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Understanding the Driving Forces of Carbon Emissions in Ireland

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1.0 Introduction and background

1.1 Study background

The advancements in the science of climate change, which hardened in the early 1990's and further crystallised in the years since, have led to a number of conclusions that form the context for mitigation and low-carbon transition. The Intergovernmental Panel on Climate Change (IPCC) conclude that: the warming of the global climate system is unequivocal; it is attributable to human activity in the form of increasing concentrations of greenhouse gases (GHG); and the risks of severe, pervasive and irreversible impacts are increasing (IPCC, 2014). According to this scientific consensus through the IPCC, established through consultation with experts and governments worldwide, a political consensus through the United Nations Framework Convention on Climate Change (UNFCCC) has followed. Economically advanced and wealthier countries such as Ireland must lead the transformation to a low-carbon future.

Following in the footsteps of the science, the supra-national policy frameworks of the UNFCCC in the 'Paris Agreement' of 2015, the EU targets and Roadmaps through to 2050 and the Irish national *Climate Action and Low-carbon development Act* (2015), provide the architecture in which long-term GHG emissions reductions of -80 to -95% must be achieved. The early years of the Kyoto protocol were characterised by a capacity-building process and more flexible and achievable emissions limitation and reduction targets[1]. Urgency has since increased. The scientific study of climate change mitigation, and the policy for its achievement, has since moved from priority on short term targets to long term low-carbon transition and transformation. As the requirements of deep decarbonisation become clearer, so does the need to fundamentally alter development paths towards low emissions outcomes. This necessitates both focussed technology and holistic 'development-led' policies from national governments. Understanding the policy changes necessary requires the study of the spread of low carbon technologies, but also understanding of the underlying driving forces of emissions. The IPCC point to the policy insight that it is vital to evolve on inherently low emissions development path *and* mitigate the emissions that occur (Sathaye et al., 2007; Fleurbaey et al., 2014), rather than an uncontrolled growth in emissions drivers, and relying on investment in mitigation technology alone.

Figure 1 illustrates the pattern of growth in Total Primary Energy Requirement in Ireland up to 2016 from SEAI (2017a). It shows the domination of fossil fuels and the growth of renewables, albeit from a low base. Figure 2 illustrates the associated outcome in terms of energy-related carbon emissions also from SEAI (2017a). The growth up to a peak in 2008, is followed by a fall during the economic recession and a return of growth in emissions in 2015 and 2016.

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[1] Through the Kyoto Protocol and the EU effort sharing mechanism, Ireland was afforded a +13% growth GHG limitation target to be achieved during the period 2008-2012, within an EU target of an aggregate -8% reduction.

Figure 1. Total Primary Energy Requirement by fuel type from 1990 to 2016 in ktoe

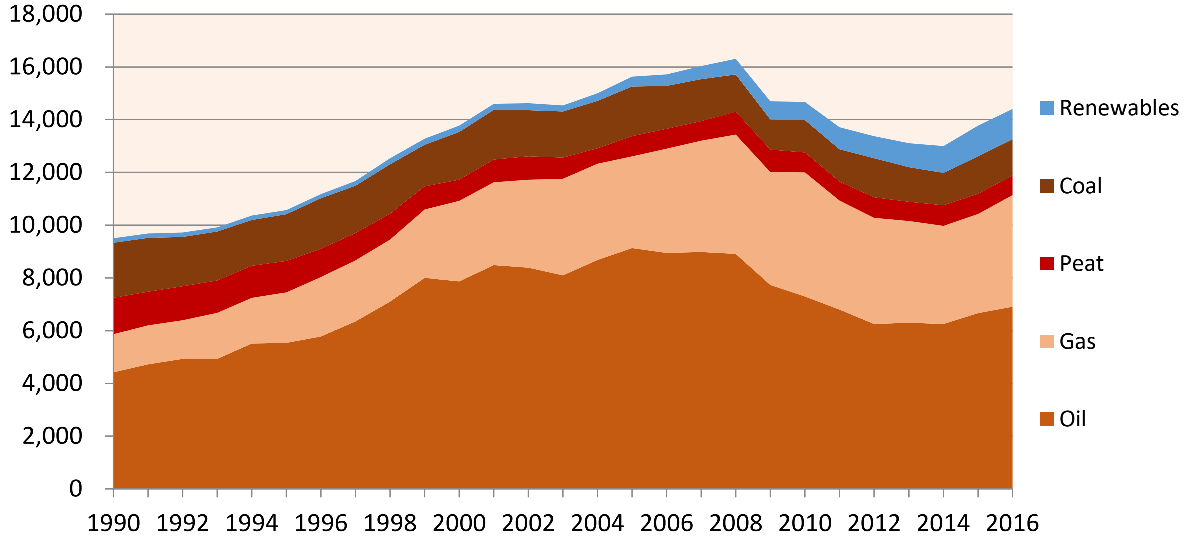
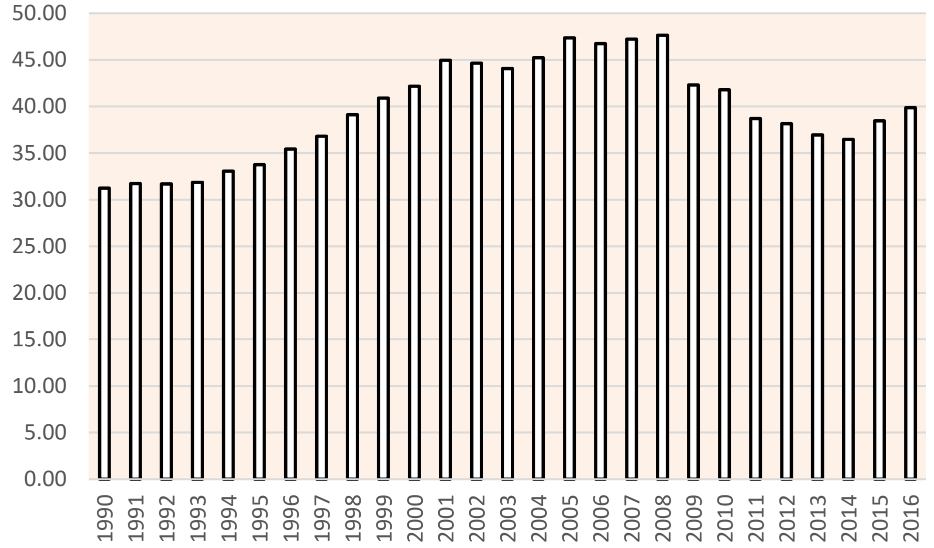
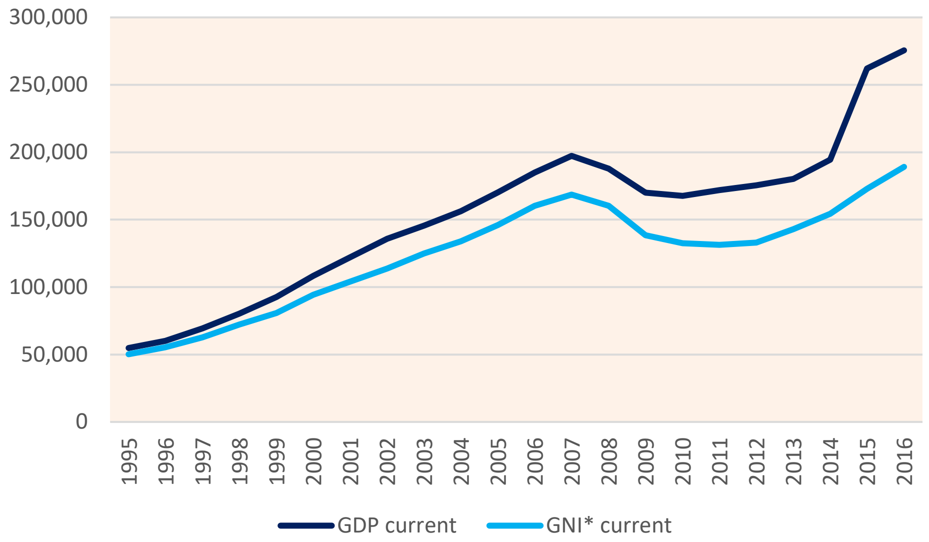


Figure 2. TPER based energy-related carbon emissions from 1990 to 2016 in MtCO$_2$



While economic growth does not have a linear relationship with emissions it is known that it is a key driver of growth, through the consumption of materials, of energy and associated greenhouse gas emissions (Fleurbaey et al., 2014). Figure 3 presents the pattern of growth in Gross Domestic Product (GDP) from 2008 to 2016. It is known that the GDP data in Ireland is distorted by globalisation, chiefly the movement into Ireland of profits from intellectual property by multinationals. This presents in national economic accounts but does not have a corresponding energy and emissions footprint, the associated production and consumption occurred activity occurs in other countries. In order to consider the impact of this distortion, the Central Statistics Office have developed a new measure termed '*modified Gross National Income*' or GNI*[2] (CSO, 2017a). In order to compare the difference between these two indicators. Figure 3 also presents the results for GNI*. Population growth has also been strong in Ireland over this period. Understanding the relevant contribution of the different driving forces, and monitoring their progression, has become an increasingly important input into policy discussions worldwide.

Figure 3. Growth in GDP and GNI* in current prices from 1995 to 2016 in million €



1.2 From the 'Kaya identity' to decomposition analysis: tools to understand change in energy and carbon emissions

Some of the major driving forces of past and future anthropogenic greenhouse gas (GHG) (including the most significant GHG - carbon emissions), were described in the IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000). These include demographics, economics, resources, technology, and non-climate policies that dictate the direction of development in general. The SRES highlighted the complexity of economic social and technical systems, and their interactions, and pointed to a frequently used approach to discuss environmental pressures from human activities. This is known as the '*IPAT identity*'. IPAT is a sustainability evaluation framework from the early 1970's (Commoner, 1972; Ehrlich and Holdren, 1972) and is mathematically structured as follows;

$$Impact = Population \; * Affluence \; * Technology \tag{1}$$

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[2] The modifications include depreciation on research and development related intellectual property, factor income of redomiciled companies and depreciation on aircraft leasing.

According to the IPAT identity environmental impacts (e.g. emissions) are the product of the level of population times affluence (income per capita, i.e. gross domestic product (GDP) divided by population) times the level of technology deployed (emissions per unit of income). This identity was further crystallised by Yoichi Kaya to specifically consider CO_2 emissions from energy combustion, and became known as the Kaya Identity (Kaya, 1990; Yamaji et al., 1991). The Kaya identity is mathematically structured as follows;

$$CO_2\ Emissions = Population\ *\ (GDP/Population)\ *\ (Energy/GDP)\ *\ (CO_2\ /Energy) \tag{2}$$

The Kaya identity is a simple yet powerful multiplicative identity that relates population growth, per capita income, energy consumption per unit income, and emissions per unit energy on the left side of the identity, with total CO_2 emissions on the right side. Thus it decomposes emissions into four main driving forces.

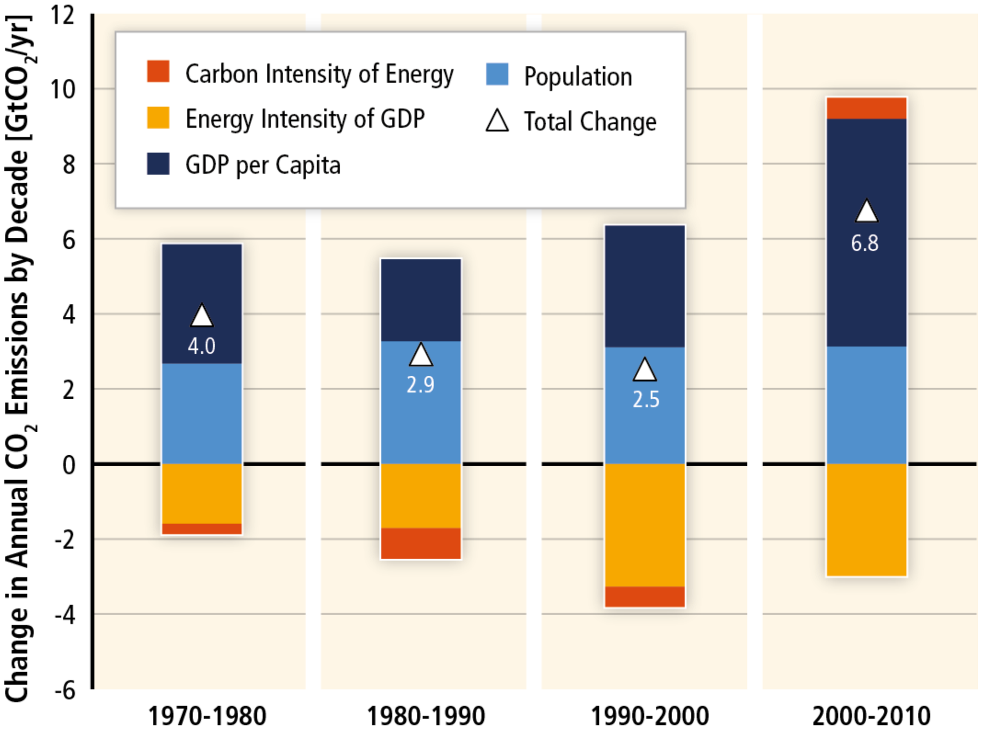
The Kaya identity has risen to prominence in mitigation studies since the early 1990's, as it allows the economic and social driving forces of emissions to be monitored both historically and in scenario analysis. It has featured as the key framework for analysis in both the IPCC fourth and fifth assessment reports. The IPCC fifth assessment report, in working group III on mitigation, focussed on these novel identities as the organising principle in the general analytical framework (Blanco et al., 2014). The recent European Environment Agency "*Analysis of key trends and drivers in greenhouse gas emissions in the EU between 1990 and 2015*" (EEA, 2017) applied a variant of the Kaya identity to measure change in GHG emissions. This highlights the flexibility of the technique and its application in cross-national comparisons. The Kaya identity has frequently also been employed as the organising framework for consideration of the future evolution of driving forces. The IPCC *Special Report on Emission Scenarios*, also known as the 'SRES' (Nakicenovic et al., 2000), is a major example of the use of Kaya to structure scenario studies.

At the Dublin workshop of the UNFCCC in 2004, a marked interest was noted in the Kaya decomposition analysis reported in the in-depth review of Germany. Based on studies such as Schleich et al. (2001) on the driving forces of emissions, this technique was recommended to explain problems and success stories, allowing quantitative assessment to separate effects on emissions from improvements in energy efficiency, changes in the energy supply mix, and growth in population and GDP (UNFCCC, 2004). Recognising its flexibility, 'decomposition analysis' using Kaya-type identities has become a mainstay of analysis of changes in energy and carbon emissions (Ang, 2004), national and sectoral energy efficiency programmes (Ang et al., 2010), and has spread to renewable energy programmes (O'Mahony and Dufour, 2015).

Decomposition analysis has been applied to Ireland's energy and carbon emissions for a number of tasks. Studies have included a national extended Kaya identity (that also measures the impact of renewable energy on emissions) in O'Mahony (2013), industry decomposition (Cahill and ÓGallachóir, 2009), transport decomposition (Jennings et al., 2013) multi-sectoral decomposition of energy-related carbon emissions in eleven sectors[3] (O'Mahony et al., 2012), exploratory scenarios of multisectoral carbon emissions to 2020 (O'Mahony et al., 2013), and long term 'no-policy' Kaya scenarios to 2050 (O'Mahony, 2012).

The IPCC fifth assessment report documented global aggregated changes in the Kaya identity as presented in Figure 4. Though there is substantial heterogeneity at the national level beneath these results, the aggregated global analysis shows the pressure of economic and population growth to increase emissions, and of 'energy intensity' in the reverse direction. Considering how such driving forces are evolving in Ireland is the subject of this report.

Figure 4. Global Kaya identity by decade from the IPCC fifth assessment report



Source: Figure 1.7 from IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y.Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schloemer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

1.3 Approach to study and structure of report

This study seeks to update the extended-Kaya identity decomposition analysis of Ireland, from 1990 to 2007, that was published in *Energy Policy* journal in 2013 (O'Mahony, 2013). The updated study applies from 1995 to 2016, up to the most recent year for which data as available at the time of the research. It uses both Kaya and extended-Kaya identity schemes, with a variety of economic data; real GDP, current GNI* and current GDP. The objective is to measure the annual change in emissions

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[3] Four economic sectors, six transport sectors and the residential sector.

driving forces over the study period, and to consider the potential implications for low-carbon transition.

After section 1 the report is structured as follows. Section 2 provides detail on the methodology and the data used. Section 3 presents the results of the various analyses, Kaya and extended-Kaya, periodic 1995 to 2016 and annual time series, and by the different economic indicators: real GDP, current GNI* and current GDP. Section 4. Interprets the quantitative results, discusses the implications and identifies potential options for low-carbon transition to 2050. Section 4 also discusses the limitations and caveats to the analysis, and options for further research to respond to gaps in knowledge in Ireland. Section 5 concludes the report.

2.0 Methodology and data

2.1 Implementing decomposition analysis the Kaya way

In conducting a decomposition analysis, the study begins by defining a ‘governing function’. The governing function is the framework for the ‘breaking down,’ or ‘decomposing’ of change in an indicator into a number of predefined ‘driving forces’ or ‘effects’. In this study, the indicator of interest is the observed change in total energy-related CO_2 emissions[4], and the governing function is the ‘Kaya identity’ (Kaya, 1990). Implementing the Kaya identity requires a decomposition analysis technique, for which a range of techniques have been established under the umbrella of ‘Index Decomposition Analysis’ (IDA). The Log Mean Divisia Index I (LMDI I) has become increasingly established as the preferred approach[5] (Ang, 2004; Ang et al.,2003). (IDA) has been widely accepted as an analytical tool for supporting policymaking on national energy and environmental issues (Ang, 2004b). The decomposition of the change in an aggregate indicator into a pre-defined set of factors helps to understand the progression of driving forces, the impact of major processes occurring and policy dimensions tied to these processes (Steenhof et al., 2006). The results of an IDA application study have direct policy implications such as evaluation of energy conservation programs (Ang, 2004b; Ang and Liu, 2007). They also provide a basis for forecasting (Ang, 2004a) and for scenario analysis of future evolution (O’Mahony et al., 2013).

At the United Nations Framework Convention on Climate Change (UNFCCC) Dublin Workshop on Fourth National Communications from Annex I Parties (UNFCCC, 2004), IDA was recommended to quantify key drivers of emissions and separate effects such as energy efficiency and GDP growth. In the literature, applications of IDA have undergone substantial changes since the late 1970’s. Recently, IDA methods particularly the Logarithmic Mean

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[4] Human activities in the economy and society that burn fossil fuel energy sources (peat, coal, oil and gas) lead to the emission of CO_2 or ‘energy related carbon emissions’. Burning different fossil fuels emits varying amounts of CO_2, with peat the most carbon-intensive, followed by coal, oil and finally gas. The renewable energy sources; such as wind, solar, hydro, geothermal and biomass, are carbon-free. Only biomass involves the combustion of a fuel type, but theoretically this does not involve an addition of any carbon emissions to the stock in the atmosphere. ‘Energy-related carbon emissions’ are distinct from those that result from industrial processes such as cement production.

[5] This is due to a number of desirable mathematical properties of the Divisia index including: perfect decomposition, consistency in aggregation, path independency and an ability to handle zero values.

Divisia Index (LMDI) technique, have been widely applied to track economy-wide energy efficiency trends by different countries and organisations (Ang et al., 2010). Sectoral analysis has been expanding from energy demand and CO_2 emissions in industry and manufacturing sub-sectors, to analysis such as UK road freight in Sorrell et al. (2009) and multi-sectoral economic, transport and residential analysis (O'Mahony et al., 2012). An extended Kaya identity has been applied using LMDI I in a number of studies (Zhang and Ang, 2001; Wang *et al.,* 2005; Ma and Stern, 2008). The identity proposed by Zhang and Ang (2001) is instructive to decompose changes in energy-related carbon emissions top-down at the national level and uses the following variables:

E = Total Primary Energy Requirement (TPER) of all fuel types

E_i = TPER of fuel type i

C = Total CO_2 emissions from all fuel types

C_i = CO_2 emissions from fuel type i

Y = GDP

P = Population

This leads to the following identity which is a direct reflection of Kaya;

$$C=\Sigma_i C_i=\Sigma_i (E_i/E)(C_i/E_i)(E/Y)(Y/P)P \qquad (3)$$

However, function 1 does not represent the effect of change in CO_2 resulting specifically from the increased penetration of or carbon-free renewable energy. The identity decomposes CO_2, and as emissions from renewables are theoretically zero the effect of renewables is not measured. In order to overcome this Wang *et al.* (2005), Ma and Stern (2008) and O'Mahony (2013) proposed an 'extended Kaya identity,' that also accounts for change resulting from increased penetration of renewables. Renewable energy is particularly important in Ireland because it is central to national mitigation efforts, nuclear generation is prohibited, and there is strong growth potential particularly for on-shore wind (OECD/ IEA, 2007). The following variables are described for Ireland, as an extended Kaya identity:

E = Total Primary Energy Requirement (TPER) of all fuel types

FF_i = TPER of fossil fuel type i

FF = TPER of all fossil fuels

C = Total CO_2 emissions from all fossil fuel types

C_i = CO_2 emissions from fossil fuel type i

Y = GDP

P = Population

Within this scheme i denotes fuel type (coal, oil, peat, gas, renewables). The CO_2 emissions using this approach can be written as the following extended Kaya identity;

$$C = \Sigma_i C_i = \Sigma_i (C_i/FF_i)(FF_i/FF)(FF/E)(E/Y)(Y/P)P = \Sigma_i F_1 S_1 S_2 IGP \tag{4}$$

Within this scheme the following nomenclature is applied;

$F_1 = C_i/FF_i$ the CO_2 emission coefficient for fossil fuel type i

$S_1 = FF_i/FF$ is the share of fossil fuel type i, in total fossil fuels

$S_2 = FF/E$ is the share of fossil fuels, in total fuels

$I = E/Y$ the aggregate energy intensity

$G = Y/P$ the GDP per capita or affluence

P = population

The decomposition of an observed change in C associated with these factors, are referred to as, the emission intensity effect (ΔC_{emc}), the fossil fuel share effect (ΔC_{ffse}), the renewable energy effect (ΔC_{repe}), the energy intensity effect (ΔC_{int}), the affluence effect (ΔC_{ypc}) and the population effect (ΔC_{pop}). The index of annual change in total CO_2 emissions (C_{tot}) can be expressed in the multiplicative form as follows;

$$C_{tot} = C_t/C_0 = C_{emc}C_{ffse}C_{repe}C_{int}C_{ypc}C_{pop} \qquad (5)$$

The detailed mathematical scheme for the application of LMDI I, taken from O'Mahony (2013) is detailed in Appendix A.

A decomposition analysis is flexible in its construction depending on the environmental pressure under study. It allows the total change to be decomposed into a series of activity (scale), intensity (efficiency) and structural (share) effects that determine overall change. An IDA can be conducted in two forms either additive or multiplicative, to explore absolute or ratio of change respectively (Ang, 2005). While in LMDI I the two forms are linked through a simple mathematical relationship (Ang, 2005), the choice of form depends on considerations such as the purposes of the study, the existence of negative changes in the data set, and ease of application. In this study the Divisia index is employed in multiplicative form chain-linked year-by-year. This allows for annual analysis that can also be aggregated by sub-period and over the entire period. Results are reported as index change in effects annually, but also as additive changes in absolute emissions ($MtCO_2$) to facilitate ease of interpretation and understanding. and also grouped by period in both index and percentage annual change. An explanation of the driving forces measured in the Kaya decomposition analysis are provided in Table 1.

Table 1 Effects measured in the Kaya identity decomposition analysis

Effect	Type	Description of determinant effect
C_{emc}	Intensity	Change in the total emissions intensity of energy due to the carbon content per unit fossil fuel, the substitution between fossil fuels and the penetration of renewable energy into total energy.
C_{int}	Intensity	Change in energy requirement per unit GDP due to supply side structure and efficiency in economic production, infrastructure and the energy system, and demand side drivers including spatial patterns, technological choice, behaviour and lifestyle.
C_{ypc}	Scale	Change in average GDP per capita, or affluence.
C_{pop}	Scale	Change in number of inhabitants, or total population.
C_{tot}	Aggregate	Total change in carbon emissions aggregating the determinant effects.
C_{rsd}	Residual	Residual from the attribution of change to determinant effects above. This should be zero as LMDI I gives perfect decomposition.

In the extended Kaya identity in Table 2, the emissions intensity is further decomposed into the emissions intensity per fossil fuel, the share of fossil fuels and the share of renewable energy.

Table 2 Further decomposition of emissions intensity in the extended Kaya identity decomposition analysis

Effect	Type	Description of determinant effect
C_{emcf}	Intensity	Change in carbon content per unit fossil fuel: coal, peat, oil and gas, attributable to fuel quality and potentially also to abatement technologies.
C_{repe}	Structure	Renewable energy penetration that displaces fossil fuels including; hydro, wind, biomass, biofuel, solar, geothermal etc. as a technological effect.
C_{ffse}	Structure	Substitution or fuel switching of fossil fuel types (coal, oil, peat and gas) in total fossil fuels, also a technological effect.

2.2 Data

The annual economic data for GDP (both real[6] and current) and GNI* (current) is taken from the Central Statistics Office (CSO, 2017a). Population estimates are also taken from the CSO (CSO, 2017b). While data for energy, CO_2 and population is available back to 1990, for economic output, a continuous data set is not available prior to 1995. A break in the dataset occurs as pre-1995 data excludes Financial Intermediation Services Indirectly Measured (FISIM)[7]. In response to this, to exclude the break in the dataset , he analysis period begins in 1995 rather than the standard Kyoto protocol base year of 1990. A caveat to all analysis that uses economic indicators such as GDP or GNI is their limited scope and exclusion of social and environmental dimensions[8].

Energy data is compiled by the Sustainable Energy Authority of Ireland Energy Policy Statistical Support Unit (SEAI EPSSU). Reported in the annual 'energy balance sheets' these include Total Primary Energy Requirement (TPER) by fuel type, including renewables. This establishes the supply-side profile and consequently includes kerosene used in international aviation and stock changes (SEAI, 2017a). The data used consists of sub-fuel types aggregated as kilo tonnes of oil equivalent (ktoe) of peat, coal, oil, gas and renewables. The data set also includes linked energy related carbon emissions reported in $ktCO_2$, calculated by SEAI using the Intergovernmental Panel on Climate Change sectoral methodology (IPCC, 1997).

3.0 Results

3.1 Kaya identity decomposition analysis

The results of the Kaya identity decomposition analysis by real GDP are presented in Figure 5, covering the full period from 1995 to 2016. The results are presented in additive form by change in $MtCO_2$ for ease of understanding. These results show that while there was some significant progress in improving energy intensity per GDP (-31.10 $MtCO_2$), accompanied by a more minor improvement in the carbon intensity of energy (-5.26 $MtCO_2$), this occurred alongside a significant growth in GDP per capita (32.39 $MtCO_2$) and a large increase in population (10.08 $MtCO_2$). The driving forces acting to limit or reduce emissions were insufficient to counter the growth in GDP per capita and in population, and the net result was a 6.12 a $MtCO_2$ increase in national carbon emissions.

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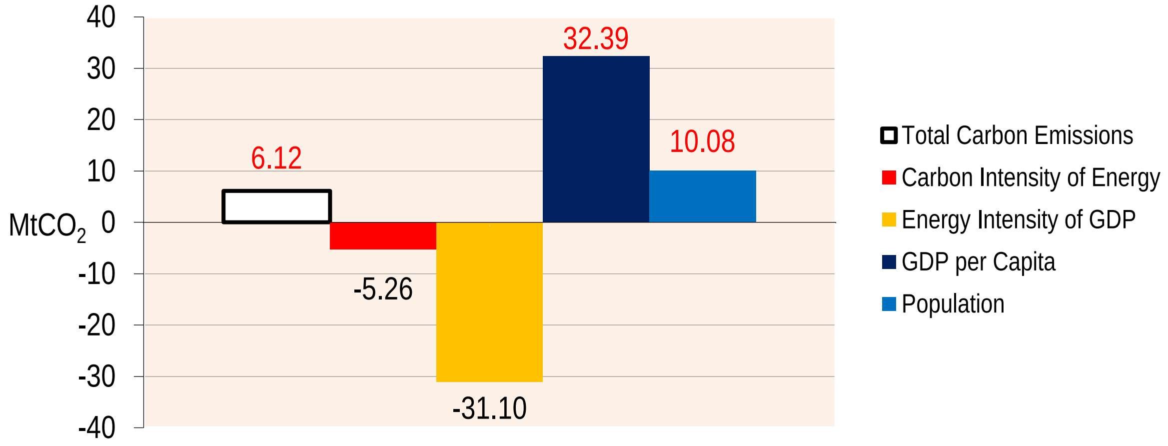
[6] The constant or 'real' GDP data is chain-linked and referenced to 2015 as the common year for prices. Current data is not adjusted for inflation and is in the prices of the year in which it was measured

[7] 'FISIM' is an estimated service charge in respect of non-invoiced services in the case of banks and similar businesses. It was included in the new EU standard framework ESA 2010, but excluded from the previous framework ESA 1995 that was used to calculate data from 1970 to 1995. In CSO data, 1995 has been calculated using both approaches, but from 1996 onwards only the ESA 2010 framework is applied. Pre and post 1995 data is consequently not entirely compatible.

[8] These indicators were not originally designed for the purposes of measuring human welfare or wellbeing and are a gross tally of everything produced good and bad. They obscure equality and the disparity in income and welfare, the cost of pollution damage is calculated as positive, there is a failure to account for the lost value from depleted natural resources or the unpaid costs of environmental harm, and the non-formal economy is excluded. A short review of these limitations is provided in O'Mahony (2013).

Figure 5 Kaya identity decomposition analysis of Ireland's carbon emissions from 1995 to 2016 by real GDP



As discussed in section 1, it is known that GDP presents a distorted picture of growth in the Irish economy. In order to give an alternative representation of the change in income per capita Figure 6 presents the decomposition analysis from 1995 to 2016 using the modified GNI*. As the GNI* data is current rather than real it does not strip out the effect of prices. Figure 7 presents the decomposition analysis from 1995 to 2016 using current GDP data as a comparator. Both Figures show greatly increased effects of income per capita (real GDP 32.39, nominal GNI* 38.62 and nominal GDP 49.20) and higher improvements in energy intensity (real GDP -31.10, nominal GNI* -37.33 and nominal GDP -47.91). This shows that the effects of moving to real data are significant (nominal GDP data shows a 51.90% higher increase in GDP per capita) but also that nominal GNI* has a far lower impact (19.23% higher increase in GNI* per capita). It allows a removal of some of the anomalously high effect of income per capita and energy per unit income. However, firmer conclusions can be drawn by comparing real GDP with real GNI* once both data sets are available from the CSO.

Figure 6 Kaya identity decomposition analysis of Ireland's carbon emissions from 1995 to 2016 by current GNI*

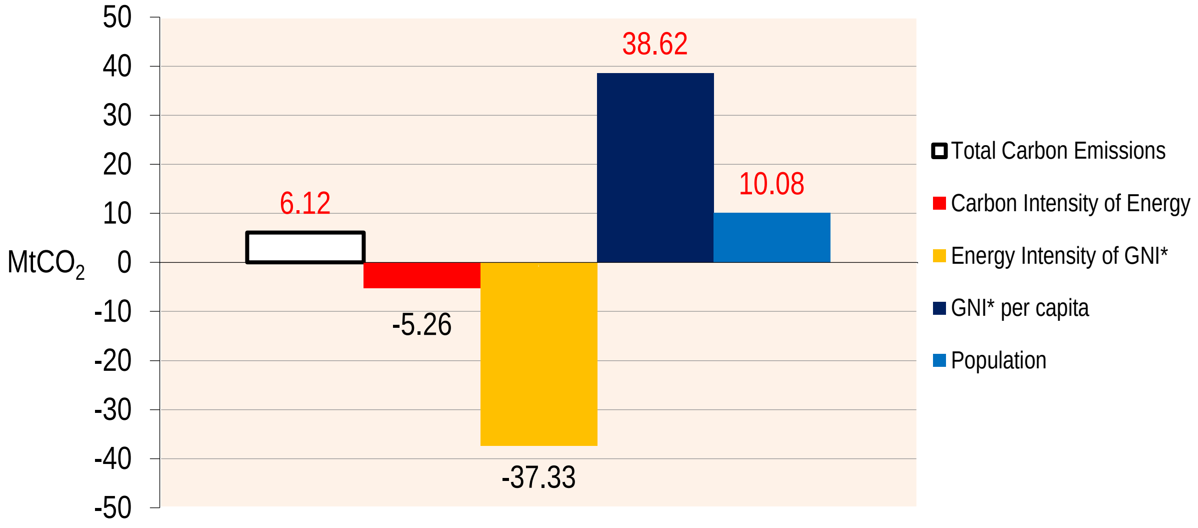
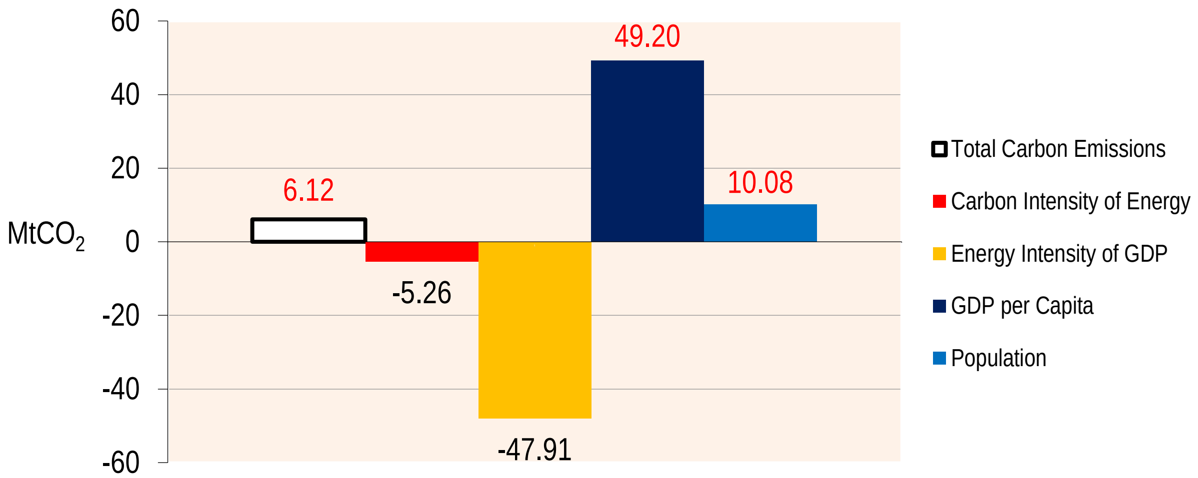
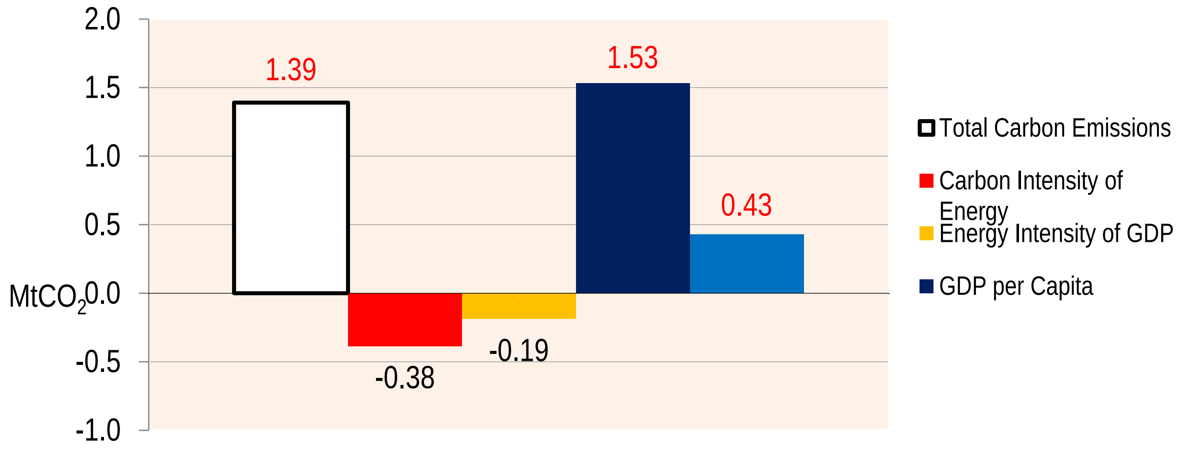


Figure 7 Kaya identity decomposition analysis of Ireland's carbon emissions from 1995 to 2016 by current GDP



The change in the most recent year of the analysis, 2016, is presented in Figure 8. This shows a small improvement in the carbon intensity of energy (-0.38 MtCO$_2$), which is double the greatly reduced improvement in energy intensity energy (-0.19 MtCO$_2$). Substituting real GNI* for real GDP may show that there the economy became more energy intense in 2016. Continuing robust growth in GDP per capita energy (1.53 MtCO$_2$) and in population (0.43 MtCO$_2$), led to a 1.39 MtCO$_2$ or 3.6% increase in emissions on 2016. This illustrates that trends vary from year to year. It suggests that deeper analysis and interpretation of the annual results will provide further insights into the trends in driving forces, and potentially also the relationships between them.

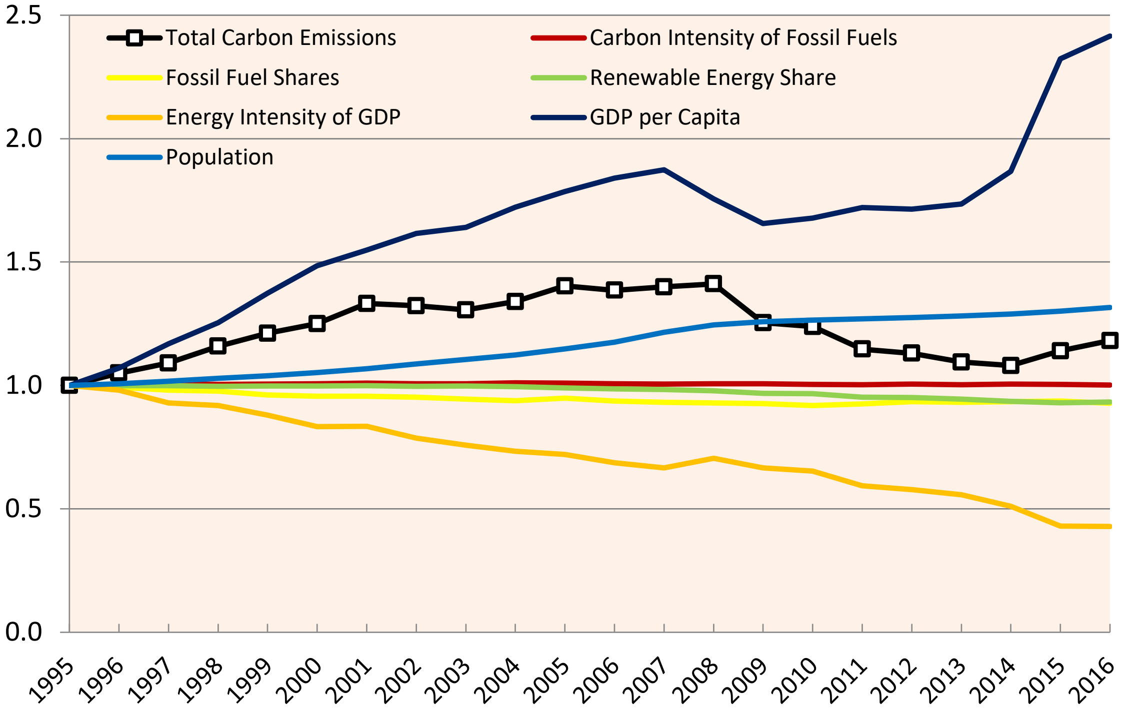
Figure 8 Kaya identity decomposition analysis of Ireland's carbon emissions from 2015 to 2016 by real GDP



3.2 The extended Kaya identity decomposition analysis

The analysis from the beginning to end year through the Kaya identity was presented in section 3.1, along with illustration of the effect of utilising GNI* data. Section 3.2 returns to analysis by real GDP (to remove the effects of inflation) and presents the more detailed results in the extended Kaya identity by the annual time series of change from year to year. Figure 9 presents the accumulated annual time series from 1995 to 2016. It is presented as change multiplicative index change as is common with time series decomposition.

Figure 9 Extended Kaya identity decomposition analysis by index change from 2015 to 2016 for real GDP



These results can summarised as follows:

1. The scale effect of GDP per capita (navy line) is the dominant driving force of growth in carbon emissions. Population is also a major driver of growth (blue line), but it is a fraction of that driven by per capita GDP.
2. The intensity effect (orange line), reducing the intensity of energy per unit economic output, is the most significant factor acting to limit growth in carbon emissions.
3. Changes in the shares of fossil fuels (yellow line) and in renewable energy penetration (green line) both contribute to limiting growth in emissions, albeit with relatively minor impact. The change in the carbon intensity of fossil fuels (dark red line) is negligible.
4. The accumulated drivers that act to reduce emissions are more than offset by drivers acting to increase emissions, leading to a continuing increase in total energy-related carbon emissions (black marked line).

5. The analysis illustrates four distinct periods in development trends a.) the economic boom period 1995-2001 with a rapid increase in emissions, b.) 2002-2008 period of moderated growth where emissions increase but at a slow rate, c.) a large drop in emissions during the economic recession from 2009 to 2014 and d.) from 2015-2016 emissions resume a high upward trend similar to the boom period of the 1990's.

4.0 Interpretation and discussion

4.1 Discussion of results by driving force

In order to form conclusions about the evolution of the driving forces of energy-related carbon emissions in Ireland it is useful to consider the driving forces separately, in terms of what underlies observed change in each driving force.

4.1.1 GDP per capita

Kaya identity results internationally typically show the importance of economic growth in driving up energy-related carbon emissions (Fernández González et al., 2014). The pattern observed for GHG emissions in general, is that as income per capita grows, so material consumption and emissions increase (Fleurbaey et al., 2014), this also holds for energy and carbon emissions in Ireland (O'Mahony, 2013). A simplified understanding of the underlying mechanisms is that increased GDP per capita drives growth in demand for final energy and for goods and services, and growth in economic production to meet rising demand. GDP per capita grew significantly in Ireland over the historical period, by 217.99 per cent, with factors behind this growth variously attributed (O'Mahony, 2010)[9]. Output growth occurred in all sectors of the economy when viewed by Gross Value Added (CSO, 2017a), driven primarily by manufacturing, but also in service sectors such as professional services and information and communication.

Despite the deep economic recession experienced at the end of the last decade, economic growth rates have recovered to rates previously seen during the 'boom years,' accompanied by rising carbon emissions once more. However, much of the economic growth was driven by a 93.87 per cent output growth in manufacturing from 2014 to 2015. This anomalous increase in output was more related to the repatriation of profits earned in other territories rather than actual output increases in Ireland. In order posit the impact of this effect on the decomposition, additional analyses using modified GNI* at current prices and GDP at current prices. Although caution must be exercised in interpreting these results, as the effects of inflation have not been removed[10], a substantial reduction in the impact of economic growth on emissions is observed. The net effect of growth in output per capita is therefore likely lower than appears from analysis using real GDP data. However, the actual impact of a growing economy on emissions is neither linear nor inevitable. Different relationships are possible and this depends on the unfolding of the other driving forces of carbon emissions.

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[9] The original conditions leading to growth in Ireland's economy have been variously attributed by scholars such as Čech and Macdonald (2004) and Fitzgerald *et al*. (2008). Credit has been primarily given to: state-driven economic development; social partnership arrangements; increased labour force participation of women; decades of investment in domestic higher education; targeting of foreign direct investment (FDI); a low corporation tax rate; an English-speaking workforce; and crucial EU membership which provided transfer payments and export access to the Single Market.

[10] The CSO envisage re-calculating the GNI* dataset in constant real prices in the second half of 2018.

4.1.2 Population

Ireland has also experienced a significant growth in population of 31.61% between 1995 and 2016. Net migration (immigration minus emigration) reached a peak in 2007 at 104.8 thousand (CSO, 2017b). Evidence suggests, that in response to labour demand and skills shortages, labour migration has dominated European migration for decades (Zaiceva and Zimmermann, 2008). During the recent recession, immigration tailed off in parallel to an increase in emigration leading to a net loss in population from 2009 to 2014. This has been followed by a return to positive net migration in 2015. The natural increase in the population (births – deaths) remains relatively high in Ireland, and the rate of natural increase has outstripped immigration in every year since 2009.

Population growth can act to increase energy requirement and carbon emissions, as a scale growth in energy demand. However, decades of decomposition analysis studies have shown that population growth is not the key factor in economically advanced countries (Raupach et al., 2007; Fernández González et al., 2014; EEA, 2017). The effect of economic growth on carbon emissions is often a multiple of population, a result borne out in the results for Ireland. An unequivocal conclusion on the primacy of affluence in driving global GHG emissions was provided in the IPCC fifth assessment report, attributing growth in emissions to the global spread of high-consumption lifestyles (Fleurbaey et al., 2014)[11]. Relating the outcomes of growth in GDP per capita and in population, to actual emissions outcomes, can be further explained by considering the carbon intensity of energy and the energy intensity of GDP.

4.1.3 The carbon intensity of energy

The extended Kaya identity decomposition analysis in this study attributes change in the carbon intensity of energy to three factors, the emissions intensity of fossil fuels, the fuel shares or fossil fuels and the share of renewable energy in total primary energy requirement. The emissions intensity of fossil fuels is attributable to fuel quality and abatement technologies. The effect has been negligible in Ireland in comparison to the other driving forces. With a 6.12 $MtCO_2$ total increase in emissions this effect accounted for 0.06 $MtCO_2$. The fossil fuel share effect (-2.78 $MtCO_2$) and the renewable energy penetration (-2.54 $MtCO_2$) are far more significant in limiting emissions. The substitution of the more carbon-intensive fossil fuels of peat and coal for oil and gas acts to reduce carbon intensity of energy through the fossil fuel share effect. This is a technological change on the energy supply side, where electricity generation moves to natural gas, and on the energy demand-side where consumers move away from solid fuel space and water heating to oil and gas.

Fossil shares previously dominated the reduction in the carbon intensity of energy (O'Mahony, 2013). Renewable energy has increased dramatically in recent years, by 649.02 per cent between 1995 and 2016, although this occurred from a very low base in the 1990's. It is primarily driven by wind, biomass and biofuels[12]. The growth in renewable energy is now offsetting a similar magnitude of carbon emissions as the substitution of fossil fuel shares. While both of these factors are acting to limit emissions through avoiding a commensurate requirement for fossil fuels, they remain relatively minor in comparison to the magnitude of the other effects.

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[11] Where increased wealth coincides with lifestyles and structural factors that direct the achievement of human wellbeing through increased consumption.

[12] With small but growing contributions from geothermal, landfill gas, biogas and solar. A larger albeit declining contribution from hydro has been existence in Ireland since the Ardnacrusha hydroelectric scheme was opened on the River Shannon in 1929.

4.1.4 The energy intensity of GDP

While a key factor is economic growth, this factor must be understood in context. It is the type of growth and its relationship to energy and emissions that ultimately determines the outcome. This can be explained by considering the energy intensity of GDP and the carbon intensity of energy. The energy intensity of GDP is typically recorded as the largest effect acting to limit growth in emissions (Fernández González et al., 2014). Rosa and Dietz (2012) note that the 'declining-impact hypothesis' has been the subject of far more empirical testing than any other hypothesis about drivers, through the inverted U-pattern posited by the Environmental Kuznets Curve (EKC).

Energy intensity tends to improve more steeply with higher rates of economic growth, and can indicate normal market processes rather than mitigation policy. In the context of economic growth, decoupling of energy intensity (sometimes termed delinking), can be described in two categories; relative ('weak') decoupling and absolute ('strong') decoupling. A weak decoupling occurs where the energy required per unit output is reduced. Following weal decoupling if the economy grows energy consumption will continue grow, albeit more slowly. An absolute decoupling occurs where the energy requirement itself is reduced. The pattern in Ireland's energy intensity per GDP is an example of 'weak' decoupling and may be largely a spontaneous occurrence due to normal market processes[13]. While energy intensity has improved, it has lagged behind the increase in economic growth. Total Primary Energy Requirement declined during the recession but is now climbing once more.

Caution is required in using 'economic energy intensity' as an indicator of national development. As discussed in O'Mahony (2013)[14], while primary energy requirement includes all energy that is consumed by activities in a country, GDP only accounts for 'activity' in the form of economic output[15]. Consequently, 'non-economic' energy consuming activities in the transport and residential sectors may skew results. Nevertheless, energy per unit GDP is often regarded as a useful indicator of national progress as envisaged by the Kaya identity (Kaya, 1990). Trends in the economic, transport and residential sectors can aid interpretation, particularly when the latter two are measured by physical indicators that are more suitable than economic output[16]. Sectoral analysis can give deeper insight into which sectors are increasing or reducing emissions, and whether the changes are due to change scale growth in activity, change in structure[17] or through the improvements in technical efficiency and behaviour that are measured by intensity.

Decomposition analysis of sectoral driving forces have shown that energy intensity improvement before the recession was high in Irish industry (Diakoulaki and Mandaraka, 2007; O' Mahony et al., 2012), largely attributable to structural change rather than technical efficiency (Cahill and Ó Gallachóir, 2009). However, energy intensity in commercial services, public services and agriculture either weakly improved or dis-improved (O'Mahony et al., 2012). O'Mahony et al. (2012) also

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[13] A 2011 study by the United Nations Environment Programme found that a relative dematerialisation of the global economy (namely the use of fewer material resources per unit of GDP) has occurred 'spontaneously' but that "much more is needed if society is to be sustainable over the longer run, as resources come under more pressure with population growth and increasing GDP" (UNEP, 2011: 73).

[14] Energy intensity is described as "Change in energy requirement per unit GDP due to the structure and efficiency of the economy and energy system, technological choices and socioeconomic behaviour and lifestyle" (O'Mahony, 2013: 576).

[15] It is also well-established that GDP is a poor indicator of human wellbeing (Stiglitz et al., 2009).

[16] In order to overcome this, the multisectoral decomposition analysis of Ireland in O'Mahony et al., (2012) used non-economic indicators for both the transport and the residential sectors. For transport, passenger kilometres (pkm) and tonne kilometres (tkm) were used, and for the residential sector house numbers were employed.

[17] Between sub-sectors of higher and lower energy intensity such as heavy and light manufacturing.

showed retrograde developments in Irish transport from 1990 to 2007. Increasing transport activity co-occurred with shifts to more intense modes and increased intensity within mode. While the technical potential for efficiency improvement was available, and would lead to lower fuel costs, choices were made towards options with higher costs and increased emissions. Counter to assumptions of economic rationality, this clearly illustrates that other factors are in operation. It is an illustration of rebound effects and the importance of socio-cultural, systemic factors and carbon lock-in.

A comprehensive decomposition analysis of the sectors has not been completed since O'Mahony et al. (2012), leaving a gap in monitoring of sectoral driving forces from 2007 to 2016. However, the SEAI "*Energy in Ireland 1990-2016*" report (SEAI, 2017b) provides some insights. Primary Energy Requirement declined significantly in all sectors during the recession but is now climbing once more in all sectors. The Irish residential sector, while coming from a low efficiency base in the 1990's, is an example of a positive policy achievement, a continuation of a pattern identified up to 2007 (O'Mahony et al., 2012). The residential sector is one of the three largest sectors at a 24.8 per cent share of primary energy in 2016, along with industry (22.4 per cent) and transport (37.4 per cent), and is therefore important in overall trends. Even though total floor areas have increased, thermal and appliance efficiency has improved (SEAI, 2017b). The report also notes the potential impact of reduced household incomes. However, as total floor area has significantly increased this may be a trend that has specifically affected households in poverty, rather than all households. Industry has improved intensity, but much of this is attributable to re-domiciled profits as is shown by GNI* results.[18]

Power generation efficiency has continued to improve up to 2016. This arises due to technological effects, with upgrade of generation to new CCGT and increased wind, hydro and electricity imports. The efficiency trend has been slowed in some years by increases in peat supported by the Public Service Obligation levy, and by variable years for renewables, with weather-related declines for wind and hydro. The SEAI (2017b) report highlighted that while transport emissions dropped during the recession they are now growing once more. For the largest transport sub-sector: road private car, the report emphasises major improvements in fuel efficiency since 2008[19]. However, this has been offset by scale growth in activity through increased vehicle kilometres. Overall, carbon emissions from private cars are now higher than before the recession. Scale growth in activity[20] is therefore overwhelming technical efficiency.

It is clear that technological change has failed to deliver absolute decoupling of energy intensity in Ireland. Weak decoupling is the characteristic long-term pattern since 1990, over the last 26 years for which decomposition analysis results are now available. While economic growth can drive some factors that partially facilitate mitigation, such as capital for technological change, it also tends to drive consumption per capita, which overwhelms efficiency. Rosa and Dietz (2012) offer that while there is some evidence that rising GDP leads to reduction of impacts of emissions of some air and water toxins, evidence shows that greenhouse-gas emissions and other systemic impacts, which are not geographically circumscribed, do not follow the inverted-U pattern. The IPCC have noted the

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[18] SEAI (2017b) acknowledge that in 2015 GDP grew by 26.3 per cent, with much of this attributed to the transfer into Ireland of profits by multinationals. This falsely improves economic energy intensity as it artificially increases GDP without the related energy demand. This will consequently lead to false improvements in energy intensity when measured as energy consumed per unit GDP.

[19] Attributable to the successful introduction of policy measures aimed at improving the CO_2 emissions of new cars, which translated into improved fuel efficiency.

[20] Modal shift towards private car rather than public transport may also be contributing, as was noted in O'Mahony et al. (2012).

general econometric evidence for an EKC is not robust (Blanco et al., 2014), but the concern for Ireland may be more pronounced. Blanco et al. (2014) note that wealthier slower growing economies tend to have slower growing or declining emissions per capita. In the rapidly growing Irish economy emissions per capita have been climbing since 2014[21].

4.2 Implications for low-carbon transition

A national development pathway characterised by the trends in driving forces measured by the Kaya identity in this study: decades of economic and population growth; weak decoupling in energy intensity and limited decarbonisation of energy, is fundamentally at odds with a low-carbon transition. This is further compounded when recognising that development paths of emissions tend to become 'locked-in' (Halsnaes et al., 2007). The IPCC fourth assessment report noted that development paths are self-reinforcing and difficult to escape[22]. Impending emissions targets, the economic costs of purchasing emissions credits to meet target shortfalls, and relatively high agriculture non-CO_2 emissions, will all place further pressure on long-term transition in Ireland. The basic types of decoupling for transition towards sustainable development are presented in the IPCC fifth assessment report (Fleurbaey et al., 2014): the decoupling of material resource consumption (including fossil fuels) and environmental impact (including climate change) from economic growth, and the decoupling of economic growth from human well-being. These decoupling processes can be viewed as policy options for low-carbon transition in Ireland. They are articulated in Box 4.1 as: *decoupling emissions from energy*; *decoupling energy from growth* and *decoupling growth from wellbeing*.

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[21] Emissions per capita grew up to 10.32 ktCO_2 per person in 2008, declined during the recession (5.61 ktCO_2 in 2013), but have been climbing since 2014 (6.01 ktCO_2 in 2016). It is not clear if this growth in emissions per capita is a temporary trend of economic recovery, or a long term trend associated with higher economic growth than other wealthy countries.

[22] In the context of 'path dependency' of emissions, an extensive literature on technological 'path dependency' and 'lock-in phenomena' has been increasingly supported by global emission scenario literature (Halsnaes et al., 2007:150). Lock-in tends to occur to alternatively high or low emissions trajectories rather than central scenarios. Ireland is becoming increasingly locked-in to a high emissions development path.

Box 4.1: Three approaches to a long-term low carbon transition for Ireland

i) Decoupling emissions from energy: deep energy decarbonisation to near zero

In the context of low-carbon transition, substitution of fossil fuel shares is a short term measure that can also cause lock-in. Fossil fuels must ultimately be replaced by carbon-free energy in the form of renewables, nuclear or carbon capture and storage. Renewable energy potential in Ireland is high. It also comes with co-benefits and retains investment nationally. Nevertheless, renewable energy requires capital investment and can have unintended environmental and social impacts. Nuclear energy is subject to a statutory prohibition in Ireland. Carbon Capture and Storage is not yet proven technically and economically feasible at scale. Delay in decarbonisation of energy since the 1990’s necessitates an unprecedented rate and scale of change by 2050. Without decoupling energy from growth and growth from wellbeing, continuing economic and population growth in Ireland will add further to energy requirements. Relying on decarbonisation alone would require exponential rates of growth in renewables.

ii) Decoupling energy from growth: deep and absolute dematerialisation

Dematerialisation of the economy, of both consumption and production, is generally considered crucial for sustainable development including mitigation. This involves structural change in the economy to less material and energy intense forms, deep technical efficiency improvement, but also preventative measures for demand reduction. The IPCC fifth assessment report highlight key systemic themes including geography and spatial patterns, the characteristics of the energy system, production methods, waste management, household size, diet and lifestyle (Fleurbaey et al., 2014). Adopting this approach would require consistently high rates of absolute decoupling through efficiency policies, but also through mainstreaming sustainable development and synergies between ‘climate’ and non-climate policies. Irish mitigation policy has been characterised by a focus on technical efficiency and decarbonisation rather than sustainable development. Sustainable development is difficult to capture in energy and emissions models, and challenging for policy integration, but it is an underlying requirement of transition.

iii) Decoupling economic growth from wellbeing: strategic re-focussing of development towards immaterialisation

Immaterialisation is supported by a fundamental re-direction of national development strategy that prioritises improvements in human wellbeing and environmental enhancement, rather than economic growth. It is conceptually related to established perspectives on re-directing the objectives of development, such as Amartya Sen’s capability approach (Sen, 1985). It has been further articulated in '*prosperity without growth*' (Jackson, 2009), ‘*welfare diagnostics*’ (Jakob and Edenhofer, 2015) and '*sustainable wellbeing*' (O'Mahony and Luukannen, 2017). Degrowth also prioritises human wellbeing and the environment but places an emphasis on an economy in stasis or decline. While degrowth may be an option in some economically advanced countries, or in some sectors, it is criticised by Jakob and Edenhofer (2015) due to the emphasis on growth rather than social progess. These strategic approaches to transition have yet to feature substantially in discussion of policy in Ireland.

It is likely that reaching a sustainable low-carbon transition will require an integrated approach, a balanced mix of the three decoupling approaches detailed in Box 4.1 to decouple; i) emissions from energy, ii) energy from growth and iii) growth from wellbeing. In support of this, the IPCC fifth assessment report (Fleurbaey et al., 2014) acknowledged the importance of holistic *sustainable development pathways* as an integrated economic, social and environmental concept, rather than one which relies on technology and mitigation alone. This was usefully illustrated in Fleurbaey et al. (2014) as 'choosing a pathway' rather than focussing on mitigation (Figure 10). Political economy models that facilitate sustainable development pathways are discussed in Kirby and O'Mahony (2017). In an integrated approach the domain of emissions and mitigation is treated as an integral element of sustainable development, rather than of efficiency and cost-effectiveness alone. The IPCC fourth assessment report described "development first" mitigation as placing emphasis on making development more sustainable, balancing the economic, social and environmental and recognising the potential for conflicts and trade-offs (Sathaye et al., 2007: 695). The option od purchasing of emissions credits to meet targets may be required as part of a bridging approach for Ireland in the coming decade, but should be used with caution. A long-term arrangement to purchase emissions credits comes with economic costs and risks, in addition to implicit ethical concerns. Purchasing emissions credits could also distort the economic and policy signals required for transition.

Figure 10. Three frameworks for thinking about mitigation

Source: Figure 4.1 from IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y.Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schloemer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

4.3 Caveats and limitations

Some of the advantages of using the Kaya identity (Kaya, 1990) are that it provides a holistic ‘macro-picture’ of the national development pathway, and a focus on the driving forces of emissions rather than technology and costs. It allows the monitoring of trends relevant to policy levers and is flexible in application to a variety of indicators, sectors and scales. However, the Kaya identity as a theoretic conception also entails caveats. As noted by the IPCC SRES, the four driving forces in the equation should be considered neither as fundamental driving forces in themselves, nor as generally independent from each other, each play a role in an interconnected system (Nakicenovic et al., 2000). It has even been concluded in prominent discussions that culture, power and values are the conditioning framework or ‘ultimate drivers’ through which the indirect socio-economic drivers such as population, economic and technological drivers produce an environmental impact (Raskin et al., 2005).

There are also conceptual limitations in the construct of TPER energy per GDP. ‘Economic energy intensity’ only measures ‘activity’ from the economically productive sectors in GDP, while TPER measures the energy requirement of all activities, including those outside of economic production. In addition, a general assumption that increased GDP delivers improved human wellbeing is now widely considered as limited (Stiglitz et al., 2009). From an emissions accounting perspective, the Kaya identity is based on territorial accounting as per the UNFCCC. It does not address the considerable additional emissions embedded in trade as in consumption-based accounting.

For caveats specific to Ireland, the Kaya identity does not address the other greenhouse gas emissions, of which emissions from agriculture are particularly important. In Ireland GDP is known to be a limited indicator of economic activity due to distortions. The alternative indicator, that removes distortions, GNI*, is now published by the CSO in current prices and has also been used in this study. However, it is not currently available from the CSO as a time series in constant real prices that excludes the effects of inflation. This is an additional Irish-specific limitation to the economic energy intensity limitations noted above. Finally, a new category of energy and emissions is now counted in SEAI energy balance sheets from 2009 onwards, but has been excluded from the decomposition analysis in this study. This is in the form of municipal waste, healthcare waste and tyre-derived fuel. These fuel types are combusted in waste to energy incinerators and cement kilns but have been excluded from the study as they comprise both renewable and non-renewable portions. These fuels constituted an additional 0.35 per cent of energy-related carbon emissions in 2016.

4.4 Further applications of the Kaya identity and decomposition analysis

Decomposition analysis in general, and the Kaya identity in particular, are both regarded as useful tools to consider the evolution of the driving forces of emission, both for analytical-inquiry and policy-strategic reasons. Decomposition analysis is a highly flexible analytical tool that is now widely applied to analysis of development pathways and transition (Blanco et al., 2014), long-term scenarios of emissions (Nakicenovic et al., 2000) monitoring of national (UNFCCC, 2004) and cross-national mitigation progress (EEA, 2017), renewable energy programmes (O'Mahony and Dufour, 2015) and national and sectoral energy efficiency programmes (Ang et al., 2010).

Further development of Kaya decomposition analysis in Ireland could benefit from applying an IPAT style analysis of all greenhouse gas emissions as per the EEA (2017). It would also be useful exercise to compare the outcomes using modified GNI once data in constant prices becomes available from the CSO, and potentially also alternative economic indicators such as the Index of Sustainable Economic Welfare (ISEW). At the sectoral level, it may be useful to update the multi-sectoral analysis of the energy-consuming sectors in O'Mahony et al. (2012). Decomposition analysis could also be applied to understand the progression of driving forces in priority sectors such as agriculture through GHG emissions from the national herd and proposed long-term 'carbon neutrality' of the sector.

In addition to historical analysis, decomposition is a useful approach to structure thinking on potential future change. It could be used at either national or sectoral level to consider development pathways to 2050, including: forecasting likely outcomes, exploring alternative scenario pathways or backcasting low emissions scenarios that meet long-term transition objectives.

5.0 Conclusion

Ireland's total primary energy requirement and related carbon emissions decreased during the economic recession, but have begun increasing once more in 2015 and 2016. Understanding the driving forces of change is important to monitor progress and consider the policy levers for reduction. The Kaya identity has a prominent international heritage in mitigation and transition studies (Nakicenovic et al., 2000; Blanco et al., 2014; EEA, 2017) and is employed in various tasks for the study of national energy and emissions driving forces (UNFCCC, 2004) including a study of Ireland from 1990 to 2007 (O'Mahony, 2013). Decomposition analysis using the 'divisia index' is usually the preferred approach to applying schemas based on constructs such as the Kaya identity, to study the evolution of national macro and sectoral level studies including energy efficiency (Ang et al., 2010). This study has applied the Kaya identity decomposition analysis to Irish energy-related carbon emissions, updating previous analysis up to 2016 using real GDP in constant prices. Alternative analyses detail results when using modified GNI in current prices, and the comparator of GDP in current prices. This allows the impact of recent increases in redomiciled income to be discerned (using GNI*), and consideration of the inflationary effects in GNI* by comparison with current GDP. An extended Kaya identity is also applied that separates the emissions intensity of fossil fuels into changes in the shares of fossil fuels and in the share of renewable energy.

The results show that GDP per capita is strongly driving carbon emissions, population growth is also a contributor albeit to a lesser extent and energy intensity per GDP is the major factor acting to limit growth in emissions. However, energy intensity has only weakly decoupled and fossil fuel substitution and renewable energy are relatively minor. The results suggest that none of the driving forces are evolving on pathways compatible with low-carbon transition by 2050. A broad set of potential options are articulated for Ireland, based on the decomposition framework presented in the IPCC fifth assessment report (Fleurbaey et al., 2014), including; i) deep energy decarbonisation, ii) deep energy dematerialisation, and, iii) decoupling wellbeing from economic growth. It does not appear plausible that a focus on economic growth coupled with mitigation by technological change will be sufficient (Rosa and Dietz, 2012), particularly in the case of Ireland. International evidence suggests that a balanced mix of all three approaches, in strategic *sustainable development pathways*, will be necessary for a low-carbon transition to be achieved.

The advantages of Kaya identity decomposition are the promotion of the 'big picture' strategic focus on driving forces rather than the narrowed focus on technology and costs. Further research that uses this approach could provide evidence-based policy insights on the current national and sectoral challenges that have emerged. It can also be used to consider the implications of the variety of future pathways, including those that lead to transition and the outcomes of those pathways that continue current trends and dynamics.

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Appendix A The mathematical scheme of the 'divisia index' of decomposition analysis

The detailed mathematical scheme for the application of LMDI I is taken from Ang and Liu (2001) and O'Mahony (2013). The following LMDI I formulae apply to each of the effects;

$$C_{emc}: \exp\left(\sum_i \frac{\left(C_i^T - C_i^0\right)/\left(\ln C_i^T - \ln C_i^0\right)}{\left(C^T - C^0\right)/\left(\ln C^T - \ln C^0\right)} \ln\left(\frac{F_1^T}{F_1^0}\right)\right)$$

$$C_{ffse}: \exp\left(\sum_i \frac{\left(C_i^T - C_i^0\right)/\left(\ln C_i^T - \ln C_i^0\right)}{\left(C^T - C^0\right)/\left(\ln C^T - \ln C^0\right)} \ln\left(\frac{S_1^T}{S_1^0}\right)\right)$$

$$C_{repe}: \exp\left(\sum_i \frac{\left(C_i^T - C_i^0\right)/\left(\ln C_i^T - \ln C_i^0\right)}{\left(C^T - C^0\right)/\left(\ln C^T - \ln C^0\right)} \ln\left(\frac{S_2^T}{S_2^0}\right)\right)$$

$$C_{int}: \exp\left(\sum_i \frac{\left(C_i^T - C_i^0\right)/\left(\ln C_i^T - \ln C_i^0\right)}{\left(C^T - C^0\right)/\left(\ln C^T - \ln C^0\right)} \ln\left(\frac{I^T}{I^0}\right)\right)$$

$$C_{ypc}: \exp\left(\sum_i \frac{\left(C_i^T - C_i^0\right)/\left(\ln C_i^T - \ln C_i^0\right)}{\left(C^T - C^0\right)/\left(\ln C^T - \ln C^0\right)} \ln\left(\frac{G^T}{G^0}\right)\right)$$

$$C_{pop}: \exp\left(\sum_i \frac{\left(C_i^T - C_i^0\right)/\left(\ln C_i^T - \ln C_i^0\right)}{\left(C^T - C^0\right)/\left(\ln C^T - \ln C^0\right)} \ln\left(\frac{P^T}{P^0}\right)\right) \qquad (6)$$

Zero values in the data set are handled in accordance with Ang (2005) proposing the substitution of a small positive constant (e.g. between 10^{-10} and 10^{-20}).

Appendix B.1 Kaya identity decomposition analysis by real GDP: annual index change from 1995 to 2016

Year	Total	Carbon intensity of Energy	Energy intensity of GDP	GDP per capita	Population	Residual
1996	1.0502	0.9926	0.9814	1.0707	1.0069	0.0000
1997	1.0386	0.9946	0.9469	1.0914	1.0105	0.0000
1998	1.0626	0.9899	0.9894	1.0736	1.0106	0.0000
1999	1.0452	0.9873	0.9572	1.0947	1.0104	0.0000
2000	1.0317	0.9945	0.9469	1.0817	1.0128	0.0000
2001	1.0656	1.0051	1.0021	1.0422	1.0152	0.0000
2002	0.9929	0.9914	0.9421	1.0441	1.0182	0.0000
2003	0.9875	0.9930	0.9644	1.0149	1.0160	0.0000
2004	1.0259	0.9946	0.9669	1.0496	1.0164	0.0000
2005	1.0471	1.0051	0.9828	1.0373	1.0219	0.0000
2006	0.9875	0.9817	0.9533	1.0305	1.0240	0.0000
2007	1.0098	0.9901	0.9694	1.0177	1.0338	0.0000
2008	1.0088	0.9918	1.0588	0.9373	1.0250	0.0000
2009	0.8885	0.9859	0.9450	0.9436	1.0108	0.0000
2010	0.9877	0.9894	0.9806	1.0132	1.0047	0.0000
2011	0.9262	0.9904	0.9080	1.0253	1.0044	0.0000
2012	0.9856	1.0110	0.9745	0.9963	1.0041	0.0000
2013	0.9681	0.9882	0.9639	1.0118	1.0046	0.0000
2014	0.9872	0.9948	0.9161	1.0761	1.0067	0.0000
2015	1.0549	0.9962	0.8435	1.2442	1.0091	0.0000
2016	1.0362	0.9902	0.9952	1.0399	1.0110	0.0000
1995-2016	1.1812	0.8666	0.4288	2.4155	1.3160	0.0000

Appendix B.2 Kaya identity decomposition analysis by GNI* in current prices: annual index change from 1995 to 2016

Year	Total	Carbon intensity of Energy	Energy intensity of GNI*	GNI* per capita	Population	Residual
1996	1.0502	0.9926	0.9579	1.0970	1.0069	0.0000
1997	1.0386	0.9946	0.9214	1.1215	1.0105	0.0000
1998	1.0626	0.9899	0.9332	1.1382	1.0106	0.0000
1999	1.0452	0.9873	0.9475	1.1058	1.0104	0.0000
2000	1.0317	0.9945	0.8876	1.1540	1.0128	0.0000
2001	1.0656	1.0051	0.9623	1.0852	1.0152	0.0000
2002	0.9929	0.9914	0.9165	1.0733	1.0182	0.0000
2003	0.9875	0.9930	0.9047	1.0819	1.0160	0.0000
2004	1.0259	0.9946	0.9618	1.0552	1.0164	0.0000
2005	1.0471	1.0051	0.9560	1.0664	1.0219	0.0000
2006	0.9875	0.9817	0.9160	1.0724	1.0240	0.0000
2007	1.0098	0.9901	0.9704	1.0167	1.0338	0.0000
2008	1.0088	0.9918	1.0692	0.9281	1.0250	0.0000
2009	0.8885	0.9859	1.0437	0.8544	1.0108	0.0000
2010	0.9877	0.9894	1.0423	0.9533	1.0047	0.0000
2011	0.9262	0.9904	0.9445	0.9858	1.0044	0.0000
2012	0.9856	1.0110	0.9621	1.0091	1.0041	0.0000
2013	0.9681	0.9882	0.9115	1.0698	1.0046	0.0000
2014	0.9872	0.9948	0.9188	1.0729	1.0067	0.0000
2015	1.0549	0.9962	0.9462	1.1091	1.0091	0.0000
2016	1.0362	0.9902	0.9563	1.0822	1.0110	0.0000
1995-2016	1.1812	0.8666	0.3618	2.8622	1.3160	0.0000

Appendix B.3 Kaya identity decomposition analysis by GDP in current prices: annual index change from 1995 to 2016

Year	Total	Carbon intensity of Energy	Energy intensity of GDP	GDP per capita	Population	Residual
1996	1.0502	0.9926	0.9633	1.0909	1.0069	0.0000
1997	1.0386	0.9946	0.9065	1.1400	1.0105	0.0000
1998	1.0626	0.9899	0.9271	1.1457	1.0106	0.0000
1999	1.0452	0.9873	0.9182	1.1412	1.0104	0.0000
2000	1.0317	0.9945	0.8867	1.1551	1.0128	0.0000
2001	1.0656	1.0051	0.9422	1.1084	1.0152	0.0000
2002	0.9929	0.9914	0.8985	1.0948	1.0182	0.0000
2003	0.9875	0.9930	0.9289	1.0537	1.0160	0.0000
2004	1.0259	0.9946	0.9616	1.0554	1.0164	0.0000
2005	1.0471	1.0051	0.9559	1.0666	1.0219	0.0000
2006	0.9875	0.9817	0.9254	1.0615	1.0240	0.0000
2007	1.0098	0.9901	0.9568	1.0312	1.0338	0.0000
2008	1.0088	0.9918	1.0683	0.9289	1.0250	0.0000
2009	0.8885	0.9859	0.9948	0.8963	1.0108	0.0000
2010	0.9877	0.9894	1.0132	0.9806	1.0047	0.0000
2011	0.9262	0.9904	0.9115	1.0215	1.0044	0.0000
2012	0.9856	1.0110	0.9548	1.0169	1.0041	0.0000
2013	0.9681	0.9882	0.9539	1.0223	1.0046	0.0000
2014	0.9872	0.9948	0.9197	1.0718	1.0067	0.0000
2015	1.0549	0.9962	0.7863	1.3347	1.0091	0.0000
2016	1.0362	0.9902	0.9950	1.0401	1.0110	0.0000
1995-2016	1.1812	0.8666	0.2713	3.8173	1.3160	0.0000

Appendix B.4 Extended Kaya identity decomposition analysis by real GDP: annual index change from 1995 to 2016

Year	Total	Carbon intensity of Energy	Fossil fuel shares	Renewable energy penetration	Energy intensity of GDP	GDP per capita	Population	Residual
1996	1.0502	1.0051	0.9880	0.9996	0.9814	1.0707	1.0069	0.0000
1997	1.0386	1.0021	0.9929	0.9996	0.9469	1.0914	1.0105	0.0000
1998	1.0626	0.9965	0.9964	0.9970	0.9894	1.0736	1.0106	0.0000
1999	1.0452	1.0020	0.9836	1.0018	0.9572	1.0947	1.0104	0.0000
2000	1.0317	1.0007	0.9942	0.9996	0.9469	1.0817	1.0128	0.0000
2001	1.0656	1.0029	1.0011	1.0011	1.0021	1.0422	1.0152	0.0000
2002	0.9929	0.9980	0.9952	0.9981	0.9421	1.0441	1.0182	0.0000
2003	0.9875	0.9990	0.9923	1.0016	0.9644	1.0149	1.0160	0.0000
2004	1.0259	1.0043	0.9930	0.9972	0.9669	1.0496	1.0164	0.0000
2005	1.0471	0.9992	1.0109	0.9951	0.9828	1.0373	1.0219	0.0000
2006	0.9875	0.9973	0.9881	0.9961	0.9533	1.0305	1.0240	0.0000
2007	1.0098	0.9987	0.9946	0.9968	0.9694	1.0177	1.0338	0.0000
2008	1.0088	1.0007	0.9971	0.9941	1.0588	0.9373	1.0250	0.0000
2009	0.8885	0.9997	0.9966	0.9895	0.9450	0.9436	1.0108	0.0000
2010	0.9877	0.9980	0.9916	0.9998	0.9806	1.0132	1.0047	0.0000
2011	0.9262	0.9987	1.0066	0.9852	0.9080	1.0253	1.0044	0.0000
2012	0.9856	1.0020	1.0106	0.9985	0.9745	0.9963	1.0041	0.0000
2013	0.9681	0.9981	0.9969	0.9931	0.9639	1.0118	1.0046	0.0000
2014	0.9872	1.0026	1.0025	0.9897	0.9161	1.0761	1.0067	0.0000
2015	1.0549	0.9986	1.0034	0.9941	0.8435	1.2442	1.0091	0.0000
2016	1.0362	0.9971	0.9894	1.0038	0.9952	1.0399	1.0110	0.0000
1995-2016	1.1812	1.0015	0.9272	0.9333	0.4288	2.4155	1.3160	0.0000