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# The Driving Forces of Change in Energy-Related CO2 Emissions in Ireland: A Multi-Sectoral Decomposition from 1990 to 2007

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# The driving forces of change in energy-related $CO_2$ emissions in Ireland：A multi-sectoral decomposition from 1990 to 2007

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## Abstract

Ireland recorded significant growth in energy-related carbon emissions from 1990 to 2007 as the country underwent rapid economic development. Using the LMDI decomposition analysis method, this paper aims to identify and analyse the driving forces of $CO_2$ emissions in eleven final energy consuming sectors. This multi-sectoral analysis is based on four economic sectors, the residential sector and gives a detailed representation of transport in keeping with UNFCCC recommendations. Scale, structure and intensity effects are explored and substantial heterogeneity in sectoral performance is observed. Scale growth in economic and transport activity was considerable. Some improvements in energy intensity were recorded in the economic sectors. In transport, increases in intensity contributed to a significant increase in emissions, while energy intensity decreased in the residential sector. The declining emissions coefficient of electricity was important in limiting emissions but renewable energy has been slow to penetrate the demand side. The results have relevance in considering development paths and can aid in identifying policy measures required to address the key driving forces of emissions in the sectors. The rapid increase in transport emissions in particular raises concerns of future lock-in to a higher emissions trajectory.

*Keywords*: Decomposition analysis; $CO_2$ emissions; Ireland

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# 1. Introduction

Energy and $CO_2$ emissions are integral to issues of development in all nations and have become a significant policy challenge in the Republic of Ireland. Through the Kyoto Protocol and the European Union (EU) Burden Sharing Agreement (Council Decision 2002/358/EC) the target agreed for Ireland was to limit the increase in greenhouse gas (GHG) emissions to +13% of 1990 levels by 2008 to 2012. This coincided with a period of rapid economic development, during which infrastructure was expanded, lifestyles changed, and energy demand and $CO_2$ emissions increased substantially. In 2007, total GHG emissions in Ireland were 25% higher than the 1990 level (McGettigan *et al.*, 2009). Energy-related $CO_2$ emissions increased by 49.4% and accounted for two thirds of all GHG emissions. Understanding driving forces of $CO_2$ emissions is essential to formulating climate change mitigation policy and the fulfilment of applicable targets. Decomposition analysis of change in emissions provides a robust means of achieving this objective.

At the United Nations Framework Convention on Climate Change (UNFCCC) Dublin Workshop on Fourth National Communications from Annex I Parties (UNFCCC, 2004), Index Decomposition Analysis (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 Divisia Index (LMDI) technique, have been widely applied to track economy-wide energy efficiency trends by different countries/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).

Insight into the driving forces underlying change in $CO_2$ emissions in Irish sectors has been limited to the decomposition analysis of manufacturing. Given the large increase in emissions, particularly from the under-investigated transport sectors, the absence of appropriate inquiry could have consequences for policy. In the In-Depth Review (IDR) of Ireland's third national communication to the UNFCCC, Rolle *et al.* (2005) highlighted this gap in knowledge. The reviewers recommended that changes in GHG emissions of Irish transport be linked to changes in modal split and changes in physical activity by passenger kilometres (p-km) and tonne kilometres (t-km). The objectives of this study were to identify and analyse trends in the historical driving forces of $CO_2$ in all of the energy end-use sectors from 1990-2007. It also forms the first response to these UNFCCC recommendations. The sectors are analysed separately but inter-sectoral shifts in the shares of activity in the economic sectors and the transport modes are also analysed. Rather than develop policy recommendations per se, this study contributes to the discussion of appropriate mitigation measures by engaging with gaps in knowledge of trends and driving forces in the end-use sectors.

The results obtained are not only relevant to Irish policy-making but may provide useful insights for other countries experiencing a development transition. The analysis of the historical progression of key indicators, particularly energy intensity, also functioned as the first step in the development of scenarios of future $CO_2$ emissions in O' Mahony *et al.* (2011). Similar to Wu *et al.* (2005) who analysed driving forces in China, the originality of this study lies in the use of a framework that gives a disaggregated multi-sectoral decomposition. Multi-sectoral decompositions in previous studies often deal with three or four sectors (Diakoulaki *et al.*, 2006; Lise, 2006; Tunç *et al.*, 2009) whereas this study disaggregates eleven final consumption sectors. Whereas the EU-ODEX has been used to track energy efficiency in some sectors

(Dennehy *et al*., 2009), this is the first comprehensive index decomposition analysis of the Republic of Ireland, including of the non-manufacturing economic sectors, the residential sector and of particular importance, the transport modes. While this study decomposes all final consumption sectors, particular focus is accorded to the disaggregation of transport recognising both that it is under-investigated and also its importance in total emissions. This is as opposed to Oh *et al*. (2010) a multi-sectoral decomposition of South Korea, which concentrated on disaggregated manufacturing but aggregated transport. This multi-sectoral analysis may provide deeper insights than the macro level approach recommended by the UNFCCC (2004).

The rest of this paper is organised as follows. Section 2 presents sectoral emissions from 1990-2007 and the classification of the sectors in Ireland that leads to the decomposition scheme. Section 3 introduces our decomposition framework, and Section 4 describes data sources. In Section 5, we present the decomposition analysis results from each sector and an aggregate analysis. Section 6 concludes this study.

## 2. Sectoral $CO_2$ emissions in Ireland

Fig. 1 shows the evolution of the sectoral contribution to total energy $CO_2$ emissions in Ireland from 1990 to 2007. The classification of final energy end-use sectors was established in the Ireland's energy balance sheets communicated to the European Commission and the International Energy Agency. It can be observed from Fig. 1 that there was an increasing trend in the total $CO_2$ emissions and a concentration of growth occurred from 1993-2001. The residential and industry sectors are the major contributors but their shares have declined over time. All transport modes experienced substantial growth in emissions with the exception of rail.[1]

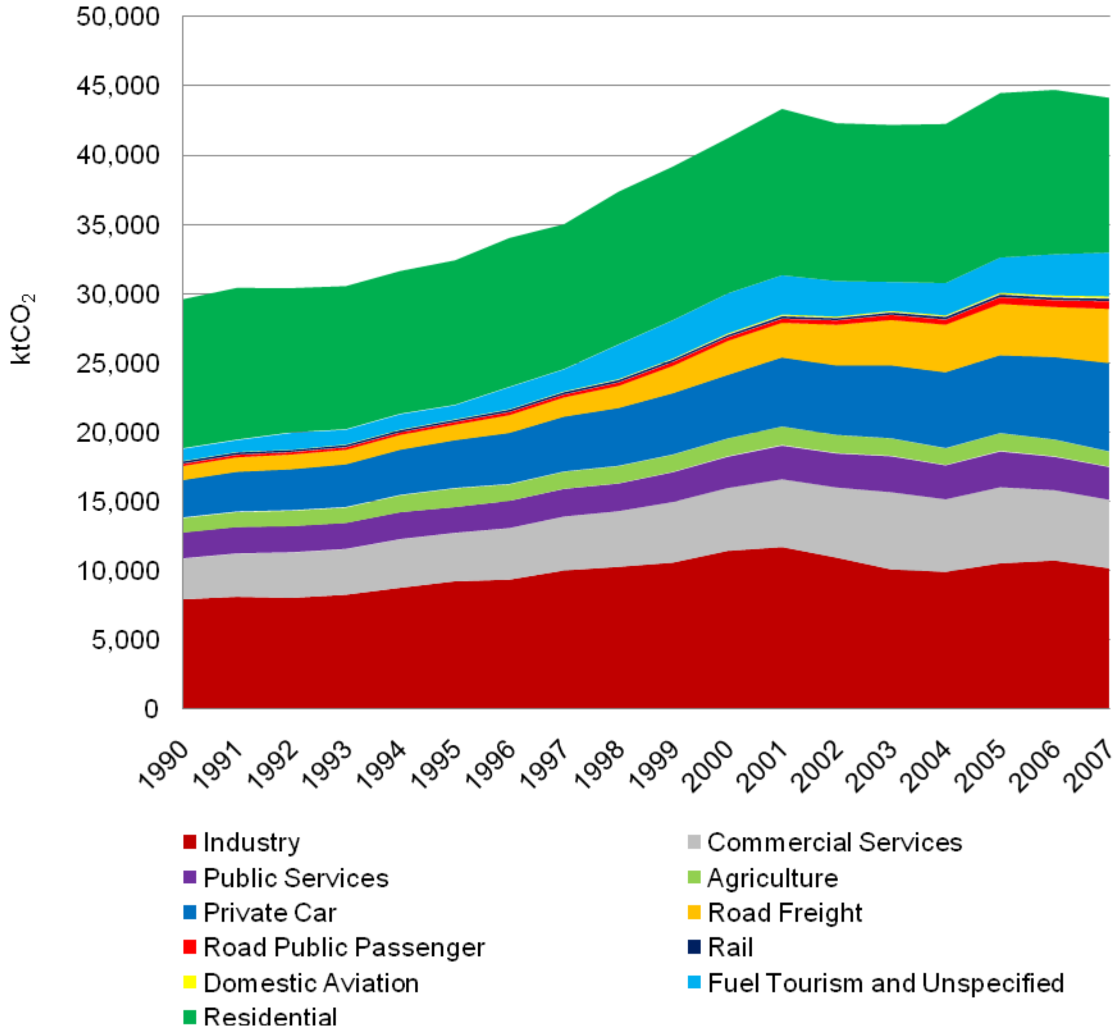


**Fig. 1. Evolution of sectoral composition of energy-related $CO_2$ emissions in Ireland from 1990 to 2007**

The decomposition framework used in this study is based on the sectoral classification previously described. This sectoral disaggregation is similar to that used in Agnolucci *et al.* (2009), Oh *et al.* (2010) and to a lesser degree that of Wu *et al.* (2005). Full coverage of the main final consumption sectors is achieved using data by sector and fuel type. The four economic sectors include; agriculture, industry, commercial services and public services, but does not separate construction as disaggregated was unavailable. Agnolucci *et al.* (2009) split industry into energy intensive/ extensive branches but Gross Value Added (GVA) data in Ireland is not disaggregated along these lines pre-1995.[2] Industry remains aggregated to facilitate a full analysis from 1990 to 2007. Agriculture and public services are given their own characterisation as agriculture is unique in its use of energy and public services are unique in the instruments necessary to reduce $CO_2$ emissions due to state control.

In our analysis, a methodological challenge arises in attempting to understand the increase in emissions from transport since 1990. A response is required to the recommendations of Rolle *et al*. (2005), that changes in emissions be linked to changes in modal split and activity by p-km and t-km. Ang and Zhang (2000) specifically suggested the use of LMDI I to measure the physical efficiency of transport. As discussed by Timilsina and Shreshta (2009) given a lack of data, a common approach in energy literature is to measure modal shift by changes in modal fuel consumption in total transport fuels (EIA, 2007; IEA, 2004). This proxy method assumes the same intensity across the different modes and weakens results. The approach adopted in this study retains the physical measure of modal shift and also intensity. As shown in Fig. 1, transport in the decomposition framework is split into six sub-sectors or modes corresponding to energy and $CO_2$ data. This reflects the considerable modal differences in the provision of transport services while responding to the recommendations of Rolle *et al*. (2005). International aviation and maritime transport are not considered as both are memo items in national inventories and excluded from national totals and quantitative targets (IPCC, 1999). It should be pointed out that a similar limitation to Agnolucci *et al*. (2009) arose in the case of rail since the data on energy use by passenger and freight components cannot be separated. As such, we aggregate the total activities performed by rail passenger transport and rail freight using the approach suggested by Diakoulaki *et al*. (2006). Since the ratio of rail p-km to t-km was not stable, the results of aggregate intensity for rail are interpreted with this in mind. The road public passenger sector is also an aggregation of bus and taxi transport modes. It is worth noting that the approach of Timilsina and Shreshta (2009) aggregates road transport and also aggregates rail transport. The activity of the unspecified and fuel tourism sectors can not be measured. These sectors are aggregated to complete the analysis but effects are not measured.

In keeping with Ekins and Barker (2001) it is recognised that energy demand is more related to energy services (heat, light, power, mobility etc.) than for energy itself per se. This has implications for the drivers that lead to change in energy $CO_2$ emissions, but it is difficult to accommodate given the huge variety of energy services required in each sector. In order to overcome this, energy services are represented by either monetary or physical indicators based on the characteristics of different sectors. Usually, the use of physical indicators is considered to be more accurate but this may only be applicable for particular sectors such as transport (Diakoulaki 2006; Freeman *et al.*, 1997). In the case of the economic sectors, both physical and monetary indicators of output can be used, but both present with potential limitations. Physical indicators can create difficulties in aggregating disparate physical outputs across different products, commodities or service groups, while monetary indicators can mislead due to changes in unit prices. Similar multi-sectoral studies have used monetary indicators of economic output (Wu *et al.*, 2005; Oh *et al.*, 2010; Lise, 2006; Diakoulaki *et al.*, 2006). In this study, using the monetary indicator GVA facilitates a commonality in the method of analysis across the sectors and also the analysis of structural shifts. For the residential sector, the number of households is taken as the activity indicator. Transport activity is represented by mobility rather than vehicle distance as mobility is the primary energy service sought (Ekins and Barker, 2001). Therefore, p-km and t-km are respectively taken as the activity indicators for passenger and freight transport modes.

## 3. Methodology

Index Decomposition Analysis (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 may also provide a basis for forecasting (Ang, 2004a) or scenario analysis of future evolution. The results of this study are used as the basis for scenarios presented in O' Mahony *et al*. (2011).

A range of techniques have been established under the umbrella of IDA, among which the LMDI I technique has been identified as the preferred approach by Ang (2004b). The mathematical properties of the technique suggest its suitability for this study including: perfect decomposition, consistency in aggregation and ability to handle zero values. In the methodological literature (Ang *et al.,* 2004b) recommends the multiplicative and additive LMDI I methods for their theoretical foundation, adaptability, ease of use and ease of result interpretation. LMDI I has both additive and multiplicative forms. In this study, it is applied in multiplicative form chain-linked annually accommodating separate decomposition of the sectors and subsequent aggregation to total change. The basic mathematical formulae for IDA and LMDI I can be found in Ang (2004b) developed from work by Ang and Liu (2001). The work of Ang and Liu (2001) was extended by Wu *et al*. (2005) as a three-level decomposition for China disaggregated by sector and province. In contrast, this study applies a two-level decomposition for Ireland without provincial disaggregation but for a greater number of sectors. The approach used facilitates the elaboration of sector-specific insights. The decomposition schemes applied to each of the sectors are detailed in Eqs. (1), (2) and (3) where index $i$ = 1, 2,…,6 respectively denote coal, oil, peat, gas, renewables and electricity and index $t$ the year from 0 (base year) to $t$ (target year). Eq. 1 is applied to each of the economic sectors for $j$ = 1,2,3,4 denoting industry, commercial services, public services and agriculture:

$$\frac{Cecon_{j,t}}{Cecon_{j,0}} = \sum_{i=1}^{6} \frac{C_{tij}}{FF_{tij}} \frac{FF_{tij}}{FF_{tj}} \frac{FF_{tj}}{E_{tj}} \frac{E_{tj}}{Y_{tj}} \frac{Y_{tj}}{Y_t} Y_t \tag{1}$$

In Eq. (2) applied to each of the transport sectors, $j$ indexes sector, for $j$ = 5,6,…10 for private car transport, road public passenger transport (bus and taxi), road freight transport, rail transport (passenger and freight), domestic aviation and aggregated unspecified and fuel tourism:

$$\frac{Ctrans_{j,t}}{Ctrans_{j,0}} = \sum_{i=1}^{6} \frac{C_{tij}}{FF_{tij}} \frac{FF_{tij}}{FF_{tj}} \frac{FF_{tj}}{E_{tj}} \frac{E_{tj}}{TD_{tj}} \frac{TD_{tj}}{TTD_t} TTD_t \tag{2}$$

Eq. (3) applies to $j$ = 11 the residential sector:

$$\frac{Cres_{j,t}}{Cres_{j,0}} = \sum_{i=1}^{6} \frac{C_{tij}}{FF_{tij}} \frac{FF_{tij}}{FF_{tj}} \frac{FF_{tj}}{E_{tj}} \frac{E_{tj}}{THN_t} THN_t \tag{3}$$

The meanings of the variables in Eqs. (1), (2) and (3) are described in Table 1.

**Table 1 Meaning of each variable in Eqs. (1), (2) and (3)**

| Item | Meaning | Item | Meaning |
|---|---|---|---|
| $C_{tij}$ | $CO_2$ emissions fossil fuel *i* sector *j* year *t* | $Y_t$ | Total economic output year *t* |
| $FF_{tij}$ | Consumption fossil fuel *i* sector *j* year *t* | $TD_{tj}$ | Passenger/ Freight Distance sector *j* year *t* |
| $FF_{tj}$ | Total consumption fossil fuels sector *j* year *t* | $TTD_t$ | Total Transport Distance year *t* |

| | | | |
|---|---|---|---|
| **$E_{tj}$** | Total energy consumption sector *j* year *t* | **$THN_t$** | Total Household Number year *t* |
| **$Y_{tj}$** | Economic output sector *j* year *t* | | |

Assume that $CE_{tij} = C_{tij}/ FF_{tij}$ is the carbon emissions coefficient for fuel *i* in sector *j* for year *t*; $FS_{tij} = FF_{tij}/ FF_{tj}$ is the ratio of fossil fuel *i* to total fossil fuels in sector *j* for year *t*; $RE_{tj} = FF_{tj}/ E_{tj}$ is the share of total fossil fuels in total energy consumption in sector *j* for year *t*; $EIE_{tj} = E_{tj}/ Y_{tj}$ is the energy intensity of economic sector *j* ( *j* = 1,2,3,4) for year *t*; $EIT_{tj} = E_{tj} / TD_{tj}$ is the energy intensity of each transport sector (mode) *j* ( *j* = 5,6,7,8,9,10) for year *t*; $EIR_{tj} = E_{tj}/ HN_{tj}$ is the energy intensity of the residential sector for *j* = 11 for year *t*; $ES_{tj} = Y_{tj}/Y_t$ is the share of economic output in sector *j* (*j* = 1,2,3,4) in total economic output for year *t*; $ET_t = Y_t/Y_0$ is the change in total economic output for year *t*; $TS_{tj} = TD_{tj}/ TTD_t$ is the share of transport distance in sector (mode) *j* in total transport distance (*j* = 5,6,7,8,9,10) for year *t*; $TT_t= TTD_t/ TTD_0$ is the change in total transport distance for year *t*; $HN_t= THN_t/ THN_0$ is the change in the total number of households for year *t*; where 0 is the base year and *t* the target year. Eqs. (1), (2) and (3) can then be rewritten as;

$$\frac{Cecon_{j,t}}{Cecon_{j,0}} = \sum_{i=1}^{6} CE_{tij} FS_{tij} RE_{tj} EIE_{tj} ES_{tj} ET_t \tag{4}$$

$$\frac{Ctrans_{j,t}}{Ctrans_{j,0}} = \sum_{i=1}^{6} CE_{tij} FS_{tij} RE_{tj} EIT_{tj} TS_{tj} TT_t \tag{5}$$

$$\frac{Cres_{j,t}}{Cres_{j,0}} = \sum_{i=1}^{6} CE_{tij} FS_{tij} RE_{tj} EIR_{tj} HN_t \tag{6}$$

The steps required to develop Eqs. (4), (5) and (6) as LMDI I are detailed in Ang and Liu (2001). The detailed decomposition formulae applied in this study are presented in the Appendix. These give the determinant effects in each of the sectors described in Table 2 along with the nomenclature used for results. These effects can be categorised into three groups: the intensity effects $C_{\mathrm{emc}}$, $C_{\mathrm{inte}}$, $C_{\mathrm{intt}}$ and $C_{\mathrm{intr}}$, the structure effects $C_{\mathrm{ffse}}$, $C_{\mathrm{repe}}$, $C_{\mathrm{es}}$ and, $C_{\mathrm{ts}}$, and the scale effects $C_{\mathrm{et}}$, $C_{\mathrm{tt}}$ and $C_{\mathrm{hn}}$. The $C_{emc}$ is the ratio of $CO_2$ per unit of energy for each fuel type in each sector. It analyses fuel quality and the installation of abatement technologies. As electricity is included as a fuel type in the consuming sectors, this effect also shows the change in the $CO_2$ coefficient of electricity due to fuel switching and renewables in power generation. The $C_{inte}$ $C_{intt}$ $C_{intr}$ effects measure the change in $CO_2$ from the change in the intensity of energy use in each sector and can represent the push and pull of both technological efficiency and socio-economic behaviour. They can also subsume intra-sectoral structural changes and energy price effects. In the economic sectors $C_{inte}$ measures change based on the energy consumption per unit of GVA. $C_{intt}$ measures change in $CO_2$ based on the energy consumption per unit of travel activity (p-km and t-km), while $C_{intr}$ measures change through the energy consumption per household unit. $C_{ffse}$ is a structural effect that represents the ratio of each fuel type in total fossil fuels. This effect measures the substitution of fossil fuels within each sector but not in electricity as this is a demand side analysis. $C_{repe}$ shows the penetration of renewable energy into total final consumption under demand side control in each sector and not that in power generation. $C_{es}$ measures the change in the structure of the economy, and $C_{ts}$ measures change in the structure of transport modes. The scale effects $C_{et}$, $C_{tt}$ and $C_{hn}$ measure the changes in $CO_2$ emissions due to the changes in total economic output of the economic sectors, total transport work performed and total number of households respectively. $C_{tot}$ indicates the aggregated change of all effects over time in each sector.

**Table 2 Definition of determinant effects from Eqs. (4), (5) and (6)**

| Item Eq. (4), (5) and (6) | Effect | Definition | Effect type |
|---|---|---|---|
| $\mathbf{CE}_{ij}$ | Cemc | Carbon emissions coefficient effect | Intensity |
| $\mathbf{FS}_{ij}$ | Cffse | Fossil fuel substitution effect | Structure |
| $\mathbf{RE}_{j}$ | Crepe | Renewable energy penetration effect | Structure |
| $\mathbf{EIE}_{j}$ | Cinte | Economic sector intensity effect | Intensity |
| $\mathbf{ES}_{j}$ | Ces | Economic share effect | Structure |
| **ET** | Cet | Economic total effect | Scale |
| $\mathbf{EIT}_{j}$ | Cintt | Transport intensity effect | Intensity |
| $\mathbf{TS}_{j}$ | Cts | Transport share effect | Structure |
| **TT** | Ctt | Transport total effect | Scale |
| $\mathbf{EIR}_{j}$ | Cintr | Residential intensity effect | Intensity |
| **HN** | Chn | Household number effect | Scale |

While each of the sectors have been decomposed annually from 1990-2007, results are presented as three distinct development periods to aid discussion, see Section 5.

## 4. Data

The data on energy, $CO_2$ emissions and activity indicators from 1990-2007 were collected from various sources. For energy, Total Final Consumption (TFC) data reported by sector and fuel type are collected from the energy balance sheets compiled by Sustainable Energy Ireland (SEI, 2008). While the Irish Environmental Protection Agency (EPA) publish a National Inventory Report (NIR) of Irish Greenhouse Gas

(GHG) emissions annually for reporting to the UNFCCC and the EU, the reporting format is not appropriate for this study.[3] Therefore in the case of $CO_2$ emissions, the data used in this study is also taken from SEI energy balance sheets. The EPA dataset treats electricity as a separate sector and does not allocate it to the consuming sectors. For the SEI dataset, the total $CO_2$ emissions from electricity generation, including its transmission and distribution, are allocated to the final consuming sectors in proportion to their final energy consumption. Both datasets use the IPCC sectoral methodology (IPCC, 1997), SEI energy balance sheets and the same national emission factors. In contrast to the top-down approach used by SEI, the EPA used a bottom-up methodology through reporting of individual installations under the Emissions Trading Scheme (ETS). This leads to a slight deviation of reported energy $CO_2$ where the EPA data is 1.49% greater in 2007.

Output in the economic sectors is measured by real growth in GVA in € million (CSO, 2008a). A number of data gaps for the activity of Irish transport were overcome by estimations made in this study. For the transport sectors, to complete a dataset of rail activity including all p-km and t-km, data from CSO (2008b) was completed using additional Dublin tram 'LUAS' passenger data from the Rail Procurement Agency (RPA, 2005). Road freight data in t-km was obtained from CSO (2008b, 2009b). Data on private car p-km is problematic in Ireland and is not currently compiled nationally. While data on v-km has been improved, occupancy assumptions are not available to extend this data to p-km. The revised Irish p-km estimate of the European Commission (DGTREN, 2009) was used but required modification. This data aggregates p-km of private car and 'Small Public Service Vehicles' (SPSV's) or taxis and hackneys and the SPSV p-km data was subtracted from the DGTREN estimate to allow the separate decomposition of private car. Given the importance of private car $CO_2$ in both growth and absolute terms (Fig. 1), this is an important development in the analysis of Irish emissions. For the road public passenger mode, data on p-km is also not available nationally and estimated bus and coach p-km from DGTREN (2009) was combined with an analyst estimate for SPSV.[4] Separate decomposition of bus and SPSV would be desirable, but this approach is necessary as energy/ $CO_2$ data is aggregated. Another data gap for Irish transport activity is domestic aviation p-km. An analyst estimate was produced combining passengers handled data with the national average distance travelled per domestic flight.[5,6] For the residential sector total household numbers from 1990-2007 are derived as the number of private households measured by census and interpolated for intercensal years (Cavanagh, 2009, personal communication). Unspecified and fuel tourism activity have no relevant activity measure. The unspecified category includes data errors and consumption by motorcycles, service vehicles, construction vehicles and domestic water activities. Fuel tourism is a category that accounts for fuel purchased in the Republic of Ireland and consumed in another territory. This includes both petrol and diesel purchased by motorists and hauliers from Northern Ireland arising due to a price differential between the two territories.

To characterise data quality, in keeping with Lyons *et al*. (2008), data on energy and $CO_2$ emissions in Ireland can be assumed of high quality. Data on GVA and household numbers are assumed to be of high quality since they are well reported and well understood. Data for transport activity is of mixed quality given the combination of reported data and estimates inferred to overcome gaps. Data for rail (CSO, 2008b) is reported from annual survey.[7] Data for road freight (CSO, 2008b; CSO, 2009a) is compiled annually by survey and measured for variability. The key issue for private car p-km data from DGTREN (2009) after the removal of SPSV's, is what appears to be a low occupancy assumption adopted by DGTREN reducing from 1.4 in 1990 to 1.25 in

2007.[8] Due to the absence of comparable estimates of p-km, bus and coach and taxi and hackney activity data are difficult to validate. Domestic aviation includes a minor underestimation of p-km from the smaller airports of Kerry, Knock and Galway.[9] Potential limitations are considered in the interpretation of results. Rather than just a discussion of trends, to improve robustness, observed changes and underlying factors are discussed in the context of existing analysis available in the literature. In the case of the energy intensity effects, this study analyses the general trends in each of the eleven sectors and does not attempt a finer disaggregation. A finer disaggregation is theoretically more desirable to further quantify underlying factors in energy intensity change but limits on data availability and quality must be considered (Ang *et al*., 2010). Further development of Irish data sources in response to the limitations highlighted above would benefit the analysis of energy and emissions.

## 5. Results and discussion

We perform decomposition analysis using the LMDI I method and present our decomposition results in this section. For ease of interpretation, the analysis of each sector is presented separately. The results are discussed over the entire analysis period from 1990 to 2007. Despite the annual analysis employed in this study to monitor evolving effects on a yearly basis, three distinctly different development periods emerged. Results have therefore been presented for ease of interpretation as the periods from 1990-1993 before the economic boom in the Republic of Ireland, from 1993-2001 as emissions increased rapidly along with economic development and 2001-2007 as emissions growth moderated.

### *5.1 Economic sectors*

Fig. 2 shows the decomposition results for the industry sector. It can be seen from Fig. 2 that the change in industry $CO_2$ is predominantly explained by growth of the overall economy ($C_{et}$=2.7678). This is attributable to Ireland's pursuit of economic growth through industrial development policy and is illustrated by an increased structural share of industry in the economy ($C_{es}$=1.3378) with particular prominence from 1993-2001. Energy intensity ($C_{inte}$) is the major factor in reducing industry emissions in all sub-periods and over the entire time series (0.4215). Improving energy intensity can be attributed either to technical efficiency or to structural change. A more detailed sub-sectoral disaggregation could provide a better understanding, but this was limited due to the lack of disaggregated data over the full time period. However, previous studies have shown that the significant achievement in energy intensity of Irish industry is more attributable to structural change (Cahill and Ó Gallachoir, 2009; Diakoulaki and Mandaraka, 2007; Dennehy *et al.*, 2009).[10] Development concentrated on high-value, energy extensive branches such as chemicals, petrochemicals and ICT and changes to industrial structure also included the cessation of steel production in 2001 and fertiliser production in 2002. This shift can be linked to national industrial development policy and global economic influences and Diakoulaki and Mandaraka (2007) consider Ireland a pioneer in integrating the sustainability concept into the development strategy. Considering these assertions, we conclude that structural change was the dominant contributor to energy intensity improvement.

Following the increase in earlier years, from 2001-2007 $CO_2$ emissions dropped and the emissions coefficient effect ($C_{emc}$=0.8282) became important. This arose from the decarbonisation of electricity supply, fuel switching and the use of renewables in power generation, and an increase in the ratio of electricity in the industrial fuel mix. Although progress in industry fuel substitution ($C_{ffse}$=0.9938), renewable energy

($C_{repe}$=0.9879) and energy intensity ($C_{inte}$=0.7829) were made, a significant proportion of the achievement in manufacturing industry from 2001-2007 is consequently attributable to power generation.

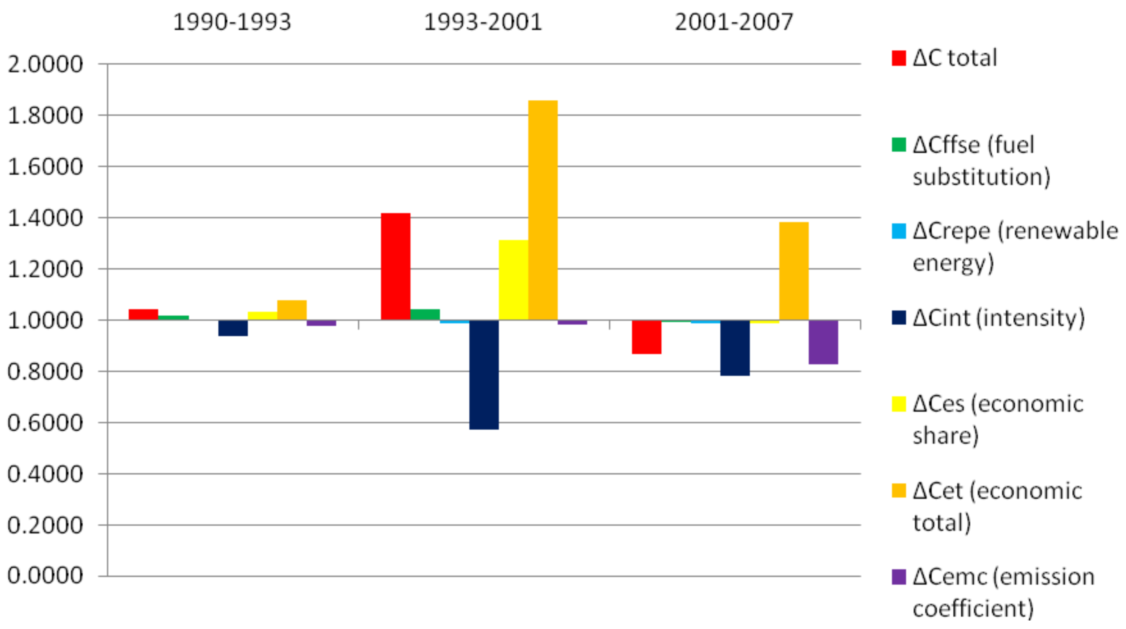


**Fig. 2. Industry decomposition by sub-period**

Fig. 3 presents the results for commercial services where scale growth in the economy also dominated the increase in emissions ($C_{et}$=2.7624) with a significant increase in emissions predominantly from 1993 to 2001 and stabilising from 2001 to 2007. A reduction in the energy intensity of commercial services ($C_{inte}$=0.7203) acted to limit growth in emissions. Despite output growth, the sectoral share of services slightly diminished over the entire period ($C_{es}$=0.9740) and a structural transition to services was not evident. Fossil fuel substitution increased notably ($C_{ffse}$=1.2283), particularly since 1993. Despite a reduction in the effect of oil, there is an increase in the effect of electricity on $CO_2$, as absolute electricity consumption expanded through office use of ICT and air-conditioning, despite reductions in the emissions coefficient of electricity supply in general. Little progress in reducing emissions was achieved through renewable energy in the fuel mix which registered from 2004-2005 onwards.

The effects acting to reduce emissions in commercial services were energy intensity and the emissions coefficient. From 2001-2007, improvements in intensity ($C_{inte}$=0.8530) were exceeded by improvements in the emissions coefficient ($C_{emc}$=0.7603) due to reduction in the carbon intensity of power generation. It is more difficult to form conclusions about the energy intensity of services as energy data is calculated as a residual and information on branches is unavailable[11] (Howley *et al.*, 2008). The sector is the most heterogeneous in the economy, from high value added/ lower energy intensive offices, research and development, to lower value added/ higher energy intensive restaurants, bars and catering. Output growth in services was dominated by office-based branches such as financial intermediation, real estate and business activities and also in retail.[12] The shares of fuel types are also heterogeneous by sub-branch ranging from those with higher space heating requirements consuming a higher proportion of oil and gas to higher electricity consumption correlated with office employees.

This sector along with residential and public services sectors would tend to be the most climate dependent due to space heating requirements but historically this has not been a significant factor. Previous studies have shown climate correction has had a negligible impact on results (O' Leary *et al.*, 2005; Howley *et al.*, 2009) due to Ireland's relatively benign climate.

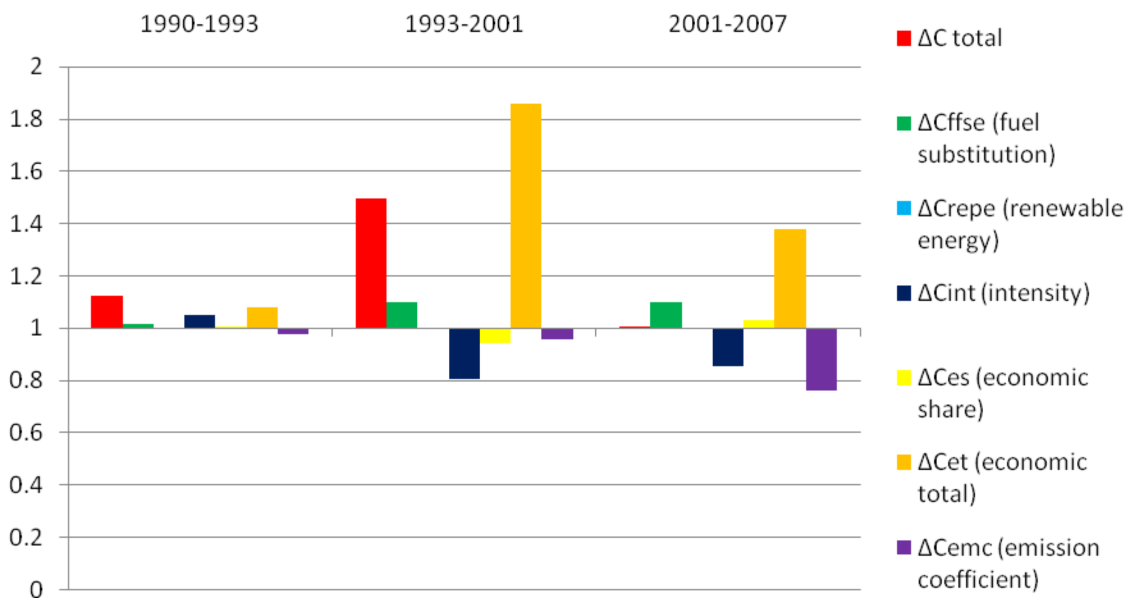


**Fig. 3. Commercial services decomposition by sub-period**

Despite a reduction in the economic share of public services ($C_{es}$=0.4744) scale growth in the economy again dominates in Fig.4. The $C_{ffse}$ effect (1.2629) increased despite declines in oil and peat as gas increased and electricity use increased significantly. Although renewable energy penetration begins to take effect in the 2001-2007 period ($C_{repe}$=0.9961) it has relatively little effect over the entire period. The intensity effect fluctuated annually and is relatively stable over the entire period with no improvement ($C_{inte}$=1.0013). Within public services the dominant negative effects are the loss in economic share occurring since 1990 and the reducing emissions coefficient attributed to electricity.

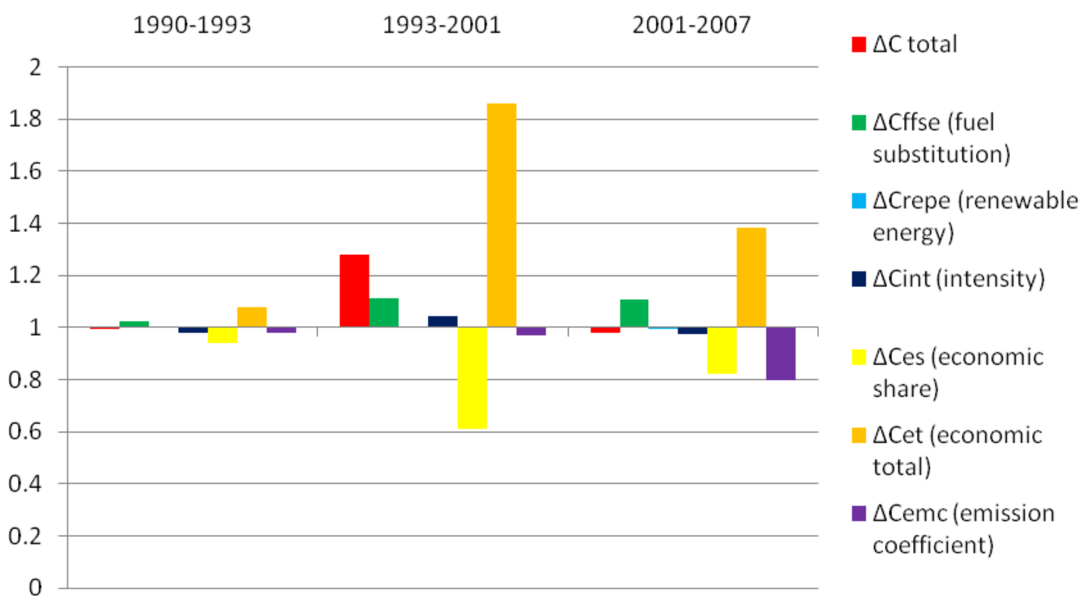


**Fig. 4. Public services decomposition by sub-period**

The agriculture sector in Fig. 5 was also dominated by overall economic growth ($C_{et}$=2.7696) but only marginally increased emissions over the full period ($C_{tot}$=1.0328). Industry and services were the strategic economic development priorities as Ireland further moved away from its agrarian past. Increases in emissions arising in the first two periods were countered by a reduction from 2001-2007 ($C_{tot}$=0.8182). The structural effect of economic share declines in all sub-periods and over the entire period as the other sectors grew. The fuel switching ($C_{ffse}$=1.0238) and renewable energy penetration ($C_{repe}$=0.9995) effects were relatively static. While energy intensity increased over the entire period ($C_{inte}$=1.0496), it reduced emissions from 2001-2007 ($C_{inte}$=0.8621) as growth in output exceeded that of energy consumption. The emissions coefficient effect also reduces emissions ($C_{emc}$=0.8458) but electricity is a smaller component of the fuel mix in agriculture.

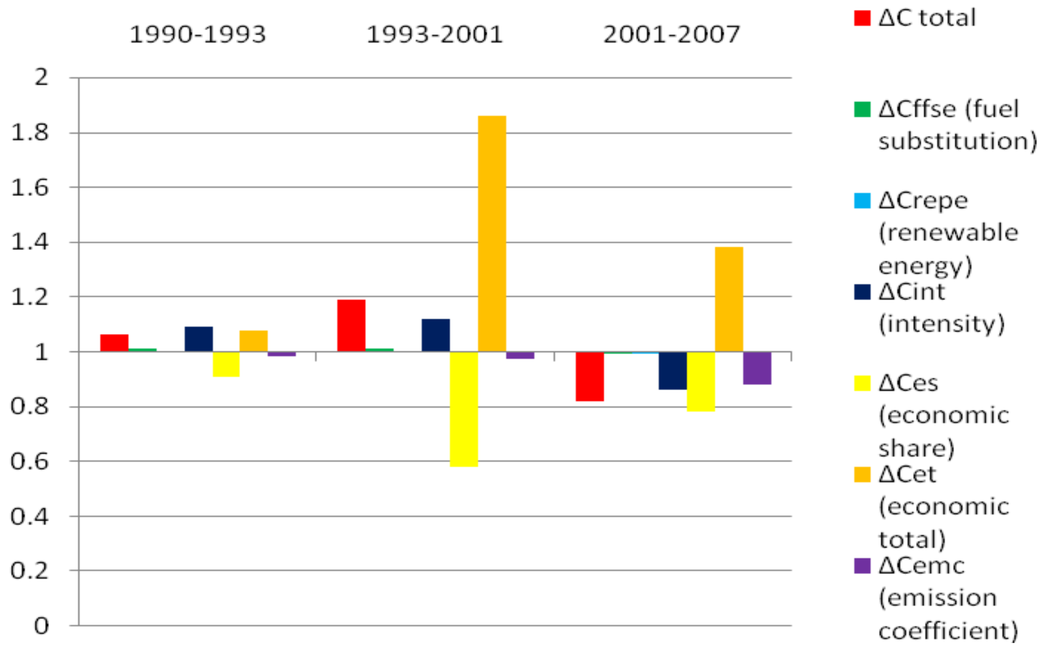


**Fig. 5. Agriculture decomposition by sub-period**

### *5.2 Transport modes*

Over the entire period and in all sub periods, private car presents a significant increase in emissions. It is of significant concern to climate mitigation policy in Ireland due to its share of total emissions and the rate of increase since 1990 (Fig. 1). The dominant driver is the scale effect of overall growth in transport ($C_{tt}$=2.2563). Although its share of total transport declines ($C_{ts}$=0.8795) this may mislead due to the considerable growth in total transport. Expected reduction effects for private car failed to materialise. The energy intensity of private cars increased in all sub-periods and over the entire period ($C_{intt}$=1.1879). While technological progress may be expected to lead to a decrease in intensity, the observed increase per p-km can be attributed to two factors; the occupancy rate of private cars and increasing average engine size. The fall in private car occupancy is the primary reason for increasing intensity.[13] Occupancy rates are not yet comprehensively monitored in Ireland[14] and are assumed in the p-km data of DGTREN (2009). Nevertheless, the occurrence of falling occupancy is consistent with the underlying trends in Ireland; including the rapid growth in car ownership,[15] personal incomes and falling household size. The reducing occupancy is also in agreement with trends observed throughout Europe by the European Environment Agency (EEA, 2003, EEA 2005).[16] In addition to falling occupancy, engine sizes have increased. While energy consumption per v-km would tend theoretically to improve due to technical efficiency, concomitantly the actual purchasing patterns in Ireland tended towards larger engine sizes that offset efficiency gains (Ó Gallachóir *et al*., 2009).[17] Considering this evidence, we conclude that the net effect of reducing occupancy and increasing engine size led to an increase in intensity per p-km.

Private car transport is an energy intensive form of passenger mobility. In Ireland with reducing occupancy and larger engine size it became less defined by efficient mobility and more as a lifestyle choice. However, it is not inevitable that enhanced incomes will lead to these trends and also to increased v-km and motorisation of mobility choices in addition. The manifestation of this consumption pattern in Ireland was aided by cultural development towards individualisation and a range of government policy choices. Dispersed pattern settlement, urban sprawl and the prioritisation of private over public transport in policy and investment[18] contributed both to the increasing requirement for the private car as a modal choice and increased vehicle distances. The impact of biofuels on emissions through renewable energy penetration presented a small reduction from 2004-2007 ($C_{repe}$=0.9902).

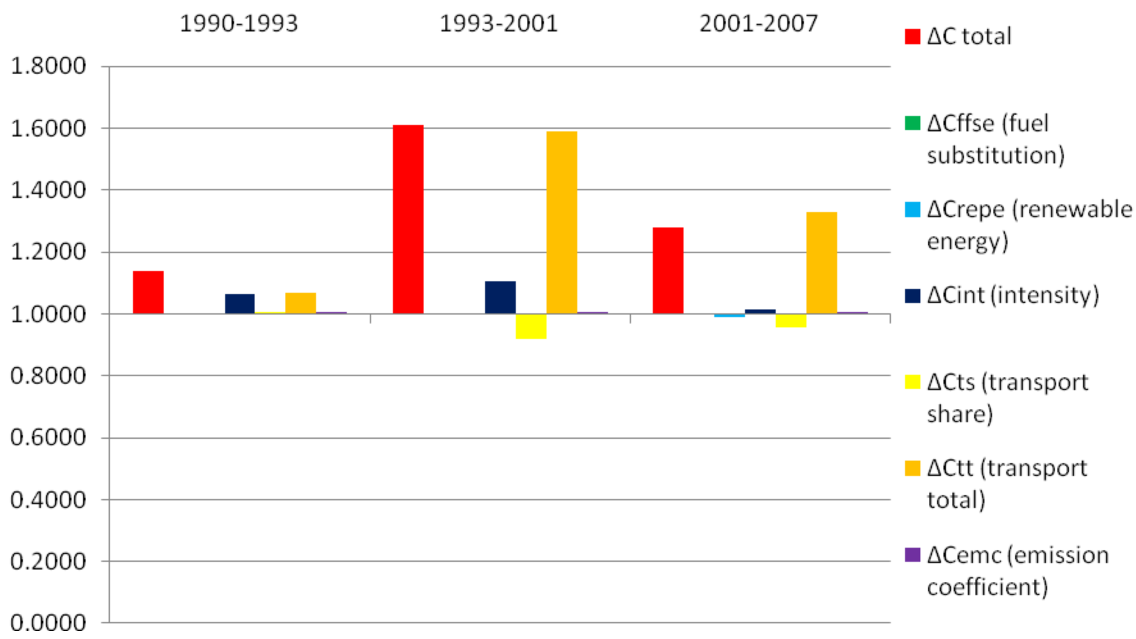


**Fig. 6. Private car decomposition by sub-period**

Road freight increased more than any other sector as industry required increased freight movement due to economic growth. The scale effect ($C_{tt}$=2.2563) was accompanied by an increase in the structural share ($C_{ts}$=1.6162). Increases in freight activity were handled by road rather than rail and in later years a modal shift actually occurred away from rail to road. Road freight share growth was particularly high during the boom years of 1993-2001 ($C_{ts}$=1.5178), but was still increasing from 2001-2007 ($C_{ts}$=1.1445) despite increases in fuel price over the period. Of considerable importance to this pattern is the failure to introduce policies leading to a reduction effect. Neither fuel substitution ($C_{ffse}$=1.0000) nor renewable energy ($C_{repe}$=1.0000) made progress. The energy intensity effect improves marginally from 1993-2001 ($C_{intt}$=0.9842), but over the entire period ($C_{intt}$=1.0538) and in the most recent period from 2001-2007 ($C_{intt}$=1.0231) this indicator increases. The increase in intensity occurred despite a surge in diesel fuel prices by 47.2% from 1997-2007 (CSO, 2008b) and contrary to the decreasing intensity observed internationally including in South Korea and the United Kingdom (Oh *et al.*

2010; Sorrell *et al*. 2009). Previous studies of Ireland based on the ODEX method (Dennehy *et al*., 2009; Howley *et al*., 2007) have recorded a marginal reduction and an increase in energy intensity respectively. This was attributed to the growth in low-value heavy transport for construction as intensity was measured with respect to economic activity. Heavier loads should reduce intensity measured with respect to t-km consequently the increase in intensity is attributable to physical and logistical factors. Studies such as Kamakaté and Schipper (2009) and Leonardi and Baumgartner (2004) identified factors influencing intensity as not only the fuel economy of vehicles but also logistics and driving, load factor, empty running and matching of truck capacity to load.

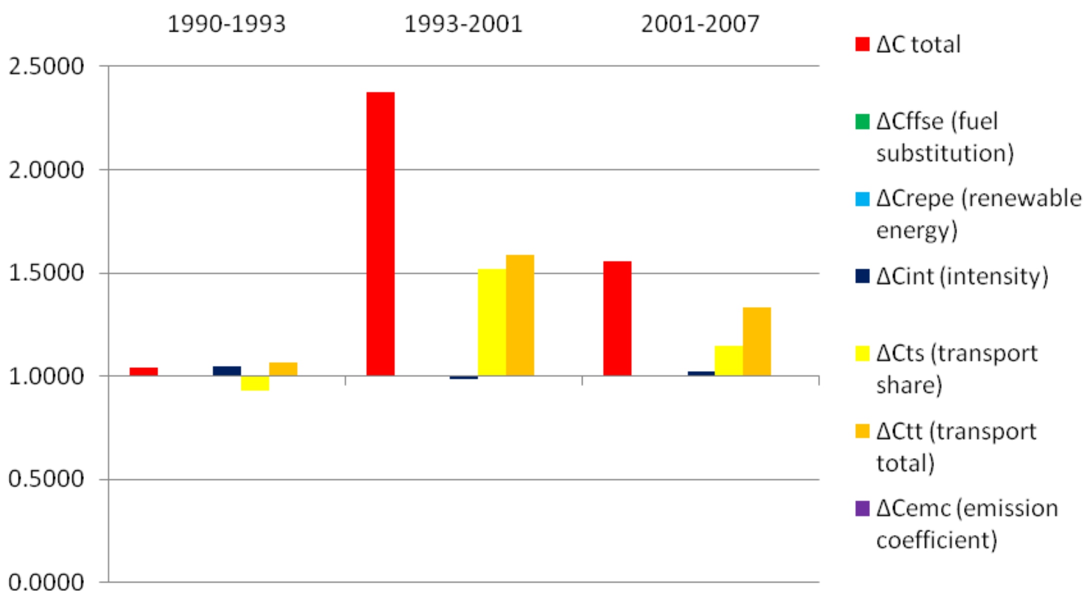


**Fig. 7. Road freight decomposition by sub-period**

Road public passenger emissions also increased significantly over the analysis period. Scale growth was a considerable factor ($C_{tt}$=2.2563) as transport demand increased with affluence. The key result in this mode is the large increase in intensity ($C_{intt}$=1.4613), particularly in the 2001-2007 period ($C_{intt}$=1.4360). Owing to data limitations this category includes not only buses and coaches, but also SPSV's.[19] The number of SPSV's and their use has increased dramatically in Ireland with the liberalisation of taxis and hackneys from 2000 and co-occurred with the increasing intensity from 2001-2007.[20] Bottom-up analysis by Howley *et al*. (2007) shows that fuel consumption of SPSV's has increased significantly since 1990 and consumed more fuel than the bus and coach category by 2003.[21] As p-km completed by SPSV's are more energy intensive than that by bus and coach this led to increasing intensity in this mode.[22,23]

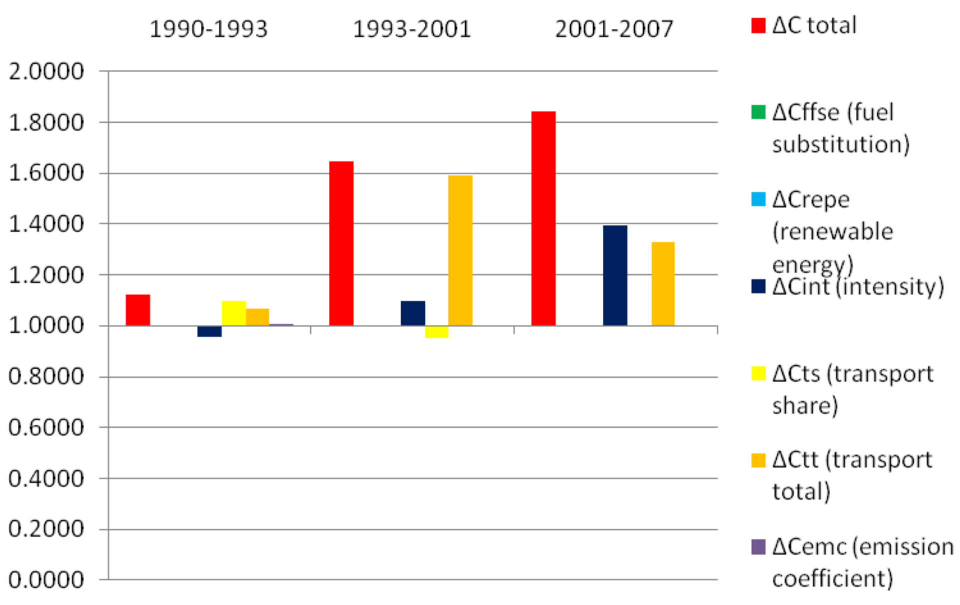


**Fig. 8. Road public passenger decomposition by sub-period**

The growth in rail $CO_2$ over the analysis period ($C_{tot}$=1.1189) was smaller than the other modes and incidentally is within the Ireland's Kyoto benchmark of +13% on 1990. This sector was subject to considerable scale growth in all periods ($C_{tt}$=2.2051). Its structural share declined ($C_{ts}$=0.7721) over the entire period but increased from 2001 to 2007 period as passenger numbers increased and the LUAS electrified tram scheme was commissioned in Dublin. The substitution effect acted to increase $CO_2$ emissions in all periods due to absolute increases in electricity consumption ($C_{ffse}$=1.0980).

Considerable improvement in the energy intensity of rail transport was achieved in the entire period ($C_{intt}$=0.6248) and in all sub-periods. This is mainly due to modernisation of the rail system to upgrade locomotives and the rail network. This modernisation delivered increasing passenger kilometres[24] and improved intensity. It is likely that the opening of the LUAS tram system also contributed to decreasing intensity.[25] The decline in rail freight activity contributes to the decrease in rail intensity but this does not appear to be significant.[26,27] A minor improvement in the emissions coefficient is measured due to electricity ($C_{emc}$=0.9580).

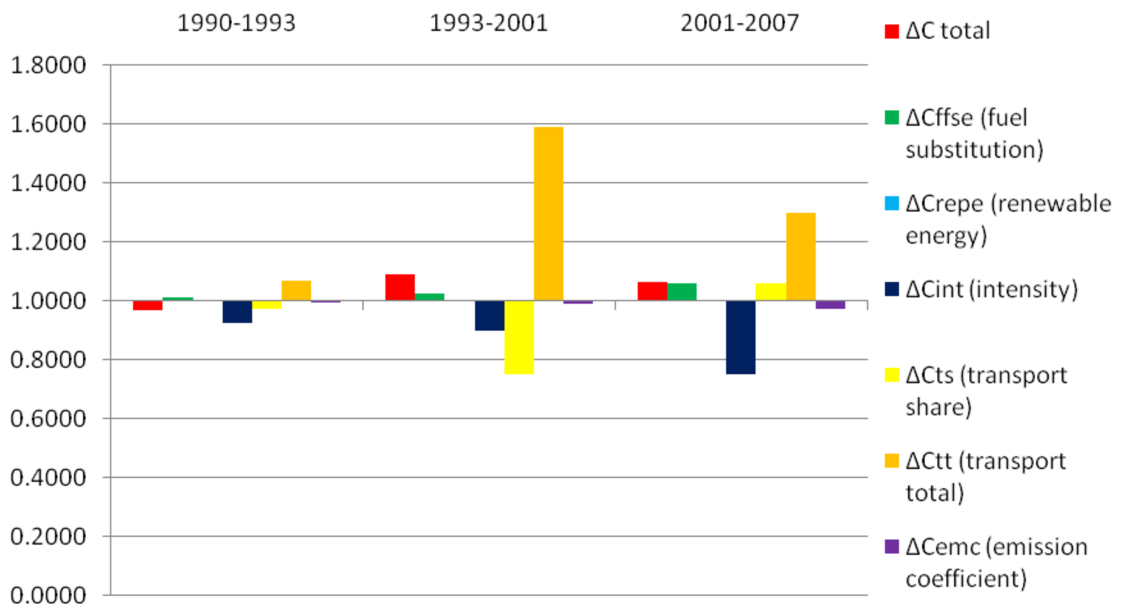


**Fig. 9. Rail decomposition by sub-period**

Considerable growth in $CO_2$ from domestic aviation was recorded with scale growth in activity ($C_{tt}$=2.2563) predominantly responsible. This sector experienced both increasing activity and increasing energy intensity ($C_{intt}$=1.3631). Increasing intensity was considerable from 1990-1993 ($C_{intt}$=1.2745) and slowed from 2001 to 2007 ($C_{intt}$=1.0044). In domestic aviation the growth in aircraft movements exceeded the growth in passengers handled.[28] Improvement in technical efficiency through replacement of aircraft was consequently insufficient to counter the resulting increase in intensity per p-km. Domestic aviation is in receipt of a subsidy in Ireland with the objective of facilitating regional development.[29] The domestic aviation mode accounted for just 1.12% of transport $CO_2$ in 2007 but has a higher energy intensity per p-km and competes with other less energy intense modes. The analysis also excludes the other aviation GHG's and sources of radiative forcing described in IPCC (1999).

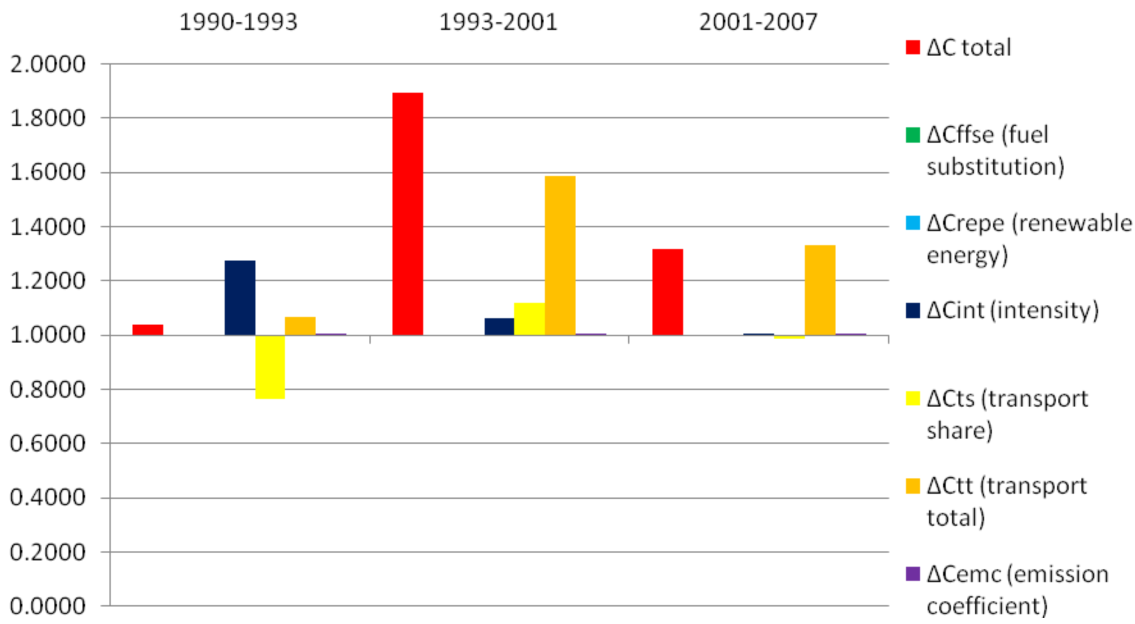


**Fig. 10. Domestic aviation decomposition by sub-period**

The unspecified and fuel tourism categories have been aggregated and included in the decomposition to complete sectoral coverage at the final consumption level but do not have effect measurements as such. Absolute growth of these aggregated categories was considerable ($C_{tot}$=3.6342).

## *5.3 Residential sector*

In the residential sector, progress was made in limiting the increase in $CO_2$. Emissions increased slightly over the entire period ($C_{tot}$=1.0396) but decreased from

1990 to 1993 ($C_{tot}$=0.9607) and from 2001 to 2007 ($C_{tot}$=0.9305) despite a significant increase in house numbers ($C_{hn}$=1.4910). The most significant factor in reducing emissions was energy intensity ($C_{intr}$=0.8658). Energy is consumed in the residential sector for a diverse range of energy services from space and water heating to the use of appliances. Increased affluence contributed to investment in the building stock to improve thermal performance ($C_{int}$) and other forms of technological replacement ($C_{ffse}$) and ($C_{repe}$).

As discussed in DBERR (2007) and Oh *et al.* (2010) energy consumption in households can vary with climate, house size and type, lifestyle, energy prices and energy efficiency. With respect to space heating, energy intensity has improved due to tightening thermal standards[30]; a high proportion of newly built dwellings[31]; changes in heating equipment[32] and increases in heating fuel prices[33]. The impact of change in heating degree days on energy consumption was negligible.[34] Despite these positive trends and the decreasing intensity per household, some negative trends have also arisen. Increased affluence facilitated a preference for larger floor areas in detached houses[35] and also higher residential electricity demand due to increased penetration and use of electrical appliances[36] (Howley *et al.*, 2008; Dennehy *et al.*, 2009), although legislative change has encouraged energy efficiency of domestic appliances.[37]

The emissions coefficient effect ($C_{emc}$=0.8153) reduced in all periods attributable upstream to changes in power generation. The substitution effect reduced emissions ($C_{ffse}$=0.9767) as coal and peat was replaced by oil, gas and electricity. Renewable energy reduced as a share of the fuel mix over the entire period ($C_{repe}$=1.0113), but had begun to reduce emissions again from 2004 onwards.

The improvement in the residential sector as typified by energy intensity should be placed in context. International comparison suggests substantial further mitigation potential to reduce both energy and carbon emissions particularly given Ireland's relatively benign climate. According to O' Leary *et al.* (2008), the average Irish dwelling in 2005 emitted 47% more $CO_2$ than the average UK dwelling and 104% more than the average for the EU-27.

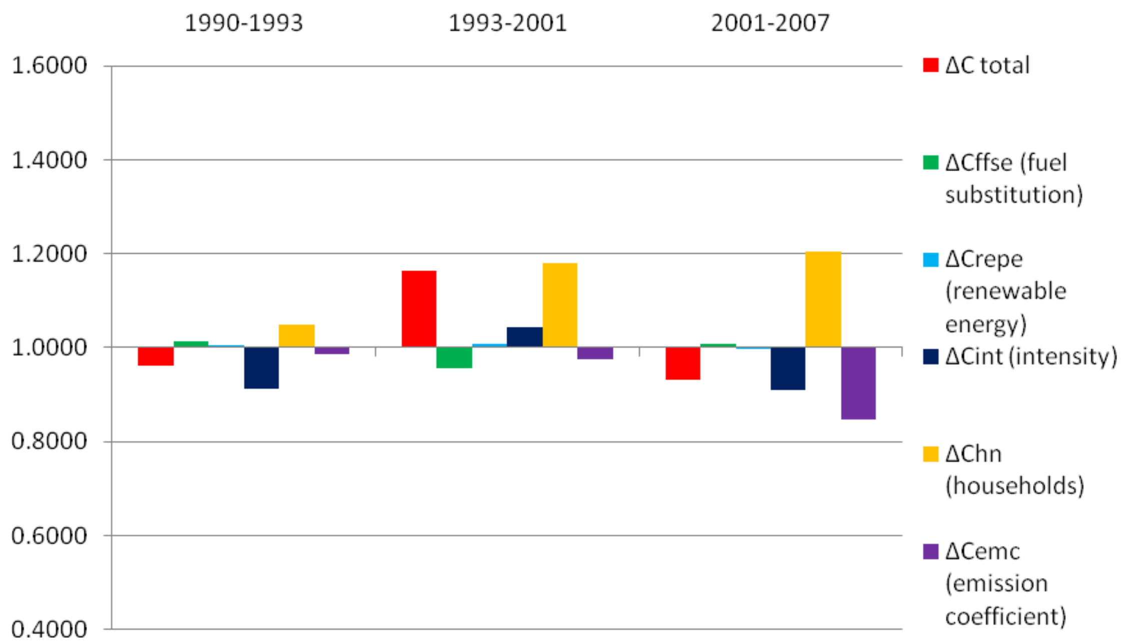


**Fig. 11. Residential decomposition by sub-period**

## *5.4 Synthesis and aggregated change*

For the economic sectors development followed a lower emissions trajectory achieved through development policy to restructure the economy coined as "the Irish way" by Kaivo-Oja and Luukkanen (2004). While emissions did increase, economic restructuring favoured a lower emissions trajectory but technical efficiency appears to have been less successful. Economic growth does not necessarily lead to linear increases in emissions as it can potentially facilitate reducing energy intensity and it is the nature of growth that is critical in determining outcomes. The economy and society relationship with energy and emissions is more complex than a simple linear interpretation can provide and can be elucidated by a multi-sectoral analysis. In the residential sector affluence led to demand increases for energy e.g. appliance use increasing electricity consumption, but also facilitated technological change to reduce energy intensity, deliver fuel substitution and renewable energy penetration through legislative and policy change. In transport, increases in GVA drove higher freight demand and increasing personal affluence drove higher personal mobility demand. Demand evolved towards more energy intensive modes of transport and increased intensity within mode. This illustrates where governance and societal choices evolved towards a weaker pattern of sustainability and resulted in poor "delinking". In the context of sustainability, the economic and societal development that occurs with a growing economy can potentially be directed to delinking emissions from growth through immaterialisation, dematerialisation and decarbonisation (Tapio *et al*., 2007).

The aggregation of transport activity in the $C_{ts}$ and $C_{tt}$ effects of the decomposition framework allowed the consideration of transport as an integrated whole. While aggregation may not be correct from a strictly mathematical point of view due to aggregation of p-km and t-km, it gives two potential advantages in the context of data constraints; i) the use of physical indicators which in general give more robust measures of transport intensity and, ii) proximate insights into modal shift can be identified that may not otherwise have been possible due to the lack of disaggregated energy/ $CO_2$ data for rail. In transport, growth in private car activity has been particularly problematic, as was growth in SPSV's and growth in road freight. The increasing intensity indicated in these modes is a significant concern for policy. Ireland's third In Depth Review (Rolle *et al.*, 2005) noted the importance of limiting growth in emissions from transport and that no single measure could address this problem sufficiently. The various results for intensity illustrate the diversity of the dynamics in the sectors that can not be measured without sectoral disaggregation.

In Fig. 12, aggregated changes in $CO_2$ emissions for the sectors are presented; the $C_{emc}$ $C_{ffse}$ and $C_{repe}$ effects are aggregated across all sectors, the intensity effects $C_{int}$ are aggregated for the economic and transport sectors as $C_{intec}$ and $C_{intt}$ respectively and $C_{intres}$ represents the energy intensity of the residential sector separately. This allows comparison of the relative importance of changes in the driving forces of the sectors to total emissions.

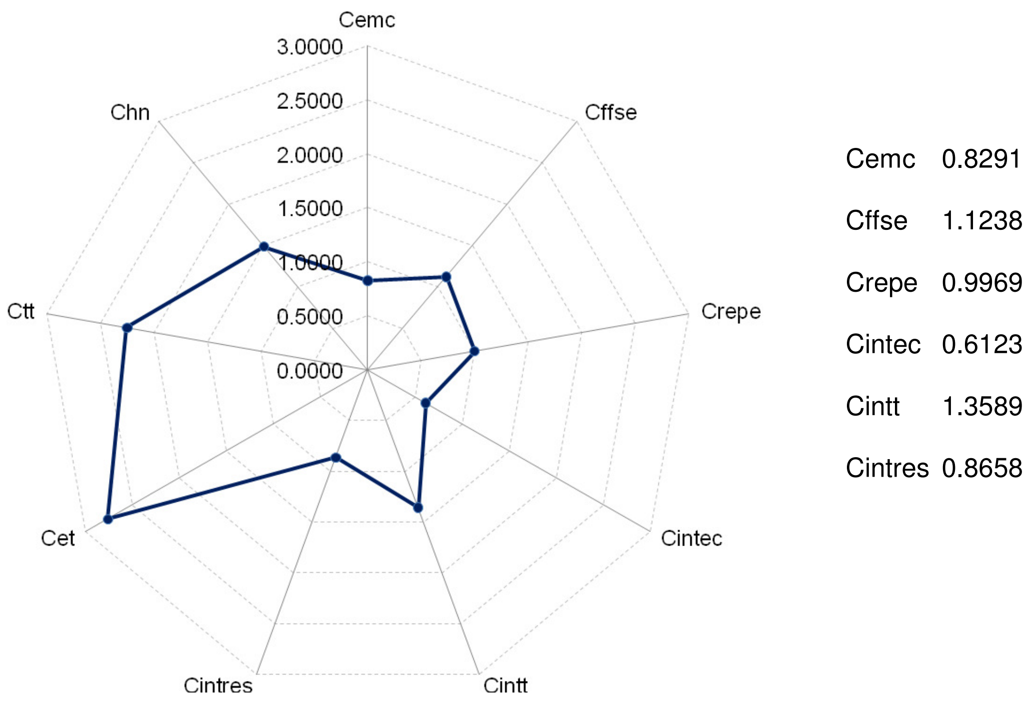


**Fig. 12. Radar of aggregated sectoral decomposition 1990 to 2007**

The $C_{intec}$ effect (0.6123) reflects a substantial decrease in energy intensity of the economic sectors predominantly from economic re-structuring as discussed. The $C_{intt}$ effect (1.3589) illustrates the intensity increase of aggregated transport as a whole and the $C_{intres}$ effect shows the decrease in intensity of the residential sector (0.8658). The scale effects $C_{et}$ (2.7669), $C_{tt}$ (2.2545) and $C_{hn}$ (1.4910) are reflective of not only the magnitude of the impact of economic growth and affluence on the system but of its nature. Production and consumption expanded to increase the size of the economy in $C_{et}$. With $C_{tt}$ transport scale expanded to reflect increased economic demand for freight and increased passenger mobility demand. The increase in $C_{hn}$ is consistent with both growth in affluence and population leading to increasing house numbers. The significance of the economic growth and affluence that evolved is not just in the historical increase in driving forces of carbon emissions that was observed. As short and medium term decisions have long-term consequences (Fisher *et al*., 2007), when a period of economic growth occurs future lock-in to a higher emissions trajectory can result unless the development path is directed into forms that do not increase emissions. Given the pattern of the historic results across the energy system, the 'carbon lock-in' phenomenon[38] (Unruh, 2000; Unruh, 2002) provides some insight into potential future evolution in Ireland and the challenges that national mitigation policy will face. It may also provide lessons for other countries experiencing a development transition.

In general, given the evidence of causation in the transport sectors, confidence can be expressed in the conclusion of increasing intensity of private car, road public passenger, road freight and domestic aviation and also the decreasing intensity of rail. However, further analysis of Irish emissions from the sectors would benefit from development of activity data in the transport sectors and also disaggregation of energy and $CO_2$ data for rail and the road public passenger category.

## 6. Concluding remarks

This paper applied the LMDI I method in a multi-sectoral framework to decompose Ireland's energy-related $CO_2$ emissions from 1990 to 2007. The study is not only the first multi-sectoral decomposition of Ireland, but also the first decomposition of many of its sectors, which may be particularly valuable for the under-investigated transport modes as recommended by the UNFCCC. As a demand-side analysis, the results generated aid the understanding of historical driving forces of sectoral emissions and can consequently contribute to the discourse on mitigation policy. The patterns of sectoral development that emerged through the analysis may also contain lessons for other countries in development transition. Ireland has had a relatively unique recent history given its economic growth path. In addition to monitoring historical progression, the results were necessary for the development of scenarios of future sectoral emissions in O' Mahony *et al.*, (2011). Results have shown three different periods of distinct differences in the national development path while overall a considerable increase in emissions was recorded. As expected, scale growth in the economy played a significant role in the increase in emissions from the economic sectors. This economic driving force may also be related to the increase in emissions from the transport sectors. Greater affluence resulted in expanding mobility requirements but also more energy intensive mobility choices characterised development.

The sectoral results illustrate a diversity of dynamics in driving forces. Scale effects predominate in acting to increase emissions in the economic and transport sectors. Improvements in energy intensity are notable in the economic sectors and in the residential sector. Overall, transport experienced a significant growth in $CO_2$ emissions due not only to scale growth in activity but also crucially due to increasing energy intensity. Despite the moderation of growth in emissions from 2001-2007, due to the pattern of development Ireland may experience significant challenges in overcoming future potential path dependency and the concept of 'carbon lock-in' is increasingly relevant (Unruh, 2000; Unruh, 2002). It is widely acknowledged that long-term emission reductions will depend on development paths[39] in general in addition to energy and mitigation policies (Sathaye *et al*., 2007). While mitigation requires sectoral policies in Ireland, particularly in transport, to prevent increasing long term lock-in to a higher emissions trajectory, the sustainability of the development path in general requires consideration.

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## Endnotes

[1]It should be noted that domestic aviation emissions in this study are solely energy-related $CO_2$ and do not account for the other aviation GHG's or other sources of radiative forcing described in IPCC (1999).

[2] In addition, decomposition analysis of various Irish industry branches has already been completed from 1995 to 2005 using LMDI I (Cahill and Ó Gallachóir, 2009).

[3] Electricity from renewable sources is not included in energy data in the NIR and peat is aggregated with coal as 'solid fuel'. Further limitations are the lack of allocation of electricity to the consuming sectors and electricity from renewable sources is not included in energy data. This renders the NIR unsuitable in the context of this study.

[4] Based on vehicle stock of taxis and hackneys (Department of Transport, 2008), average v-km (CSO, 2009b) and a constant occupancy factor of 2.4. Given the absence of national data, the occupancy factor is an intermediate value from Noble and O' Hara (2001) as a UK proxy.

[5]As the product of the number of passenger journeys multiplied by the theoretical average distance of journeys. 'Passengers handled' by Dublin, Cork and Shannon airports were compiled by DAA (2009) completed with data for previous years from 1990-2003. As this data registers a passenger twice in both departing and arriving location passengers handled was divided by two to arrive at the number of passenger journeys. The theoretical average distance of all domestic aviation journeys is 125 nautical miles (231.5 kilometres), as used by Irish authorities in calculating the NIR.

[6] The passengers handled data also includes journeys to or from the smaller airports in Ireland including Kerry, Knock and Galway. As journeys originating in these airports only register once the division by two results in a minor under-accounting. These airports contributed 9.01% of total passengers handled in 2006 and 12.45% in 2008 suggesting an underestimate of passenger journeys (and hence p-km) of 4.5% and 6.23% in the years where comparison is possible using CSO (2009b).

[7]The aggregation of rail must be considered in the analysis as the energy intensity indicator can measure both technical efficiency and structural change through the reduction of rail freight in total rail activity.

[8]Using private car p-km data incorporating a low occupancy assumption could underestimate the increase in energy intensity.

[9]See footnote 6.

[10]Using a divisia index at constant structure across the branches of industry Cahill and Ó Gallachoir (2009) calculated an 11.3% improvement in energy intensity from 1995-2005. Dennehy *et al*. (2009) propose that structural changes accounted for 63% of intensity change in industry from 1995-2007.

[11]Data on floor area is unavailable and the necessary branch energy data to analyse structural shifts is unavailable. Per employee, fuel consumption decreased by 46% from 1990 to 2007 and electricity consumption increased 41% signalling the effect of ICT and air-conditioning (Howley *et al*., 2008).

[12]In Commercial Services total output grew by 52.8% from 2000-2007, within which the share of Financial Intermediation in grew from 18.4% in 2000 to 22.3% in 2007, Real Estate, Renting and Business activities grew from 35.9% to 38.9% and Wholesale and Retail Trade from 22.7% to 22.8%. Hotels and Restaurants declined from 6.8% to 5.5% and Transport, Storage and Communication from 16.2% to 10.5%.

[13]This study adopted the private car p-km data of DGTREN (2009) which assumed a drop in occupancy of 10.71% from 1.4 in 1990 to 1.25 in 2007.

[14]Data on private car occupancy in Ireland is poorly reported. NRA (2003) suggests a possible value of between 1.13-1.92 for transport modelling based on flow group. These assumptions do not establish a temporal pattern. In the Urban Environment Project, Casey (2009) suggests occupancy of 1.1 in 2006. This is limited the Greater Dublin Area and it is based around one trip type only through commuting data from the census (POWCAR). The Dublin Transportation Office estimated private car occupancy for all trip purposes of 1.37 in 2006 from survey

data (McCabe, 2009, personal communication). Again this data is limited temporally and spatially to the Greater Dublin Area in 2006.

[15]Car ownership in Ireland has risen by 91.2% from 1990 to 2007 from 227 to 434 private cars per thousand of the population (Howley *et al*., 2008).

[16]Private car occupancy rates are poorly reported in general throughout Europe. Nevertheless, the 'TERM' indicators of the European Environment Agency (EEA, 2003, EEA, 2005) have shown falling occupancy for each of the ten states with a multi-annual time series. Average occupancy for the United Kingdom, Germany and the Netherlands drops from 1.62 in 1990 to 1.46 in 2002, or 1.8-1.5 from 1990-1998 for the UK alone. This is not the same in absolute terms, but is similar in pattern to the occupancy assumption adopted for Ireland by DGTREN (2009). The pattern in Europe has been attributed by the EEA to increased individualisation in society including higher car ownership and smaller household size. These trends have been more pronounced in Ireland as it followed a path of rapid development catch –up, therefore it could reasonably be assumed that the occupancy assumptions should be higher and also the fall more significant. This increases confidence in the conclusion that intensity per p-km has increased and that falling occupancy is primarily responsible.

[17]According to Ó Gallachóir *et al*. (2009), the increase in engine sizes led to an increase in the specific fuel consumption of new Irish petrol cars by 1.6% from 2000 to 2005 from 6.91 litres/100 km to 7.02 litres/100 km. This fell slightly in 2006 to 6.74 litres/100 km. The equivalent for diesel cars was an increase of 1.78% from 6.19 litres/100 km in 2000 to 6.30 litres/100 km in 2005 followed by a drop in 2006 to 6.18 litres/100 km.

[18]Ireland's bias of investment and policy focus towards roads over public transport has been criticised (McDonagh, 2006). In recent decades, investment in transport in Ireland has favoured roads over public transport. From 2000 to 2005, investment in roads was €6.62 billion and in public transport was €2.5 billion (DTTAS, 2005).

[19]As discussed in section 4 data, the Road Public Passenger mode is an aggregation of bus and coach and taxi and hackney (SPSV's), as separate energy and $CO_2$ data for these modes are unavailable.

[20]SPSV vehicle kilometres increased by 168.5% from 362 to 972 million v-km from 2000 to 2007 (CSO, 2009b). During this same period the activity of bus and coach increased by just 42.6% from 188 to 268 million v-km.

[21] Fuel consumption by bus and coach increased from 40-77 ktoe from 1990-2007, while fuel consumption in the SPSV category increased from 17-119 ktoe from 1990-2007 (Howley *et al*. 2007; Howley *et al*. 2009).

[22]Using the fuel consumption data from Howley *et al.* (2009) and the p-km activity data adopted in this study, the 2007 energy intensity for SPSV's is estimated at 0.048 toe/thousand p-km and for buses and coaches 0.011 toe/thousand p-km.

[23]In addition, annual average v-km for SPSV's have decreased from 2000 to 2007 in the two smallest engine categories; 0-900 cc and 901-1200cc, and increased in all of the larger engine categories from 1201 – 1500cc upwards including the over 2200cc band (CSO, 2009b). This trend offsets technical efficiency gains in SPSV's.

[24] Rail p-km increased by 63.77% from 1990-2007.

[25]A noticeable reduction in rail intensity ($C_{intt}$=0.7757) occurred from 2004 to 2005, the first full year of LUAS operation. From 2004-2005 rail freight activity also declined -24.01%, but later years appear to show that reducing rail freight does not have a significant impact on decreasing intensity. Large reductions in rail freight activity occurred from 2005 to 2006 (-31.81%) and 2006 to 2007 (-37.65%) while overall rail intensity ($C_{intt}$=0.9855) and ($C_{intt}$=0.9903) did not decline significantly during these years. This suggests that rail freight is not a significant factor in decreasing intensity.

[26] Rail freight has declined significantly as a proportion of total rail activity (p-km + t-km) from 588.55 million t-km in 1990 to 128.91 million t-km in 2007 or from 32.44% to 5.48%.

[27]See footnote 25.

[28]Domestic aircraft movements increased by 106.74% from 1990-2007 while passengers handled increased by 90.21% (DAA, 2009).

[29]Under EU Council Regulation (EEC) No. 2408/92 Public Service Obligation (PSO) air services were established for connections from Sligo, Donegal, Knock, Kerry, Galway and Derry with Dublin. This PSO was established on the policy assumption that these services were considered vital for the economic development of their regions, and that services would not otherwise be provided on a commercial basis.

[30]Older dwellings deliver lower thermal efficiency as thermal standards were first introduced in Ireland in 1979. Sustainability in construction design and performance of new housing was improved through further legislative changes in 1992, 2002 and 2006.

[31]New dwellings have increased by 4.81% from 1990 to 1993, by 23.70% from to 2001 and by 49.15% to 2007.

[32]Changes in heating equipment included a considerable expansion in the use of central heating. The proportion of homes with central heating has increased from 52% in 1987 to 91% in 2005. Central heating is more efficient than the traditional Irish residential heating technology of open-fires and back-boilers (O' Leary *et al.*, 2008).

[33]From 2000 to 2008 household electricity prices increased by 99%; the price of kerosene rose by 78%; and natural gas prices increased by 87% (O' Leary *et al.*, 2008).

[34]Using heating degree days to calculate climate corrected energy consumption, from 1990-2006 energy use per dwelling decreased 8.9% uncorrected against 9.3% climate corrected (O' Leary *et al.*, 2008).

[35]The average floor area of new households has increased by 24% for new houses and 27% for new flats and apartments from 1990-2007 (Howley *et al.*, 2008).

[36]Electricity consumption per dwelling has increased by 31% since 1990 which has been attributed partly to increasing use of appliances (Howley *et al.*, 2008).

[37]Legislative change in the EU to encourage the energy efficiency of appliances includes the energy labelling of domestic appliances directive (2003/66/EC).

[38]The concept of 'carbon lock-in' described by Unruh (2000) and Unruh (2002) exists in the *Techno-Institutional Complex* (TIC) across the energy system arising through technological, organisational, social and institutional co-evolution and due to the self-referential nature of this process, escape conditions are unlikely to be generated internally. This is closely linked to the concept of inertia in capital stock discussed in Barker *et al.*, (2007) where the timescale for replacement of appliances such as cars may be fast but of infrastructure such as roads may be very long. Notwithstanding the potential for lock-in in other elements of the energy system in Ireland, given the increase in road infrastructure, car ownership, societal preference for motorised transport and embedding of particular policy and investment approaches in institutions, the amelioration and prevention of further lock-in in transport is of much concern with respect to reducing emissions.

[39]We are unaware of the concepts of 'carbon lock-in' or of 'development paths' being discussed elsewhere in literature pertaining to Ireland. Given the observations outlined in this study, these phenomena may be crucial to future Irish policy. In an examination of barriers to sustainable transport and policy recommendations, Browne *et al*. (2011) did not explicitly discuss these concepts, but allude to some of the issues underlying such as urban sprawl. As transport is under-investigated in Ireland, this study may provide a quantitative basis to progress policy options outlined in Browne *et al*. by addressing gaps in knowledge of driving forces identified by Rolle *et al*. (2005).

## Appendix

Applying the decomposition schemes detailed in Eqs. (4), (5) and (6) as a multiplicative LMDI I requires development through a number of steps detailed in Ang and Liu (2001). In this study, following these steps yields the decomposition formula in Eq. (7) for each of the economic sectors, in Eq. (8) for each of the transport sectors and in Eq. (9) for the residential sector:

$$\frac{Cecon_{j,t}}{Cecon_{j,0}} \equiv \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{CE_{ij,t}}{CE_{ij,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{FS_{ij,t}}{FS_{ij,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{RE_{j,t}}{RE_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{EIE_{j,t}}{EIE_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{ES_{j,t}}{ES_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{ET_{t}}{ET_{0}}\right]$$

(7)

$$\frac{Ctrans_{j,t}}{Ctrans_{j,0}} \equiv \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{CE_{ij,t}}{CE_{ij,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{FS_{ij,t}}{FS_{ij,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{RE_{j,t}}{RE_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{EIT_{j,t}}{EIT_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{TS_{j,t}}{TS_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{TT_{t}}{TT_{0}}\right]$$

(8)

$$\frac{Cres_{j,t}}{Cres_{j,0}} \equiv \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{CE_{ij,t}}{CE_{ij,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{FS_{ij,t}}{FS_{ij,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{RE_{j,t}}{RE_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{EIR_{j,t}}{EIR_{j,0}}\right]$$

$$\times \exp\left[\sum_{i=1}^{6} \varpi_{ij}(t^*) \ln \frac{HN_{t}}{HN_{0}}\right]$$

(9)

Using the nomenclature for the determinant effects detailed in Table 2, for each of the economic sectors for $j = 1,2\ldots4$, Eq. (7) can then be re-written as:

$$C_{tot} = C_{emc} C_{ffse} C_{repe} C_{\text{int}\, e} C_{es} C_{et} \quad (10)$$

Further to this, for each of the transport sectors for $j = 5,6\ldots10$, Eq. (8) can then be re-written as:

$$C_{tot} = C_{emc} C_{ffse} C_{repe} C_{\text{int}\, t} C_{ts} C_{tt} \quad (11)$$

For the residential sector for $j = 11$, Eq. (9) can then be re-written as:

$$C_{tot} = C_{emc} C_{ffse} C_{repe} C_{\text{int}\, r} C_{hn}$$

(12)

In order to further aggregate the indices of change in $C_{tot}$ for each of the individual sectors for $j = 1,2,3\ldots11$ to total change in all sectors, the consistency of aggregation provided for by LMDI I must be respected. As per Ang (2005), change within each sector is aggregated using the following general IDA identity:

$$V = \sum_i V_i = \sum_i x_{1,i} x_{2,i} \ldots x_{n,i} \quad (13)$$

The decomposition framework applied in this study provides a link between the individually decomposed sectors in the case of the economic and transport activity share effects. However, as each sector is decomposed separately, aggregation to total change in emissions in all sectors for year *t* must be achieved by weighting the index of change ($C_{tot}$) for each individual sector, by the sectors' share of total emissions in 1990. In Eq. (14), the left hand-side represents the index of change in total $CO_2$ emissions from all sectors, ($C_{tij}$) indicates the aggregation of the determinant effects in each individual sector, year *t-1* is the base year for analysis, year *t* is the target year and 0 is the reference year (1990) for sector $j = 1, 2, \ldots, 11$;

$$\frac{C_t}{C_{t-1}} = \sum_{j=1}^{11} \sum_{i=1}^{6} C_{tij} \cdot \frac{C_{j,0}}{C_0} \tag{14}$$