77 | −2.52 | −62.50 | 58.16 | −0.92 | 1.92 | −4.10 | SD | −0.56 | SD |
| 2010–2011 | 0.33 | 0.53 | 4.25 | −2.70 | 1.12 | −0.16 | 3.37 | RD | −5.42 | SD |
| 2011–2012 | −1.86 | 0.38 | −1.08 | 1.37 | 1.19 | −0.17 | −0.18 | SND | −1.12 | SND |
| 2012–2013 | −0.73 | −0.01 | 0.24 | −0.90 | 0.88 | 0.08 | −0.44 | SD | −1.13 | SD |
| 2013–2014 | −0.02 | −0.08 | −1.24 | 0.25 | 0.86 | 0.10 | −0.13 | SD | −0.12 | SD |
| 2014–2015 | −0.07 | 0.12 | 0.70 | 0.94 | 0.55 | 0.47 | 2.72 | END | 0.21 | WD |
| 2015–2016 | 0.17 | 0.18 | 1.69 | −1.34 | 0.49 | 0.52 | 1.71 | END | 3.49 | END |
| 2016–2017 | −0.74 | −0.18 | 0.35 | −1.14 | 0.73 | 0.24 | −0.76 | SD | −0.33 | SD |
| 2017–2018 | −2.01 | 0.09 | 1.47 | −0.66 | 0.49 | 0.49 | −0.12 | SD | −0.04 | SD |
| 2018–2019 | −1.65 | −0.36 | −0.06 | −0.93 | 0.42 | 0.55 | −2.04 | SD | −0.88 | SD |
| 2019–2020 | −2.68 | 1.24 | 1.06 | 1.48 | 1.41 | −0.42 | 2.08 | RD | −0.81 | SD |
| 2020–2021 | 0.37 | −0.05 | −0.98 | 0.18 | 0.91 | 0.06 | 0.49 | WD | 0.42 | WD |
| 2021–2022 | −1.47 | 0.08 | −0.52 | 0.48 | 0.38 | 0.59 | −0.46 | SD | −0.25 | SD |
| 2022–2023 | −1.48 | −0.38 | −3.12 | 2.34 | 0.46 | 0.48 | −1.71 | SD | 1.53 | RD |

decoupling status for each factor, as well as the total decoupling status based on GDP and GNI*.

Between 1995 and 2023, Ireland's economic growth and carbon emissions evolved dynamically, shaped by its economic context, global influences, technological advances, and degrowth principles. Decoupling progressed gradually, tied to the "Celtic Tiger" boom, financial crises, and sustainability policies, moving from weak to strong decoupling and occasionally re-coupling. Factors such as declining carbon intensity, energy-mix optimization, and scale effects influenced this trajectory at various stages.

From 1995 to 2000, the "Celtic Tiger" boom, driven by industrialization and foreign investment in IT and pharmaceuticals, resulted in weak decoupling, with emissions growing slower than GNI*. Scale effects from foreign investment and carbon-intensive fuels limited carbon intensity gains (Hou et al., 2021). The 2000–2003 global slowdown brought volatility: expansive negative decoupling in 2000–2001 due to population growth and rising EMI, transforming to strong decoupling by 2001–2003, with improved energy efficiency and reduced carbon intensity (Ward et al., 2016). This weak decoupling transitioned from earlier coupling as foreign direct investment (FDI) surged, but heavy reliance on imported fossil fuels and rapid manufacturing expansion capped efficiency improvements, reflecting Ireland's export-led growth model without strong environmental safeguards.

The 2008–2011 global financial crisis led to passive decoupling. Recessionary coupling in 2009 shifted to strong decoupling in 2010 as economic contraction lowered emissions which reflected economic weakness, not a deliberate low-carbon shift (Paulson, 2017). The transition toward strong decoupling was also influenced by the Irish government's 2010 debt crisis, triggered by massive capital injections into the banking sector, which dramatically worsened the government's fiscal position and led to a weak macroeconomic recovery. Following the bailout framework agreed with the EU and the IMF, the Irish government implemented austerity policies, leading to a sharp decline in industrial output and transport demand, which reduced contribution from scale effect and facilitated the shift toward strong decoupling. Although this was only temporary, as emissions rebounded with the economic recovery, it highlighted Ireland's vulnerability to global financial shocks in the absence of strong decarbonisation policies.

From 2012 to 2023, economic recovery and the Climate Action Plan supported strong decoupling, with carbon intensity declines driving progress. However, economic scale and energy-mix inertia limited sustained gains (Hickel and Kallis, 2020). The Climate Action Plan's promotion of renewables and efficiency improvements produced multiple instances of strong decoupling-such as 2016–2017, 2018–2019 and 2022–2023- with sustained declines in carbon intensity as the principal driver and energy-mix optimization playing a supportive role. But pressure from economic scale persisted: expansive negative decoupling in 2014–2016 demonstrated that GNI*$_{PC}$ growth often outpaced technological advances, and inertia in energy-mix shifts continued to hinder strong decoupling (Hickel and Kallis, 2020). This negative decoupling arose from FDI-fueled data center booms (e.g., tech giants like Google and Amazon) and post-crisis transport rebounds, which spiked electricity and fuel demands, temporarily reversing decoupling gains despite emerging climate policies. Pandemic-year strong decoupling once more owed more to economic slowdown than to enduring policy effects.

In summary, Ireland saw intermittent decoupling from 1995 to 2023 but never sustained absolute decoupling. Carbon intensity reductions underpinned successes, yet economic and Pop growth increased emissions (Fu et al., 2024). Crisis-driven decoupling reflected contraction, not structural shifts, with scale effects offsetting technological gains (Ward et al., 2016). Degrowth theory argues that technology alone cannot counter growth, suggesting degrowth measures, such as curbing high-carbon activities, may be essential for sustainability (Hickel and Kallis, 2020; Jackson, 2009; Kallis, 2011).

In keeping with the established Ireland-focused literature that employs GDP as the income measure (O'Mahony, 2013; O'Mahony et al., 2012), the last two columns of Table 3 also report Tapio elasticities and state labels computed using GDP, enabling direct comparability. As shown in Fig. 2 GDP- and GNI*-based classifications diverge in several years; given the sensitivity of Irish GDP to multinational-related flows, these differences carry through to contributions of scale- and technology-side by altering the timing and state of decoupling, as well as

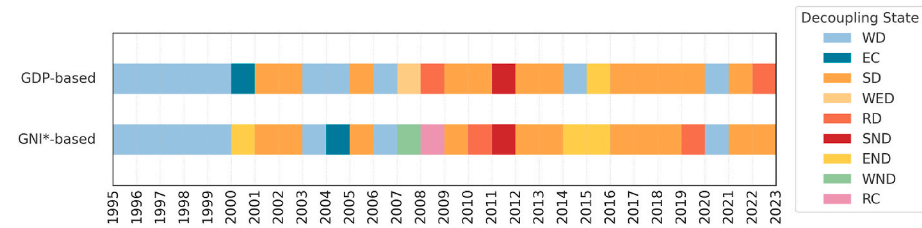


**Fig. 2.** Annual Tapio decoupling states under GDP and GNI*. Differences between the two classifications concentrate in expansion years, whereas crisis years tend to register strong decoupling. The comparison illustrates how the income metric affects state identification and the interpretation of decoupling dynamics over time.

the specific decomposition of individual factors.

This discrepancy is largely due to the features of Ireland's economy. GDP tends to overstate the role of economic growth in driving emissions, as it captures elements that do not accurately represent domestic economic activity, such as profits of multinational companies, depreciation of intellectual property and leased aircraft, and the earnings of redomiciled firms. These components inflate the scale effect and may lead to misleading conclusions about Ireland's decoupling progress. By contrast, GNI* strips out these distortions and offers a more grounded picture of income generated and retained within the country. As such, it provides a more solid foundation for assessing Ireland's true trajectory toward decoupling economic growth from carbon emissions.

### *5.2. LMDI decomposition analysis*

Six drivers (CI, ES, EMI, MI, $GNI^*_{PC}$, and Pop) are selected to capture macro-technical and scale effects, consistent with the Tapio elasticity interpretation used in this study. Second, the set is exactly decomposable under the LMDI identity and has mutually exclusive terms, minimizing double counting and maintaining interpretability. Third, each series is obtained from official sources at an annual frequency from 1995 to 2023 and is consistent with production-based national accounts, ensuring comparability over time and with decoupling frameworks. Fourth, MI is defined as direct material costs per GNI*, explicitly introducing a material throughput dimension that is crucial for degrowth-oriented analysis while remaining compatible with national accounting practices.

The drivers of emissions change are quantified with a six-factor additive LMDI. Table 4 reports annual contributions of CI, ES, EMI, MI, $GNI^*_{PC}$, and Pop, together with aggregates for the technological effect ($\Delta CI + \Delta ES + \Delta MI$), the scale effect ($\Delta EMI + \Delta GNI^*_{PC} + \Delta Pop$), and the resulting net $CO_2$ change.

Between 1995 and 2023, Ireland's total $CO_2$ emissions, measured against GNI*, declined by 2.29 Mt. LMDI decomposition attributes this reduction mainly to improvements in CI and MI. However, these effects were partially offset by scale factors, particularly the growth in $GNI^*_{PC}$ and population. The positive contribution of EMI further suggests persistent inefficiencies in resource use. Without addressing these scale-related pressures, sustained absolute decoupling remains difficult to achieve (Fig. 3).

The decomposition analysis underscores the pivotal role of reduced MI in driving Ireland's emissions cuts between 1995 and 2023 (Fig. 4). The large decline in MI reflects a shift in Ireland's economic structure toward high-value-added sectors such as information technology and pharmaceuticals. This dematerialization process was especially pronounced during the "Celtic Tiger" boom from the mid-1990s to the mid-2000s, aligning with broader sustainability principles by reducing the

**Table 4**

LMDI decomposition of annual $CO_2$ changes by driver and effect type. Annually additive LMDI contributions for CI, ES, EMI, MI, $GNI^*_{PC}$ and Pop, together with totals for the technology effect and the scale effect and the resulting net change in $CO_2$. Units are Mt $CO_2$; positive values denote an increase in emissions and negative values denote a reduction.

| Year | ΔCI | ΔES | ΔMI | ΔEMI | $\Delta GNI^*_{PC}$ | ΔPop | Technological Effect | Scale Effect | $\Delta CO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| 1995–1996 | 0.18 | −0.17 | −0.88 | −0.22 | 2.40 | 0.30 | −0.87 | 2.48 | 1.61 |
| 1996–1997 | 0.03 | −0.09 | −2.02 | 0.18 | 2.93 | 0.31 | −2.08 | 3.42 | 1.34 |
| 1997–1998 | −1.34 | 0.11 | 0.72 | −0.37 | 2.36 | 0.43 | −0.51 | 2.42 | 1.91 |
| 1998–1999 | −0.86 | 0.05 | 0.57 | −1.12 | 2.63 | 0.45 | −0.24 | 1.96 | 1.72 |
| 1999–2000 | −0.97 | 0.10 | 0.43 | −0.45 | 3.01 | 0.70 | −0.44 | 3.26 | 2.82 |
| 2000–2001 | 0.47 | 0.01 | −0.28 | 1.53 | −0.09 | 0.73 | 0.2 | 2.17 | 2.37 |
| 2001–2002 | −1.44 | −0.28 | −0.59 | −0.21 | 0.27 | 0.72 | −2.31 | 0.78 | −1.53 |
| 2002–2003 | −1.45 | −0.23 | 4.70 | −5.27 | 1.05 | 0.81 | 3.02 | −3.41 | −0.39 |
| 2003–2004 | −0.73 | 0.13 | −0.27 | −1.58 | 2.14 | 0.80 | −0.87 | 1.36 | 0.49 |
| 2004–2005 | −0.57 | −0.12 | −1.02 | 1.39 | 1.28 | 1.03 | −1.71 | 3.7 | 1.99 |
| 2005–2006 | −1.47 | −0.36 | 0.57 | −1.50 | 0.95 | 1.25 | −1.26 | 0.7 | −0.56 |
| 2006–2007 | −0.69 | 0.07 | −0.45 | −0.47 | 0.17 | 1.43 | −1.07 | 1.13 | 0.06 |
| 2007–2008 | −0.10 | −0.39 | −3.72 | 6.01 | −3.05 | 0.96 | −4.21 | 3.92 | −0.29 |
| 2008–2009 | −0.12 | −0.75 | −7.16 | 7.41 | −5.06 | 0.50 | −8.03 | 2.85 | −5.18 |
| 2009–2010 | 0.17 | −0.24 | −6.02 | 5.60 | −0.09 | 0.18 | −6.09 | 5.69 | −0.4 |
| 2010–2011 | −0.37 | −0.58 | −4.71 | 2.99 | −1.25 | 0.17 | −5.66 | 1.91 | −3.75 |
| 2011–2012 | 1.78 | −0.36 | 1.03 | −1.31 | −1.14 | 0.17 | 2.45 | −2.28 | 0.17 |
| 2012–2013 | −1.57 | −0.02 | 0.51 | −1.93 | 1.90 | 0.16 | −1.08 | 0.13 | −0.95 |
| 2013–2014 | −0.07 | −0.25 | −4.04 | 0.82 | 2.79 | 0.32 | −4.36 | 3.93 | −0.43 |
| 2014–2015 | −0.05 | 0.08 | 0.48 | 0.65 | 0.37 | 0.32 | 0.51 | 1.34 | 1.85 |
| 2015–2016 | 0.16 | 0.17 | 1.64 | −1.29 | 0.47 | 0.50 | 1.97 | −0.32 | 1.65 |
| 2016–2017 | −1.30 | −0.32 | 0.61 | −2.00 | 1.28 | 0.41 | −1.01 | −0.31 | −1.32 |
| 2017–2018 | −1.96 | 0.09 | 1.43 | −0.64 | 0.48 | 0.48 | −0.44 | 0.32 | −0.12 |
| 2018–2019 | −1.40 | −0.31 | −0.05 | −0.79 | 0.35 | 0.47 | −1.76 | 0.03 | −1.73 |
| 2019–2020 | 2.76 | −1.28 | −1.09 | −1.52 | −1.45 | 0.44 | 0.39 | −2.53 | −2.14 |
| 2020–2021 | 1.82 | −0.22 | −4.79 | 0.88 | 4.44 | 0.29 | −3.19 | 5.61 | 2.42 |
| 2021–2022 | −2.54 | 0.14 | −0.90 | 0.83 | 0.65 | 1.02 | −3.3 | 2.5 | −0.8 |
| 2022–2023 | −2.70 | −0.69 | −5.69 | 4.26 | 0.83 | 0.87 | −9.08 | 5.96 | −3.12 |
| **Total** | −14.31 | −5.72 | −30.99 | 11.87 | 20.64 | 16.22 | −51.02 | 48.73 | −2.29 |

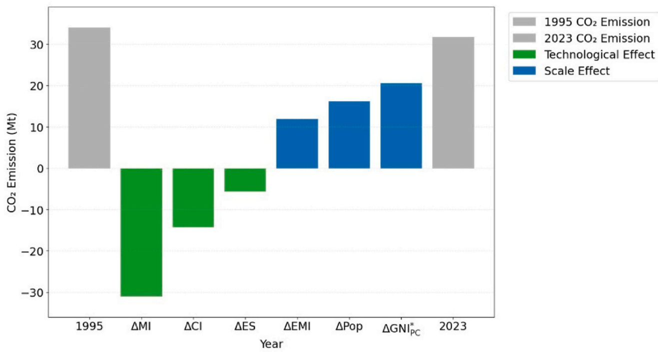


**Fig. 3.** Decomposition of $CO_2$ in Ireland, 1995–2023. This figure shows the values indicate increases in emissions and negative values indicate reductions. Technology-side drivers (CI, ES, MI) account for most annual reductions in later years, while scale-side drivers (EMI, GNI*$_{PC}$ and Pop) account for most increases; contraction years show large negative scale contributions.

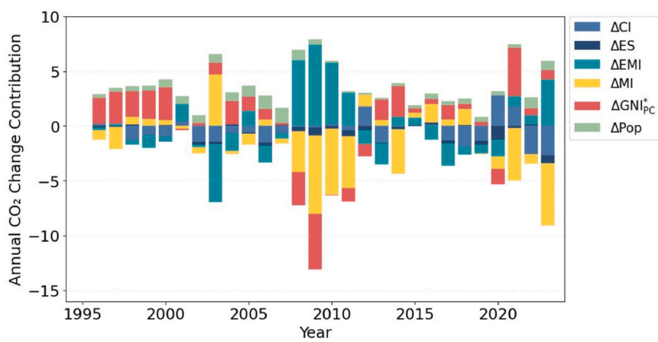


**Fig. 4.** LMDI decomposition of $CO_2$ change of Ireland (1995–2023). Cumulative LMDI contributions over the study period, shown by driver and grouped into technology-side and scale-side effects. Technology-side reductions and scale-side increases are of comparable magnitude, which explains the alternation between decoupling and recoupling observed in the time series.

economy's material throughput. At the same time, the reduction in carbon intensity highlights the effect of energy-efficiency improvements and the expansion of renewable energy sources-most notably wind power-driven by policies such as the Climate Action Plan. However, the contribution from energy structure optimization remains relatively small (Table 4) indicating that fossil fuels still dominate Ireland's energy consumption, limiting deeper decarbonisation in line with the country's current energy profile.

In contrast, the positive contributions from GNI*$_{PC}$ growth and Pop expansion reveal the persistent environmental pressure exerted by economic and demographic scale effects. The positive impact of EMI further demonstrates volatility in resource efficiency, underscoring the limitations of relying solely on technological solutions. These findings suggest that carbon intensity and economic growth are key determinants of the dynamics of decoupling in advanced economies (Berahab, 2017; Gołaś, 2023; IEA, 2024). Ireland's experience illustrates the challenge of sustaining reductions amid economic recovery.

From the perspective of degrowth theory, Ireland's emission trends between 1995 and 2023 offers important insights into both the opportunities and limitations of conventional growth models. The significant drop in MI aligns with degrowth objectives to minimize resource consumption, showing that structural economic change can support relative decoupling. However, the emission-increasing effects of GNI*$_{PC}$ and Pop growth highlight a fundamental tension between ongoing expansion and climate mitigation goals. The passive emissions reductions observed during the 2008 financial crisis came at the cost of severe social impacts and lacked long-term resilience (Fig. 4). Meanwhile, though policy-driven energy transitions have clear targets, they have not been sufficient to reverse the overall emission trend. This supports the degrowth perspective that technological progress alone may be difficult to maintain absolute decoupling currently, it will be useful to take deliberate measures to limit economic scale and resource use. For Ireland, this could mean further promoting dematerialization and decarbonisation through related policies and regulation, while exploring degrowth-inspired policies such as reduced working hours and the sharing economy.

## 6. Policy recommendations

Although Ireland has achieved significant progress in decoupling economic growth with carbon emissions, it would be difficult to meet urgent climate targets in time with only the current slow pace of progress and the uncertain results of cleaner technologies. Continued and sustained dependence on resource-intensive industries emphasizes the need of a more transformative framework. Degrowth provides this alternative path which advocates intentional reductions in energy and material intake to ensure ecological sustainability and social equity (Kallis, 2011). Empirically, LMDI results (Table 4) show scale effects nearly offset technological reductions, supporting degrowth as a strategy to curb emissions, as seen in the 2008–2012 crisis where passive scale reduction cut about 10 Mt $CO_2$. As a high-income country with robust institutions and adaptive capacity, Ireland has a well ability to follow this path. Degrowth does not reject progress, but redefines progress beyond GDP, emphasizing well-being, resilience and environmental limits.

At the governmental level, Ireland can promote a transition to a low-carbon, high-efficiency society through economic incentives and energy management policies. Selective degrowth in Ireland is defined here as targeted downscaling of high-emission, high-throughput activities alongside the expansion of low-impact public services. Consistent with empirical findings that technology-side gains are partly offset by scale-side pressures (Table 4), this policy roadmap focuses on capping energy and material throughput in specific sectors while improving welfare.

In agriculture, reforming the ecological tax system with progressive rates on high-carbon activities—such as increased levies on cattle farming—can drive transformation, paired with subsidies for low-emission alternatives like organic diversification. This includes herd stabilisation through voluntary buyouts, fertiliser benchmarks, and peatland rewetting to deliver biogenic cuts while protecting farm incomes.

In data centers and energy-intensive services, annual energy consumption caps with penalties for exceedances encourage efficiency, complemented by grid connections tied to additional renewables and 24/7 matching, PUE thresholds, waste-heat utilisation, and dynamic tariffs to curb FDI-driven expansion.

In housing and construction, mandatory energy-efficiency certification promotes zero-energy buildings, with phased MEPS, deep-retrofit-first delivery, and embodied-carbon standards reducing operational and material emissions. Green public procurement can catalyse reuse, such as construction waste recycling, further enhancing resource efficiency.

In the transport sector, promoting, kilometer-based charging, abolishing minimum parking requirements, rapid expansion of bus and rail, and supporting low-traffic communities and electric bicycles can reduce private car journeys. This approach lowers fossil fuel consumption by curbing demand for private transport.

A materials policy pillar sets MI targets and reuse/repair obligations across supply chains, dynamically adjusting carbon tax rates in line with carbon intensity and energy market prices to motivate clean transitions. Subsidies for remanufacturing, the sharing economy, and product-life-extension initiatives support these efforts (Kallis, 2011). Such measures effectively reduce resource dependency while optimizing the economic structure (Jackson, 2009). Data results from this research indicate that reductions in MI have been a key driver behind Ireland's declining emissions (Table 4), aligning with degrowth objectives in material consumption and demonstrating how policies like construction waste reuse can mitigate emissions from scale effects.

On the demand side, viable interventions may encompass the initiation of pilot programs for reduced working hours alongside the augmentation of cultural and care services, with the aim of redirecting societal well-being from dependence on material throughput. To bolster Irish social acceptability, strategies including revenue recycling, just-transition mechanisms, and phased rollout are recommended (De Bruin and Yakut, 2024).

Second, to prevent the emissions reductions achieved through technological progress from being offset by economic expansion, the government should establish sectoral and regional energy-consumption limits to secure sustainable decarbonisation outcomes. The government should substantially increase investment in renewable energy—such as wind and solar—and in energy-efficiency technologies, while piloting bioenergy with carbon capture and storage (BECCS) to utilize agricultural residues for power generation and simultaneously sequester carbon. Corporations with high wind or solar energy penetration—such as data centers—could receive corporate tax reductions, it is also possible to force an increase in the proportion of green electricity adoption. Encouraging data centers to share cooling systems and power networks will further reduce overall energy consumption and strictly review the approval of new data center construction. Moreover, significant investment in offshore wind and in distributed solar installations across both rural and urban areas is crucial.

At the societal level, Ireland should reshape work models, consumption habits, and cultural values to reduce dependence on material growth and foster well-being-centered lifestyles. Schor (2010) points out that reducing working hours and increasing leisure time can effectively curb resource-intensive consumption. These policy instruments aim to achieve structural reductions in resource use at the source. Such a shift will not only scale down economic activities—thereby lowering production- and consumption-related energy demand—but also afford individuals greater opportunities for personal development (Kallis, 2011). To foster public acceptance of sustainable living, government and civil-society organizations should intensify environmental education, promote degrowth concepts, and encourage community engagement in local cultural, artistic, and volunteer initiatives as alternatives to material-consumption-driven sources of happiness (Kallis et al., 2012; Ward et al., 2016). This transformation intends to break free from economic growth dependency via simultaneous cultural and institutional change.

At the individual level, citizens should actively participate in degrowth practices by adjusting lifestyles to reduce personal carbon footprints. Individuals ought to minimize unnecessary material consumption and shift toward experience-based activities-such as cultural events, outdoor recreation, and community service-to strengthen social bonds and enhance personal well-being (Schor, 2010). Promoting minimalist and zero-waste lifestyles can reduce demand for high-carbon products and decrease household waste and energy consumption (Jackson, 2009). Additionally, home energy-management initiatives-such as adopting energy-efficient appliances, installing solar panels, and engaging in demand-response programs-should be promoted to optimize domestic energy performance. Public campaigns and subsidies should guide citizens toward low-carbon transportation alternatives, reducing reliance on private vehicles. These micro-level efforts will translate policy objectives into concrete actions, generating bottom-up momentum for emissions reduction.

Through coordinated action by government, society, and individuals, Ireland can fully realize the core principles of degrowth: reducing economic scale, optimizing resource allocation, and enhancing well-being (Kallis, 2011). Governmental taxation and energy policies will directly curb resource use at its source, societal shifts in culture and values will reinforce a post-growth paradigm, and individuals' sustainable lifestyles will solidify micro-level emission reductions. This multi-tiered strategy avoids overreliance on technological fixes, instead achieving systemic sustainability through proactive downscaling of economic activity (Kallis et al., 2012). Crucially, this approach not only addresses the urgency of the climate crisis but also offers Ireland the opportunity to rethink its development model: in a world of finite resources, economic growth can no longer be the sole determinant of well-being, enhancing sustainability and happiness may prove the more sustainable goals.

## 7. Conclusion

This research employs a modified Tapio-LMDI model to explore the evolving relationship between Ireland's economic growth and carbon emissions from 1995 to 2023. It tackles three core questions: the extent of decoupling achieved, the main factors driving this process, and the relevance of degrowth strategies. The analysis reveals a complex and shifting decoupling trajectory, illuminating Ireland's efforts and challenges in transitioning to a low-carbon economy across diverse economic and social landscapes.

During a period of strong economic growth driven by industrialization and foreign investment, Ireland saw only limited decoupling between emissions and growth. Although emissions rose more slowly than the economy, they continued to increase due to scale effects and reliance on fossil fuels, which offset early efficiency achievements. In the following slowdown, decoupling outcomes were mixed: Pop growth and lower efficiency slowed progress, while later improvements in energy use and carbon intensity brought brief relief. The recession that followed led to passive decoupling, as emissions fell alongside output, driven by contraction rather than climate policy. Weak innovation and efficiency gains meant scale effects remained dominant. In the recovery phase, stronger climate policies and renewable energy investment led to more frequent strong decoupling. Still, scale pressures persist, revealing the ongoing challenge of aligning growth with sustained emission reductions.

Ireland's decoupling journey reflects a gradual shift from weak to strong decoupling. Yet, this progress is fragile, vulnerable to rapid economic surges or external shocks. Technology and policy have been vital, cutting emissions through reduced carbon intensity and optimized energy use. However, persistent economic and population pressures thwart absolute decoupling. Scale effects often erode technological gains, while the fluctuation of energy efficiency adds further unpredictability. These findings align with Ireland's Climate Action Plan trajectory—particularly the 51 % reduction target to 2030—by indicating that demand-side and material-throughput controls are required in addition to technological decarbonisation. They also support the EU Green Deal's emphasis on circularity and energy efficiency, suggesting that monitoring should track not only $CO_2$ and energy intensity but also MI/Dmc as national material-budget indicators.

This study affirms the degrowth perspective that technological improvements alone are insufficient to reconcile economic growth with environmental sustainability. Ireland's experience illustrates that, while advances in efficiency and low-carbon technologies contribute to emission reductions, they fall short of achieving sustained decoupling in the absence of broader structural change. A rethinking of development strategies is needed—one that prioritizes long-term resource efficiency and low-carbon transitions alongside economic resilience.

Nonetheless, the study has several limitations. The use of GNI* as the primary economic indicator, although appropriate for capturing Ireland's economic structure, may underestimate emissions linked to multinational activities. Similarly, reliance on Dmc does not account for the embodied emissions in imports—an important omission for an open, trade-reliant economy. The Tapio-LMDI approach assumes a stable, linear relationship between economic activity and emissions, making it less suited to capture the effects of economic shocks such as financial crises or the COVID-19 pandemic. In addition, the national-level analysis obscures sectoral variation, overlooking diverging decoupling trends in areas such as agriculture and data centers. Furthermore, the analysis has not sufficiently explored the political and societal challenges in Ireland arising from the implementation of degrowth-oriented policies for stronger long-term decoupling and has not deeply considered the potential resistance from affected industries and citizens. Degrowth strategies may encounter strong opposition from industries which rely on resource-intensive growth, such as high-carbon enterprises or businesses associated with material consumption. Citizens accustomed to current work patterns, consumption habits and cultural values centered on economic expansion may also oppose such changes, potentially leading to public resistance. Acceptance of these reforms may prove difficult and could require substantial public education, incentives and transitional support. Core fiscal reforms may take multiple budget cycles and one to two terms to unfold which about 10–20 years, while cultural and behavioral changes require a longer-term horizon, depending on factors including political will, economic conditions, and community coordination.

Future research could strengthen the analysis by integrating GNI* with sector-level energy and emissions data, incorporating trade-adjusted metrics, employing dynamic decomposition models, and extending the dataset to include forward-looking scenarios aligned with Ireland's evolving climate policy landscape.

## CRediT authorship contribution statement

**Tianning Zhao:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Valeria Andreoni:** Writing – review & editing, Supervision, Methodology. **Hannah Daly:** Writing – review & editing, Visualization, Supervision. **John Eakins:** Writing – review & editing, Supervision.

## Declaration of competing interest

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.

## Appendix A

**Table. A1**
Data type and their links of source.

| Data type | Source | Link |
|---|---|---|
| $CO_2$ | EPA | https://www.epa.ie/our-services/monitoring–assessment/climate-change/ghg/summary-by-gas/ |
| Dmc | Eurostat | https://ec.europa.eu/eurostat/databrowser/view/env_ac_mfa_custom_16521088/default/table?lang=en |
| Fos & Ene | SEAI | https://www.seai.ie/data-and-insights/seai-statistics/energy-data-downloads |
| Pop | World Bank | https://data.worldbank.org/indicator/SP.POP.TOTL?locations=IE |
| GDP | World Bank | https://data.worldbank.org/indicator/NY.GDP.MKTP.KN?end=2023&locations=IE&start=1960&view=chart |
| GNI* | CSO | https://data.cso.ie/table/NA002 |

## Data availability

Data will be made available on request.

## References

Akdoğan, T., Erkara, E., Mert, B., Hiçyılmaz, B., Alataş, S., Karakaya, E., 2023. Understanding material and energy use in the processes of decoupling CO2 emissions from economic growth. Environ. Sci. Pollut. Res. 30, 80863–80883.

Andreoni, V., 2020. From the Celtic tiger to the Celtic phoenix: the metabolic profile of Ireland and the main drivers of energy change. J. Clean. Prod. 246, 118975. https://doi.org/10.1016/j.jclepro.2019.118975.

Ang, B.W., 2015. LMDI decomposition approach: a guide for implementation. Energy Policy 86, 233–238.

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33, 867–871.

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J., Lenton, T.M., 2022. Exceeding 1.5 C global warming could trigger multiple climate tipping points. Science 377, eabn7950.

Aryanpur, V., Balyk, O., Glynn, J., Gaur, A., McGuire, J., Daly, H., 2024. Implications of accelerated and delayed climate action for Ireland's energy transition under carbon budgets. Npj Clim. Action 3, 97. https://doi.org/10.1038/s44168-024-00181-7.

Berahab, R., 2017. Decoupling Economic Growth from CO2 Emissions in the World.

Bianco, V., Cascetta, F., Nardini, S., 2024. Analysis of the carbon emissions trend in European Union. A decomposition and decoupling approach. Sci. Total Environ. 909, 168528.

Boyle, J., Littler, T., 2024. A review of frequency-control techniques for wind power stations to enable higher penetration of renewables onto the Irish power system. Energy Rep. 12, 5567–5581.

Chen, Y., Lin, B., 2020. Slow diffusion of renewable energy technologies in China: an empirical analysis from the perspective of innovation system. J. Clean. Prod. 261, 121186.

Chen, Y.-E., Li, C., Chang, C.-P., Zheng, M., 2021. Identifying the influence of natural disasters on technological innovation. Econ. Anal. Pol. 70, 22–36. https://doi.org/10.1016/j.eap.2021.01.016.

Circle Economy, 2020. The Circularity Gap Report - the Netherlands.

Conefrey, T., Fitz Gerald, J.D., Valeri, L.M., Tol, R.S.J., 2013. The impact of a carbon tax on economic growth and carbon dioxide emissions in Ireland. J. Environ. Plann. Manag. 56, 934–952. https://doi.org/10.1080/09640568.2012.709467.

CSO, 2024. Annual National Accounts 2023.

CSO, 2023. Annual National Accounts 2022.

CSO, n.d. Modified GNI.

Daly, H., Aryanpur, V., Suleimenov, B., Deane, P., 2024. PATHWAYS FOR IRELAND'S ENERGY SYSTEM TO 2050.

De Bruin, K., Yakut, A.M., 2024. Efficiency–equity trade-off in the Irish carbon tax: a CGE investigation of mixed revenue recycling schemes. Econ. Modell. 134, 106705. https://doi.org/10.1016/j.econmod.2024.106705.

DECC, 2023. Climate Action Plan 2024.

DECC, 2021. Climate Action and Low Carbon Development (Amendment) Bill 2021.

Engler, J.-O., Kretschmer, M.-F., Rathgens, J., Ament, J.A., Huth, T., Von Wehrden, H., 2024. 15 years of degrowth research: a systematic review. Ecol. Econ. 218, 108101.

EPA, 2024. Ireland's Provisional Greenhouse Gas Emissions 1990-2023 (No. ISBN: 978-1-80009-186-3).

EPA, 2021. Ireland's Greenhouse Gas Emissions Projections 2020-2040.

Farrell, N., 2017. What factors drive inequalities in carbon tax incidence? Decomposing socioeconomic inequalities in carbon tax incidence in Ireland. Ecol. Econ. 142, 31–45. https://doi.org/10.1016/j.ecolecon.2017.04.004.

Fu, J., Wang, F., Guo, J., 2024. Decoupling economic growth from carbon emissions in the Yangtze River economic Belt of China: from the coordinated regional development perspective. Sustainability 16, 2477. https://doi.org/10.3390/su16062477.

Gaur, A., Balyk, O., Glynn, J., Curtis, J., Daly, H., 2022. Low energy demand scenario for feasible deep decarbonisation: whole energy systems modelling for Ireland. Renew. Sustain. Energy Transit. 2, 100024.

Giblin, S., McNabola, A., 2009. Modelling the impacts of a carbon emission-differentiated vehicle tax system on CO2 emissions intensity from new vehicle purchases in Ireland. Energy Policy 37, 1404–1411.

Gill, A.R., Viswanathan, K.K., Hassan, S., 2018. The Environmental Kuznets Curve (EKC) and the environmental problem of the day. Renew. Sustain. Energy Rev. 81, 1636–1642.
Gołaś, Z., 2023. Decoupling analysis of energy-related carbon dioxide emissions from economic growth in Poland. Energies 16, 3784. https://doi.org/10.3390/en16093784.
González, P.F., Landajo, M., Presno, M.J., 2014. Tracking European Union CO2 emissions through LMDI (logarithmic-mean Divisia index) decomposition. The activity revaluation approach. Energy 73, 741–750.
Gough, I., 2017. Heat, Greed and Human Need: Climate Change, Capitalism and Sustainable Wellbeing. Edward Elgar Publishing.
Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., 2018. A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515–527.
Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., Mayer, A., Pichler, M., Schaffartzik, A., Sousa, T., Streeck, J., Creutzig, F., 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environ. Res. Lett. 15, 65003. https://doi.org/10.1088/1748-9326/ab842a.
Hickel, J., Kallis, G., 2020. Is green growth possible? New Polit. Econ. 25, 469–486.
Hou, F., Su, H., Li, Y., Qian, W., Xiao, J., Guo, S., 2021. The impact of foreign direct investment on China's carbon emissions. Sustainability 13, 11911. https://doi.org/10.3390/su132111911.
IEA, 2024. The Relationship Between Growth in GDP and CO2 Has Loosened; It Needs to be Cut Completely.
Illahi, U., Choudhari, T.P., Charly, A., O'Mahony, M., Caulfield, B., 2024. Driving green change: commercial sector adopting electric vehicles in Ireland. Transp. Res. Part Transp. Environ. 135, 104398.
Jackson, T., 2009. Prosperity Without Growth: Economics for a Finite Planet. Routledge.
Kallis, G., 2011. In defence of degrowth. Ecol. Econ. 70, 873–880.
Kallis, G., Kerschner, C., Martinez-Alier, J., 2012. The economics of degrowth. Ecol. Econ. 84, 172–180.
Kinley, R., 2017. Climate change after Paris: from turning point to transformation. Clim. Policy 17, 9–15.
Kronenberg, J., Andersson, E., Elmqvist, T., Łaszkiewicz, E., Xue, J., Khmara, Y., 2024. Cities, planetary boundaries, and degrowth. Lancet Planet. Health 8, e234–e241.
Li, R., Jiang, R., 2020. Investigating effect of R&D investment on decoupling environmental pressure from economic growth in the global top six carbon dioxide emitters. Sci. Total Environ. 740, 140053.
Lux, G., Fromont, E., Vo, T.L.H., 2023. Green business: growth or degrowth to meet IPCC targets? Discussion of an assessment tool: IPCC CAPRO change target. J. Clean. Prod. 420, 138364.
Martins, K., Carton, J.G., 2023. Prospective roles for green hydrogen as part of Ireland's decarbonisation strategy. Results Eng. 18, 101030.
Mc Guire, J., Rogan, F., Balyk, O., Mac Uidhir, T., Gaur, A., Daly, H., 2023. Developing decarbonisation pathways in changing TIMES for Irish homes. Energy Strategy Rev. 47, 101086.
McGeever, A.H., Price, P., McMullin, B., Jones, M.B., 2019. Assessing the terrestrial capacity for Negative Emission Technologies in Ireland. Carbon Manag. 10, 1–10.
Moutinho, V., Moreira, A.C., Silva, P.M., 2015. The driving forces of change in energy-related CO2 emissions in Eastern, Western, Northern and Southern Europe: the LMDI approach to decomposition analysis. Renew. Sustain. Energy Rev. 50, 1485–1499.
Okolo, C.V., Wen, J., 2022. Economics of natural disasters and technological innovations in Africa: an empirical evidence. Environ. Sci. Pollut. Res. 30, 12362–12384. https://doi.org/10.1007/s11356-022-22989-8.
O'Mahony, T., 2013. Decomposition of Ireland's carbon emissions from 1990 to 2010: an extended Kaya identity. Energy Policy 59, 573–581.
O'Mahony, T., Zhou, P., Sweeney, J., 2013. Integrated scenarios of energy-related CO2 emissions in Ireland: a multi-sectoral analysis to 2020. Ecol. Econ. 93, 385–397.
O'Mahony, T., Zhou, P., Sweeney, J., 2012. The driving forces of change in energy-related CO2 emissions in Ireland: a multi-sectoral decomposition from 1990 to 2007. Energy Policy 44, 256–267.
Pan, Xiongfeng, Guo, S., Xu, H., Tian, M., Pan, Xianyou, Chu, J., 2022. China's carbon intensity factor decomposition and carbon emission decoupling analysis. Energy 239, 122175.
Paulson, S., 2017. Degrowth: culture, power and change. J. Polit. Ecol. 24, 425–448.
Perissi, I., Jones, A., 2023. Influence of economic decoupling in assessing carbon budget quotas for the European Union. Carbon Manag. 14, 2217423.
Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. Proc. Natl. Acad. Sci. 108, 8903–8908.
Polimeni, J.M. (Ed.), 2008. The Jevons Paradox and the Myth of Resource Efficiency Improvements, Earthscan Research Editions. Earthscan, London ; Sterling, VA.
Rourke, F.O., Boyle, F., Reynolds, A., 2009. Renewable energy resources and technologies applicable to Ireland. Renew. Sustain. Energy Rev. 13, 1975–1984.
Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T., 2018. Global material flows and resource productivity: forty years of evidence. J. Ind. Ecol. 22, 827–838. https://doi.org/10.1111/jiec.12626.
Schor, J., 2010. Plenitude: the New Economics of True Wealth. Penguin Press, New York, N.Y.
SEAI, 2024. First Look: Renewable Energy in Ireland 2023.
Serrano-Puente, D., 2021. Are we moving toward an energy-efficient low-carbon economy? An input–output LMDI decomposition of CO$$_{2}$$ emissions for Spain and the EU28. SERIEs 12, 151–229. https://doi.org/10.1007/s13209-020-00227-z.
Sorrell, S., 2007. The Rebound Effect: an Assessment of the Evidence for Economy-wide Energy Savings from Improved Energy Efficiency. UK Energy Research Centre, Sussex.
Stefaniec, A., Egan, R., Hosseini, K., Caulfield, B., 2025. The challenge of making EVs just affordable enough: assessing the impact of subsidies on equity and emission reduction in Ireland. Res. Transport. Econ. 109, 101495. https://doi.org/10.1016/j.retrec.2024.101495.
Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transp. Policy 12, 137–151. https://doi.org/10.1016/j.tranpol.2005.01.001.
Wang, Q., Su, M., Li, R., 2018. Toward to economic growth without emission growth: the role of urbanization and industrialization in China and India. J. Clean. Prod. 205, 499–511. https://doi.org/10.1016/j.jclepro.2018.09.034.
Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H., Simmons, C.T., 2016. Is decoupling GDP growth from environmental impact possible? PLoS One 11, e0164733. https://doi.org/10.1371/journal.pone.0164733.
Warlenius, R.H., 2023. The limits to degrowth: economic and climatic consequences of pessimist assumptions on decoupling. Ecol. Econ. 213, 107937. https://doi.org/10.1016/j.ecolecon.2023.107937.
Wen, J., Zhao, X.-X., Fu, Q., Chang, C.-P., 2023. The impact of extreme weather events on green innovation: which ones bring to the most harm? Technol. Forecast. Soc. Change 188, 122322. https://doi.org/10.1016/j.techfore.2023.122322.
Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. 112, 6271–6276. https://doi.org/10.1073/pnas.1220362110.
Xie, W., Aryanpur, V., Deane, P., Daly, H.E., 2025. Negative emissions technologies in energy system models and mitigation scenarios-a systematic review. Appl. Energy 380, 125064.
Yang, J., Hao, Y., Feng, C., 2021. A race between economic growth and carbon emissions: what play important roles towards global low-carbon development? Energy Econ. 100, 105327. https://doi.org/10.1016/j.eneco.2021.105327.
Zhao, X.-X., Zheng, M., Fu, Q., 2022. How natural disasters affect energy innovation? The perspective of environmental sustainability. Energy Econ. 109, 105992. https://doi.org/10.1016/j.eneco.2022.105992.
Zhu, T., Curtis, J., Clancy, M., 2023. Modelling barriers to low-carbon technologies in energy system analysis: the example of renewable heat in Ireland. Appl. Energy 330, 120314. https://doi.org/10.1016/j.apenergy.2022.120314.